United States
Department of
Agriculture

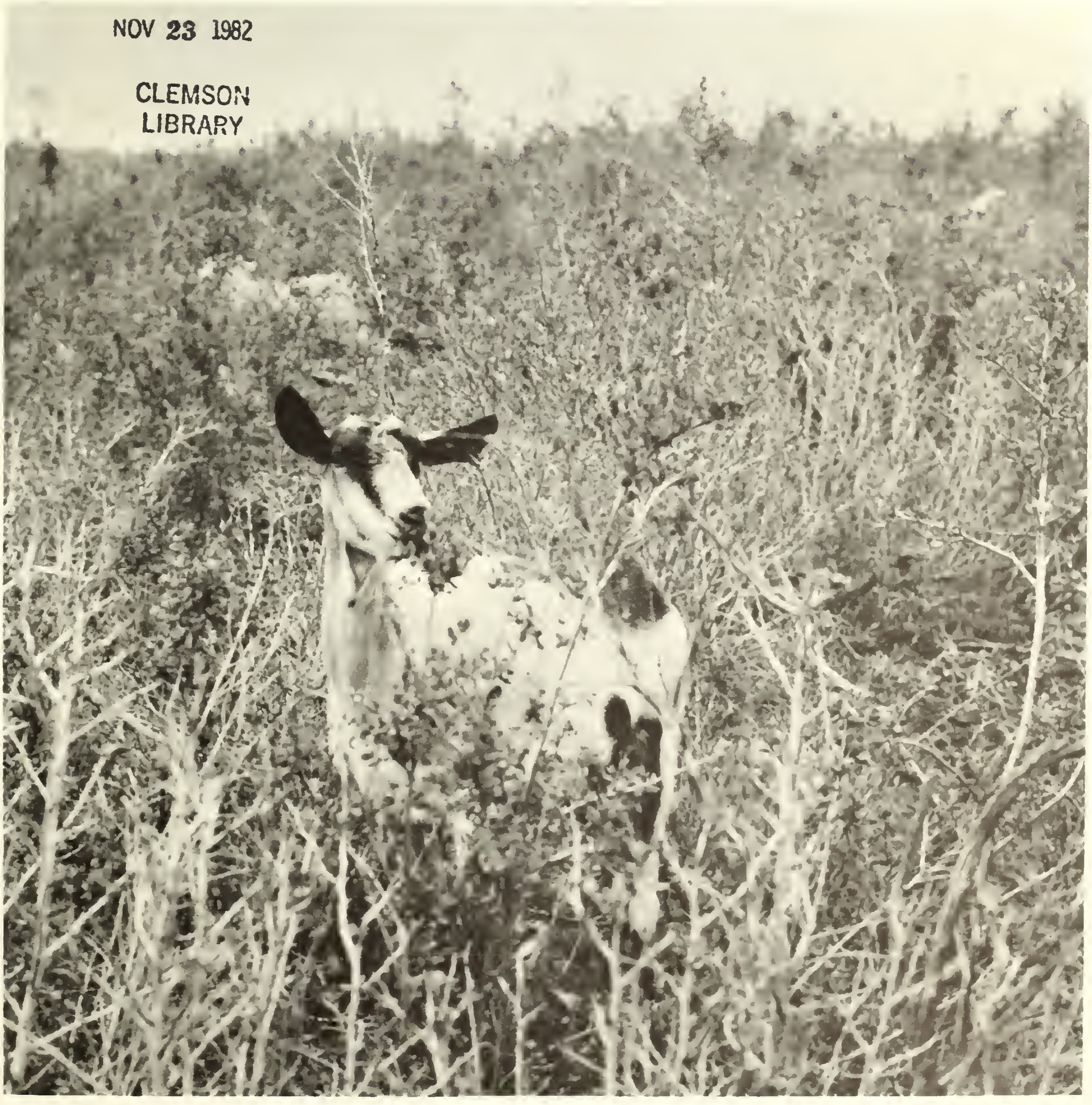
Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

General Technical
Report PSW-59

Using Goats to Control Brush Regrowth on Fuelbreaks

Lisle R. Green   Leonard A. Newell



The Authors:

LISLE R. GREEN is a range scientist with the Station's Vegetation Management Alternatives Research and Development Program, with headquarters in Riverside, California. He was formerly in charge of the Station's research on development and maintenance of fuelbreaks. He earned bachelor's (1941) and master's (1948) degrees in range management at Utah State University. He has been on the Station's research staff since 1948, except for 5 years when he taught range management and soil science at California Polytechnic State University, San Luis Obispo. **LEONARD A. NEWELL** is a manager of the California Department of Forestry's Vegetation Management Program, with headquarters in Sacramento, California. He was formerly Resource Officer, Cleveland National Forest, Forest Service, U.S. Department of Agriculture, San Diego, California, and program manager of the Forest's Laguna-Moreno Demonstration Area. He has also served on the Huron-Manistee and White Mountain National Forests in Michigan and New Hampshire. He is a forestry graduate (1967) of the University of Michigan.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

September 1982

Using Goats to Control Brush Regrowth on Fuelbreaks

Lisle R. Green, Leonard A. Newell

CONTENTS

Introduction 1
Do Goats Damage the Resource? 1
Damage to Vegetative Cover 1
Preferences for Plants 3
Comparisons with Other Livestock 5
Goat Management on Fuelbreaks 5
Selection of Breed 5
Breeding and Wether Goats 6
Rate of Stocking 6
Age of Brush 7
Herding and Fencing 7
Water and Supplemental Feeding 8
Other Considerations 9
Goats and the Environment 9
Competition with Wildlife 9
Damage to Native Plants 9
Losses to Cold Weather 9
Losses to Predators 10
Losses to Poisonous Plants 10
Economic Returns from Goat Management 11
Subsidizing Herd Owners 11
Marketing Goats 11
References 12

IN BRIEF...

Green, Lisle R.; Newell, Leonard A. **Using goats to control brush regrowth on fuelbreaks.** Gen. Tech. Rep. PSW-59. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 13 p.

Retrieval Terms: Angora, brush control, diet of goats, fuelbreaks, goat losses, predators, Spanish goats, wethers

Fuelbreaks offer a promising approach to the control of wildfires. On these wide strips through brushfields and around communities, vegetation of low volume and low growth is maintained to contribute to firefighting safety and provide a place for backfiring. After mature vegetation has been removed on fuelbreaks, herbicides have been the primary tool for controlling brush regrowth. But the continued use of chemicals is threatened by political and environmental considerations. Using goats to control this regrowth appears to be a promising alternative.

Goats have been accused of destroying the resource, but they generally reap the blame for prior mismanagement involving overgrazing by other animals, indiscriminate use of fire, and baring of the soil by various means. Goats can utilize woody vegetation on which other livestock would starve, and so they are usually present during the final stages of land degradation. Test results show that properly managed goats eliminated or controlled woody vegetation at the same time that herbaceous vegetation reoccupied the site.

Goats will eat a wider variety of plants than other classes of livestock, but unless they are subjected to grazing pressure, will only eat plant parts that are in a favorable growth stage from species they relish. Goat diets, when averaged over a year, usually contain at least half browse, the rest grasses and forbs. During spring, goats seek out the lush herbaceous growth, then concentrate more and more on browse through the other seasons. Forbs are taken more or less in proportion to their abundance.

Goats are least selective on first-year brush regrowth, and become more selective as the brush is older. In mature stands, much or most of the brush is out of their reach.

Goats ate first-year regrowth of chamise, desert ceanothus, California bush buckwheat, and Eastwood manzanita, but scarcely touched 5-year-old plants of these species, except in bedding grounds or other places of confinement. Mountain mahogany and scrub oak were most-favored species in the 5-year-old brush stands.

For fuelbreaks, Spanish goats have some advantages over Angoras. They are larger, and better able to fend off predators, and the marketable kids are larger. They are somewhat better browsers than Angoras, and are more hardy. With good feed, and intensive management, Angoras may be more profitable, however.

Recommended stocking rates for goats are 0.5 to 3 acres (0.2 to 1.2 ha) per goat the first year after clearing, depending on the amount of regrowth, and reduced stocking thereafter. Larger numbers of goats may be used for short periods. Stocking rates that continuously or two or three times annually remove all leaves and small twigs will kill small shrubs in 2 years, and most larger ones in 3 or 4 years.

An economically viable breeding goat herd would be at least 1500 goats. Buying wethers or nonfertile nannies in spring and selling them in fall should achieve management objectives, but a subsidy would probably be needed.

The question of whether goats should be herded or fenced for control is still a moot one. Some combination of practices is probably the best. Getting good herders and good dogs is a problem.

The supply of water and food helps determine whether goats can utilize an area. Fuelbreaks are frequently in dry and remote areas where water must be provided by hauling, development of springs or wells, and piping the water to where it is needed. Supplemental feeding appears to be a desirable practice during the winter, particularly for pregnant animals. Any livestock feed available can be used.

Mountain terrain offers other problems. Roads are frequently not good, especially during the winter. Rough, steep terrain encourages injury or lameness, and remoteness from urban amenities discourages herders.

Goats in southern California have been lost to cold, stormy weather and to predators. Kids are particularly sensitive to cold, wet weather, and protection should be provided for nannies and their kids. Predator losses have not been large when the goats were herded, and the herder could occasionally shoot at a coyote stalking the goats. Poison plants have not caused losses on the Cleveland National Forest, but with goats under grazing stress, poison plants are a potential source of losses.

The inability to show an economic return has restricted use of goats on wildlands. The owner-operators have not been experienced local livestock producers, banks have refused to lend sufficient funds for an economic size unit, and the market for goats is uncertain. Some form of subsidy by the using agency will probably be necessary.

Figure 1—On fuelbreaks, woody fuels on wide strips are reduced or eliminated to assist in control of wildfire.

Fire managers, land managers, and other interested citizens agree on "fuelbreaks" as one strategy to help control wildfire. Fuelbreaks are strips through brushfields or around communities, or other areas of considerable value, 200 to 400 ft (60 to 120 m) wide, on which the values at risk determine the intensity of fuel management (*fig. 1*). Low volume, low growing vegetation that will not support intense fire is generally maintained on the fuelbreaks to contribute to firefighter safety and provide a place for backfiring (Green 1977).

Clearing dense chaparral as part of fuelbreak construction is frequently an expensive procedure, and regrowth from sprouting brush crowns and seed soon negates the clearing unless countermeasures are immediate (Plumb 1961). Maintaining fuelbreaks to the prescribed vegetation level is one of the most serious problems faced by all agencies charged with doing so. The problem is compounded by these constraints:

- Maintenance with herbicides is generally unacceptable from a political and environmental standpoint.
- Maintenance with prescribed fire is often impractical because the young-age brush will burn only under severe conditions, when prescribed burning is unsafe, unless grass is sufficient to carry a light fire.
- Mechanical treatment (brush rakes, heavy disks, and other means) is expensive and possibly damaging to the site.
- Handtool labor is not only expensive (as high as $2000/acre [$5000/ha]), but slow.

Faced with limited budgets, personnel, and other constraints, and with the need to maintain fuelbreaks, some land managers have experimented with livestock—especially goats—as a promising way of lowering maintenance costs. This is an appealing idea because goats naturally consume large proportions of brush species in their diets and because the market for goat meat appears to be expanding. Some ranchers are interested because controlling brush usually improves conditions for grasses and forbs, which cattle and sheep prefer.

This paper examines the various aspects of using goats to control brush regrowth, summarizes knowledge and experience gained to date by the Forest Service and its cooperators, and considers some common misconceptions about goats and their effects on ecosystems—ideas that originate from mismanaged situations.

Our experience is mostly from using goats on fuelbreaks, on the Cleveland National Forest in southern California, but most of the lessons can be applied elsewhere on wildlands.

DO GOATS DAMAGE THE RESOURCE?

A study of the history of goat use in Arizona, California, New Mexico, Texas, and elsewhere indicates that goats under proper management are probably less damaging than any other class of livestock or large wild game. They can, however, eat more woody vegetation than other domestic livestock and because of this, managers can force them to overuse and destroy woody as well as herbaceous vegetation.

Damage to Vegetative Cover

In west Texas on ranges that were in good condition in the late 1940's, ranchers maintained predominantly English breeds of beef cattle—Hereford, Angus, and a few Shorthorn. Ranges in fair range condition were frequently stocked with sheep and Brahma cattle. On ranges in poor condition, goats were stocked alone, or with other livestock. These lands had been grazed, and often overgrazed, for more than 100 years. When grazing abuse had eliminated most desirable vegetation and much of the topsoil, only goats could efficiently harvest the remaining unpalatable, poor quality woody and herbaceous vegetation. But because goats were on the land after the range was in poor range condition, they were frequently blamed for the damage done by many decades of abuse by other classes of livestock.

Goats can survive and become a profitable commodity while consuming only coarse forages on which cattle and sheep have difficulty surviving (Merrill 1975, Merrill and Taylor 1976). Consequently goats can destroy more varieties of vegetation than cattle or sheep under conditions of mismanagement that cause severe range deterioration. With intense overgrazing, cattle are the first to go, then sheep survive for a time, but after their numbers are reduced because of poor range conditions, the goat can and will survive. In studies in Texas, goats were the least destructive grazers under proper stocking, then cattle, sheep, and horses the most destructive (Merrill 1975).

In the Mediterranean area, goats are "really only the last link in a vicious chain of land devastation brought on by indiscriminate burning, cutting, grazing, slope denudation, and cultivation" (Naveh 1972). Most of the world's deteriorated rangelands were caused by overgrazing by cattle and sheep, and this condition eventually left pasturage that only the goat could utilize (Huss 1972).

Accounts about goats damaging vegetation on mid-Pacific Islands are found in the literature (Calvopina and Vries 1979; Coblentz 1976, 1977; Spatz and Mueller-Dombois 1973; Vries 1979; Vries and Calvopina 1979). Goats have been on the Channel Islands off the southern California coast for at least 150 years (Coblentz 1976), as have sheep (Coblentz 1980, Minnich 1980). The goats were released on the Channel and other Pacific Islands during explorations or settlement, and into an environment where they had no natural enemies. To prevent further elimination of native plants and to accomplish recovery efforts for seven threatened and endangered plants and animals, the U.S. Navy removed about 20,000 goats from San Clemente Island between 1973 and mid-1981. An estimated 500 goats remained for later removal effort. Starting in 1877 large numbers of sheep were brought to San Clemente Island (Raven 1963). Sheep were confined to fenced pastures all along the plateau that forms the Island's main land mass. They were removed after the U.S. Navy acquired San Clemente Island in 1934 (Larson 1981).

We believe that a buildup in goat numbers in chaparral areas similar to that which occurred in the Pacific Islands could not occur. Goats in such areas are under the control of herders with dogs trained to bring back animals that might stray. Even more important, predators—especially coyotes but also bobcats, dogs, and occasionally mountain lions—are never far away from a goat herd. If both male and female goats escaped from a herd, any kids born would be harvested by the coyotes and bobcats, even if these predators were less successful at killing the mature goats. Many small goat herds exist throughout California and in some instances, goats were abandoned. If they had the potential to expand their numbers after escaping, this would surely have happened by now.

Goats under moderate or intermittent stocking reduced the brush cover, while annual grasses and forbs increased, during 2- to 4-year browsing periods in both central and southern California. Goats confined in small enclosures over several days or weeks bared the soil as they removed any herbaceous vegetation and the leaves and twigs from all shrubs. The effect of goats in these holding pens and other areas of concentration has evidently not been serious, however, because annual grasses and forbs occupied the bare soil between shrubs a growing season after goat use

Figure 2—Annual grasses increased as volume of brush decreased after heavy browsing for 1 or more years.

was discontinued—even where it had not previously been present under thick brush (*fig. 2*).

As Angora goats grazed at a heavy rate for 23 years at the Research Station in Sonora, Texas, a perennial grass understory developed (Merrill and Taylor 1976). In South Africa, grassland being invaded by brush (658 shrubs/acre or 1625/ha) was burned off, then stocked with goats. At the end of the season when cattle were admitted, grass production did not differ between plots with goats and those without (Trollope 1974).

Our experience then and that reported in the literature is that goats under proper stocking will control brush without damaging the herbaceous vegetation, or the soil.

Preferences for Plants

A popular assumption is that goats will eat practically anything. They will take a wider variety of plants than other classes of livestock (Bryant and others 1979, Fraps and Cory 1940, Huss 1972, Merrill and Taylor 1976, Naveh 1972), but will feed selectively if there is a choice (Green and others 1978). They will select the plant parts and species that are in a favorable stage of growth. Goats include a large proportion of browse in their diets—generally more than 50 percent over a year—and they eat more browse than other classes of domestic livestock (Askins and Turner 1972, Aucamp 1975, Bryant and others 1979, Campbell and others 1962, Dutoit 1972, Huss 1972, Wilson 1969). Grasses and forbs were dominant in goats' diet, especially during spring on lightly grazed range. And grasses and browse were dominant in ther diet on heavily grazed range near Sonora, Texas (Bryant and others 1979, Malechek and Leinweber 1972). Forb consumption tended to be limited by availability. In a west Texas study, goats fed on woody plants 65 percent of their grazing time through the year, and on weeds and grass about 35 percent (Askins and Turner 1972).

In July 1979 in southern California, 400 goats were placed in an 80-acre (32-ha) fenced area that had burned a year earlier. The goats concentrated first on a sparse stand of dry forbs, then the shrub regrowth. When this was browsed to about 50 percent of the available browse, the goats turned to a stand of dry perennial grass, mostly wheatgrass (*Agropyron* sp.), hardinggrass (*Phalaris tuberosa* L. var. *stenoptera* [Hack.] Hitchc.), and some orchard grass (*Dactylis glomerata* L.). Earlier, in 1976, goats placed in small pastures containing 5-year-old regrowth browsed two abundant shrubs—mountain mahogany (*Cercocarpus betuloides* Nutt.) and scrub oak (*Quercus dumosa* Nutt.)—but ignored chamise (*Adenostoma fasciculatum* H. & A.) and bush buckwheat (*Eriogonum fasciculatum* Benth.), except for flowers, and Eastwood manzanita (*Arctostaphylos glandulosa* Eastw.).

During the 1974-76 seasons, Angora goats in a heavily stocked central California pasture kept both woody regrowth and herbaceous vegetation closely grazed. In another pasture stocked at half the heavy stocking rate, goats kept the brush regrowth browsed back but only lightly grazed the annual herbaceous grasses and forbs. When green herbaceous feed became available, the goats in both central and southern California searched out young green grass and forbs and almost ignored brush regrowth. A rancher commented that goats help eliminate tarweed (*Hemizonia* sp.) (Elam 1952).

Goats on the Cleveland National Forest in San Diego County were selective in choosing their diets, as are all animals. They selected green, succulent, tender plants in preference to those that were dry and woody. During early spring, much of what they ate was grass and forbs. As the annuals dried, preferred shrubs made up a larger proportion of the diet. As grazing pressure increased and as preferred species became less available, goats shifted to less preferred shrubs and trees. If confined behind a strong fence, they ate all the available foliage from all woody plants as well as all herbaceous vegetation.

Western or birchleaf mountain mahogany was highly attractive to the goats and always received the heaviest use of any abundant browse during our southern California test (*table 1*). We rated use of 5-year-old regrowth on a scale of 0 = no use to 10 = 100 percent of leaves and small twigs taken. Birchleaf mountain mahogany use was usually rated 9.5 or 9.6 (Green and others 1978). The growth habit of

Table 1—*Preferences of goats for southern California shrubs under moderate grazing pressure*

Common name	Scientific name	Regrowth[1]	
		1 year	5 years
Chamise	*Adenostoma fasciculatum*	6 to 7	1 to 2[2]
Red shank	*A. sparsifolium*	ND[3]	0 to 1
Eastwood manzanita	*Arctostaphylos glandulosa*	7	0 to 1
Mexican or pointleaf manzanita	*A. pungens*	2 to 3	ND
Big sagebrush	*Artemisia tridentata*	ND	2 to 3
Desert ceanothus	*Ceanothus greggii*	7	1 to 3
Whitethorn ceanothus	*C. leucodermis*	5	5
Mountain mahogany	*Cercocarpus betuloides*	10	9 to 10
Bush buckwheat	*Eriogonum fasciculatum*	5	0 to 1[2]
Honeysuckle	*Lonicera* subsp. *Johnstonii*	ND	10
Toyon	*Heteromeles arbutifolia*	ND	6 to 7
Hollyleaf cherry	*Prunus ilicifolia*	ND	2 to 3
Scrub oak	*Quercus dumosa*	9	8
Scrub interior live oak	*Q. wislizenii frutescens*	ND	5
Redberry	*Rhamnus crocea ilicifolia*	ND	9 to 10
Sugarbush/sumac	*Rhus ovata*	ND	0 to 1
Squawbush	*Rhus trilobata*	8	1
White sage	*Salvia apiana*	0 to 1	ND
Bluecurls	*Trichostema parishii*	ND	0 to 1[2]

[1] Rating: 0 = no browsing, 10 = 100 percent consumption of available leaves and small twigs.

[2] Mostly flowers preferred.

[3] No data.

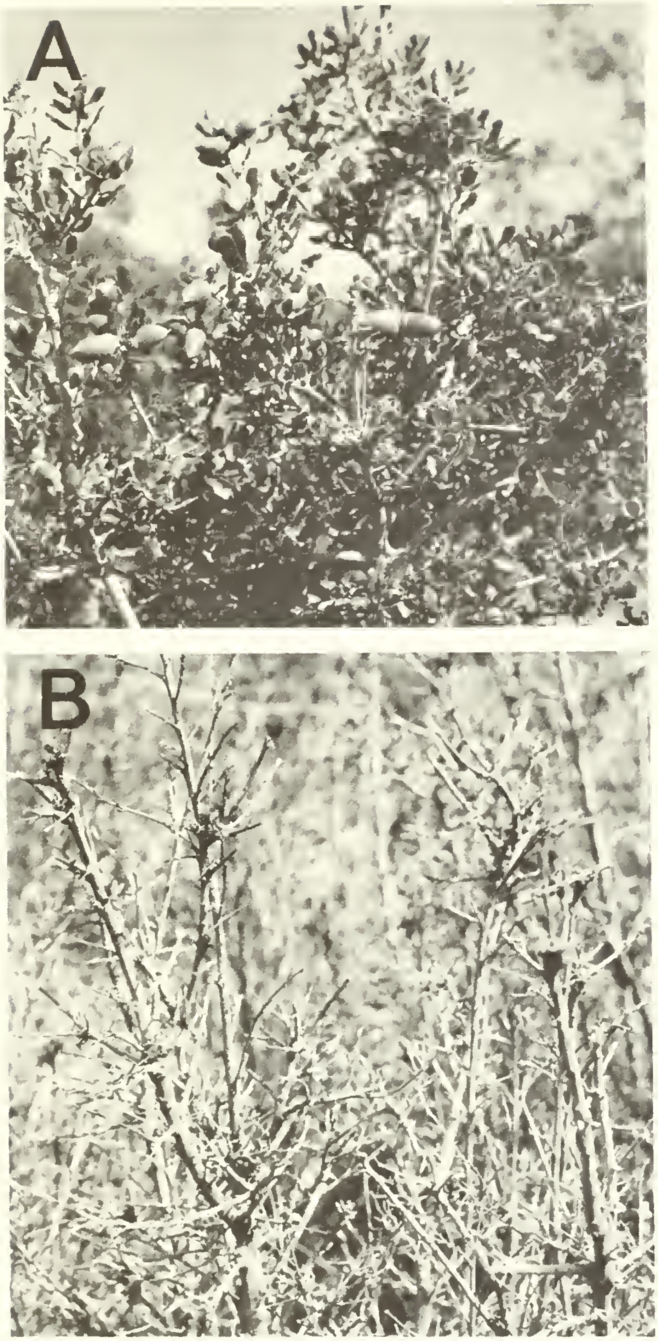


Figure 3—Goats usually favor scrub oak *(A)* and strip the plant of nearly all leaves and fine twigs *(B)*, before consuming shrubs, such as chamise, desert ceanothus, and manzanita.

mountain mahogany is open, with all the twigs readily available, except on tall plants. No sharp spines restrict browsing. Scrub oak was the second abundant, palatable shrub in southern California. Always browsed, it was rated about 8—somewhat less than the utilization of mountain mahogany (*fig. 3*).

Goats are partial to interior live oak (*Quercus wislizenii* A. DC.) sprouts (Sampson 1944). We observed in the central Sierra Nevada foothills that goats ate interior live oak avidly. However, during summer 1979 in southern California, goats seemed less interested in the shrubby form, the variety *frutescens*.

Two other southern California shrubs are palatable but grow in only trace amounts. Honeysuckle (*Lonicera subspicata Johnstonii* [Keck]) was always browsed back to stems ¼ inch (0.64 cm) diameter, or larger. Redberry (*Rhamnus crocea ilicifolia* [Kell.] Greene) was also highly favored. Its defense was to grow with a canopy of dense stiff branchlets which protected some of the leafy growth.

Chamise and Eastwood manzanita are common to abundant shrubs in southern California, but they do not attract goats. While 80 to 100 percent of available browse of some species was being taken, chamise use was rated 1 to 2. It would have been even less had not the goats selected chamise flower stalks. Only a few twigs of Eastwood manzanita were taken—a rating of about 0.5, if the goats had a selection of shrubs. When nine Spanish goat wethers were fenced inside a 0.5-acre (0.2-ha) enclosure for 2 weeks, they concentrated on green grass, forbs, and dry oak leaves during the 3 days they were available, ate mostly scrub oak during the 4 days it lasted, then chose chamise in preference to Eastwood manzanita or desert ceanothus (Sidahmed and others 1981).

California bush buckwheat usually comprised some small percentage of the available browse. Its flowers were eaten by the goats, but not its leaves.

Desert ceanothus (*C. greggii* A. Gray) was sometimes locally abundant, but we rated utilization only 1 to 3. Flowers were browsed, and sometimes twigs from seedlings or other small plants. Whitethorn ceanothus (*C. leucodermis* Greene) occurred as occasional scattered shrubs, and its use averaged about 5. Hollyleaf cherry (*Prunus ilicifolia* [Nutt.] Walp.) utilization was 2.2.

Bluecurls (*Trichostema parishii* Vasey) is a highly scented shrub found in trace amounts. It was not browsed, except for the flower stalks.

Squawbush (*Rhus trilobata* Nutt.) was generally not selected for browsing, although its habit of dropping leaves during the dry summer suggested leaf utilization. Some first-year squawbush regrowth was browsed, however. Neither sugarbush sumac (*Rhus ovata* S. Wats.) nor white sage (*Salvia apiana* Jeps.) was browsed during the limited contact goats had with them. On Santa Catalina Island, laural sumac (*Rhus lauriana* Nutt.) and white sage were abundant where goats concentrated, indicating that they are not browsed by choice (Coblentz 1977, Minnich 1980). Poison oak (*Toxicodendron diversilobum* [T. & G.] Greene) was not abundant, but was eaten wherever the goats found it.

Red shank (*Adenostoma sparsifolium* Torr.) was usually ignored, except the goats sometimes rubbed their heads and horns on it. The first browsing of red shank observed by a herder was at the approach of a storm. When bed grounds enclosed red shank, goats stripped foliage from the plants. Other use occurred in holding pastures under grazing stress.

A green herbaceous plant the goats ignored even under close utilization was wild peony (*Paeonia californica* Nutt.). Telegraph weed (*Heterotheca grandiflora* Nutt.) also had a low palatability rating, even though not quite dry.

A communal group maintained goats on the Santa Barbara Ranger District, Los Padres National Forest for four years (Brotherhood of the Sun 1974).

- Plants browsed yearlong, but especially during the fall and winter, along with dry grass, were: scrub oak (*Quercus dumosa*), coast live oak (*Q. agrifolia*), chamise (*Adenostoma fasciculatum*), California bush buckwheat (*Eriogonum fasciculatum*) (when in bloom), manzanita (during the winter), California sagebrush (*Artemisia californica* and *A. tridentata*), toyon (*Heteromeles arbutifolia*) (uncommon), and blue elderberry (*Sambucus cerulea*) (uncommon).
- Shrubs not browsed were: yerba santa (*Eriodictyon californicum*), sugar sumac (*Rhus ovata*), bigpod ceanothus (*Ceanothus megacarpus*), blue blossom ceanothus (*C. thrysiflorus*), juniper and yucca.

Comparisons with Other Livestock

At the University of California's Hopland Field Station in northern California, browse, mostly from oaks, made up 7.3 percent of the diet of both cattle and sheep during the dry summer months (Van Dyne and Heady 1965). Diet samples showed that chamise and interior live oak were eaten in significant amounts by sheep only when all herbaceous material was removed. Oak was preferred to chamise (Wilson and others 1971). In another northern California study, grazing treatments with cattle and sheep did little to delay the regrowth of brush (Murphy and others 1975). In studies at the San Joaquin Experimental Range in central California, browse made up 1 to 2 percent of the diet of beef cattle in one study (Wagnon 1963). In another Experimental Range study, less than 1 percent of the diet of Hereford steers on fertilized range during summer was browse; but forbs, representing 27 percent of the fertilized herbage, was 23 percent of the diet one year and 25 percent the next (Green and others 1958).

Cattle diets averaged approximately 0 to 3 percent browse, 10 to 20 percent forbs, and 70 to 90 percent grass on 18 large study areas near Roswell, New Mexico during 1979-80. Sheep diets averaged from about 5 to 11 percent browse, 40 to 70 percent forbs, and 20 to 50 percent grass (Beasom 1980). Similarly, in north central Texas, cattle ate only limited amounts of tender browse and did not keep brush regrowth under control (MaGee 1957). On the Angeles National Forest in southern California, sheep did not touch 2-year-old chamise regrowth even though herded through a study area. At Sonora, Texas, 60 percent of the sheep diet averaged over a year was grass, 22 percent was browse, and 18 percent was forbs (Bryant and others 1979).

GOAT MANAGEMENT ON FUELBREAKS

Two breeds of goats—Angoras and Spanish—are used in brushlands. The Angora, developed primarily for mohair production, takes its name from the capital city of Turkey where it was introduced to the western world (Merrill and Taylor 1976, Spurlock and others 1978). The Spanish goat, also known as hair goat or meat goat, is descended from goats brought to the United States from Spain. A third type of goat is the milk goat, which is generally not considered for brush control because of the formidable problem of handling and transporting milk in backcountry areas. The milk goat has been crossed with Spanish goats, however, and the Spanish goat may be descended from milk goat breeds.

Selection of Breed

The Angora nanny or doe should weigh 70 to 80 pounds (32 to 36 kg) if in good condition, the billies 125 to 175 pounds (56 to 80 kg). Spanish nannies in good condition will weigh 80 to 100 pounds (36 to 45 kg), the billies commonly 150 to 175 pounds (68 to 80 kg) (Spurlock and others 1978). The larger size of the adult Spanish goat gives it some advantage in fending off predators.

The Spanish goat is considered to be a somewhat better browser than the Angora. On the Edwards Plateau in Texas, Spanish goats consumed little grass, moderately grazed forbs, and completely utilized available browse. Angoras grazed grasses to a short stubble, took 100 percent of the forbs, and 80 percent of the available browse (Merrill 1975). Taylor (1975) suggested that Spanish goats are more efficient browsers and are more efficient in controlling brush under poor range conditions than the Angora. On ranges in excellent condition at Sonora, Texas, however, Angora and Spanish goats did not differ significantly in what they ate (Bryant and others 1979).

The Spanish goat is considered to be hardier than the Angora and has a wider range of weather adaptability. In Texas, for example, the Spanish goat can be produced in all sections, while Angora production is limited to low rainfall areas (Groff 1973). Angoras probably need more human help during kidding than do the Spanish goats (Spurlock and others 1978), and browsing in brush tends to degrade the mohair more than grazing in grassy areas.

From 1963 to 1972, mohair sold for 40 to 80 cents per pound—an unrewarding price to the grower. Since then the price has escalated rapidly, and $2.50 (in 1973) to $7.00 per pound has made the return from mohair an important consideration when choosing between the two breeds.

Angora nannies will normally kid once each year and frequently produce twins. Spanish nannies will sometimes breed twice a year, or once each 8 or 9 months, and produce twins (or sometimes triplets) with greater regularity than do the Angoras. Kid crops in either breed run from 40 percent under poor range conditions to 150 percent under a high plane of nutrition (Dollahite 1972, MaGee 1957, Merrill and Taylor 1976, Spurlock and others 1978). Spanish goats on Catalina Island averaged less than one birth per 16 months and only 1.2 young per birth due to the poor nutritional level in areas of high goat density (Coblentz 1976). Nannies that are undernourished tend to miscarry or suffer fetal absorption (Spurlock and others 1978). In southern California during one winter on poor browse, many nannies simply refused to claim their kids, or abandoned them. A kid crop of 100 percent is suggested as a desirable goal under wildland conditions.

Which type of goat then for California brushlands? Spurlock and others (1978) suggested that if the goats will be given only rudimentary care, especially under harsh, dry conditions, the Spanish goat should be chosen. If the flock is to be well and intensively managed, however, an Angora flock will eat almost as much brush and will produce more income.

Breeding and Wether Goats

Besides selecting the breed of goat for the brush control job, the goat operator or forest manager must decide between maintaining a breeding herd or a herd of wethers, the castrated male goats. In some respects, wethers appear to be the better choice for fuelbreaks.

The wether is a large animal, weighing about the same as the billies or bucks, and considerably more than the nannies. This extra size makes him less vulnerable to predators. It also results in a large mohair clip if the wether is of the Angora breed. Wethers can be retained for 5 to 7 years, or they can be sold after 1 or 2 years, and new animals purchased (Plaister and Dal Porto 1973).

Brush eradication with goats frequently requires temporary overbrowsing during parts or all of 3 or 4 years needed to kill brush. Breeding animals are more sensitive to the lack of adequate quality feed, and the kid crop and size of kids produced may be affected adversely by overbrowsing or overgrazing. The needs of wethers are less critical (Spurlock and others 1978).

Another advantage of wethers is that the rancher does not have the bother and expense of kidding his flock. Kidding requires night work, extra fencing, and extra handling of the animals, including maintaining two herds during the kidding season.

Wethers are not without problems that the goat owner and land manager must consider:

- The greatest source of income from Spanish goats is the sales receipts from a good kid crop. With wethers, the sales receipts from the cull goats may be less than the cost of replacements.
- The main source of replacement wethers is the Edwards Plateau area of Texas. Market conditions and transportation costs fluctuate widely through the year and from year to year. Favorable prices may not coincide with needs for fuelbreak browsing.

We believe that a Spanish breed wether goat operation will probably have to be subsidized by the benefiting agency. We are less sure if the wethers are from the Angora breed, and mohair brings a good price. We have not had enough experience to predict whether or not a breeding herd could be economically viable under fuelbreak conditions, but believe subsidy requirements might be less than for wethers. Additional research is needed in these areas.

Rate of Stocking

The stocking rate will depend upon the density and vigor of woody regrowth, on whether the objective is to kill the brush rapidly or to simply restrain it, and whether the goats will be in the pasture continuously or intermittently.

Huss (1972), working in Mexico, stocked goats at 0.9 and 1.8 acres (0.36 and 0.73 ha) per goat year. Grass use was "slight," and there was selectivity among the brush species at both rates. In the Edwards Plateau, of Texas, one animal unit[1] per 18 acres (7.3 ha) is considered moderate stocking. However, this rate of stocking—3 acres (1.2 ha) per goat—did not control brush regrowth, and Merrill (1975) recommended one goat per 2 acres (0.8 ha). In Israel, the recommendation is for 1.6 to 1.8 acres (0.65 to 0.73 ha) per goat on a continuing basis (Naveh 1972). When brush was uniformly dense and continuous in New Zealand, and up to 6 ft (1.8 m) tall, six goats per acre (15/ha) for a 12-month grazing season opened up the stand. Three goats per acre (7/ha) prevented reversion to brush or mixed brush and weeds (Batten 1979).

For northern California, Sampson (1944) suggested that three goats per acre (7/ha) yearlong on productive site and as low as one goat per acre (2.5/ha) on poor sites for 2 years would keep brush regrowth from getting out of the reach of goats. A reduced stocking rate the third and succeeding year would be in order if goat stocking was to the full capacity of browse production the first 2 years.

In Amador County, California, in the Sierra Nevada foothills, the recommended stocking rate is two mature goats per acre (5.0 goats/ha) the first year after brush clearing, one per acre (2.5 goats/ha) the second year, and one goat to 2 acres (1.2/ha) thereafter (Spurlock and others 1978).

The stocking rate may be heavier for short periods and frequently should be to get utilization of unpalatable species

[1]One mature cow, or five or six sheep or goats.

without excessive, continuous browsing of palatable shrubs. Merrill and Taylor (1976) suggest five to eight goats per acre (12 to 20/ha) for 30-day periods on the Edwards Plateau. At the San Juan Basin Research Center in Colorado, gambel oak regrowth was stocked at eight goats per acre (20/ha) for 25 days, with a second browsing period later in the year. The stocking rate was reduced each year for 4 years at which time 95 percent of the sprouts were dead (Davis and others 1975). In southern California, 400 goats on 2.5 acres (1 ha) for 2 days stripped the leaves and small twigs from the palatable species making up 80 percent of the 5-year-old, dense shrub cover. Less palatable species—chamise, Eastwood manzanita, and bush buckwheat making up about 15 percent of the available browse—were not browsed until after available leaves and small twigs had been removed from the palatable shrubs (Green and others 1978).

Age of Brush

For the reduction or maintenance of brush stands, goats are most effective on first-year regrowth—least effective in mature chaparral. The young and tender sprouts characteristic of regrowth following burning or mechanical clearing are more palatable and probably more nutritious (Huss 1972, Sidahmed and others 1982) than the old growth. And they are also more available.

First-year regrowth was more acceptable to goats than 5-year regrowth on the Cleveland National Forest (Green and others 1978). They were selective, but 1-year-old chamise, desert ceanothus, California buckwheat, and Eastwood manzanita were browsed to ratings of 5 to 8 on a 0 to 10 scale, whereas their ratings in 5-year-old stands were 0 to 3. It appeared that goats concentrating on 1-year regrowth would graze all species more uniformly than they would older brush (*table 1*).

When 5-year-old brush regrowth was stocked with goats, herbage preferences were at once apparent. Leaves and tiny twigs were 90 to 95 percent removed from some species while others were untouched. With continued animal pressure, the less palatable species were taken—eventually almost as completely as the palatable species. This occurred where small pastures were used as holding pens at night.

In Colorado pastures in which the gambel oak (*Quercus gambelii* Nutt.) brush had been cut, goats eliminated regrowth in 4 years, but in control pastures, much of the uncut brush grew out of the goats' reach (Davis and others 1975).

In the early 1900's the Forest Service arranged with a goat operator to place goats on the Lassen National Forest in northeastern California, on mature manzanita-dominated brushfields. Neither the goat owner nor the Forest Service was satisfied with the effort to control the mature brush, and the attempt was terminated during the second season (Hatton 1913). On the Cleveland National Forest in 1974, about 5 acres (2 ha) of mature brush was fenced as a holding pasture. The goats were taken elsewhere during the day, but at night they gradually worked through the dense brush and opened it up considerably. Both on the Lassen and Cleveland Forests, kid crops were reduced when browsing mature brush.

After considering South African experience with goats, Dutoit (1972) suggested that goats should not be regarded as brush-clearing agents, that goats cannot destroy mature brush without damage to the environment, but that they can effectively check reversion to brush after initial clearing.

Plants consume energy during production of new growth, but once growth is mostly completed for the year, food storage takes place in roots, stems, and seeds. If the objective of goat browsing is to destroy woody plants, they must be continuously or intermittently browsed so that green leaves cannot accumulate. As new growth is repeatedly browsed away, food reserves are depleted and the shrub eventually dies. Carbohydrate levels in shrubs are low at about the full leaf stage in late spring, and later, after late summer regrowth (Jones and Laude 1960).

In Colorado, at least two defoliations per year for 4 years were necessary to kill 95 percent of gambel oak regrowth (Davis and others 1975). Shinoak (*Quercus havardii Rydb., Q. mohriana* Buckl., *Q. undulata* Torr.) in west Texas was killed in 3 years with two to three defoliations per year. In northern California, Sampson (1944) suggested keeping the area continuously stocked to the full capacity of the browse for 3 to 5 years. In the central Sierra Nevada foothills, small interior live oak plants were killed during 2 years of heavy continuous browsing. Live oak plants with larger root systems were killed in 3 years, although occasional plants sprouted weakly into the fourth or later years. Toyon (*Heteromeles arbutifolia* M. Roem.) was less closely browsed than interior live oak at first, but it was also mostly killed in 3 years. In southern California, after two seasons of repeated heavy browsing, small plants of the favored mountain mahogany and the slightly less favored scrub oak were dead. Goats were not placed in these pastures the third year, but a third year of heavy browsing would have killed much of the brush.

Herding and Fencing

Whether to herd goats or fence them for control is a rather troublesome question in southern California. Knowledgeable opinion and some experience support each position.

Those who favor herding goats claim a lower initial investment, great flexibility in planning and execution of plans, good protection against predators, slightly less environmental/visual impact, and a more fitting pastoral image of biological control.

Among the negative aspects of herding are the difficulty in achieving desired levels of vegetation control because the goats seek better feed before control of all species meets fire management standards, and the need for skilled, dedicated herders with well-trained dogs to keep the band together and to prevent losses. Such skills are in short supply, and costly. Futhermore, herding without supplementary fencing is expensive for the herd owner and active herding interferes with the kid-nanny relationship and can lead to kid losses.

To keep the goats within bounds with fences, it is necessary to use net fence or special electric fence. Most ranges or pastures fenced for cattle have fences consisting of three to five, usually four, barbed wires. These are adequate for cattle, but they will not confine goats—particularly if feed is not to the goats' liking. In Amador and Calaveras Counties, the center of California's goat industry, the recommendation is for woven wire net fence with 6- by 12-inch (15- by 30-cm) mesh. A barbed wire is placed below and one or two above the mesh. A minimum of 48 inches (1.2 m) total height is suggested. The reason for the 6- by 12-inch mesh specification is that goats sometimes push their heads through the fence as they reach for browse on the outside. With the square mesh typical of hogwire mesh, goats cannot retract their heads, especially if they have horns, but they frequently can extract themselves from the 6- by 12-inch mesh by turning their heads sidewise.

Those who favor fencing rather than herding for control maintain that fencing simplifies the herding. If just one side of a fuelbreak is fenced, the herder's work is reduced by half or more. With dogs, the herder can readily control the herd from the unfenced side. Fencing allows the most natural movement of the goats possible, within the confines of the fence. And it makes possible the confinement of goats until all shrub species are browsed to meet management's objectives.

The negative aspects of fencing are primarily related to costs. A relatively high initial cost investment is required. Goat fence (40-inch [1-m] net wire and two barbed wires) would cost about $1600 per mile ($994/km) for materials alone. Installation costs would be greater than on a mostly level, rock free, accessible site. Another negative aspect is the undesirable visual effect of fencing.

Water and Supplemental Feeding

Supplying water to goats on fuelbreaks can be an irksome and expensive chore. Fuelbreaks are frequently on ridgetops or other dry and remote areas, where water may not be available, especially during dry years. Goats on the Cleveland National Forest, in southern California, consumed about a gallon (3.8 *l*) per day each during hot weather after herbaceous feed was dry.

Water can be provided in three basic ways:

- Truck hauling from a well, spring, or reservoir to where the band is working. This usually requires upslope hauling over rough, truck-trail type roads. It can consume a large proportion of a person's day, and requires a mechanically sound truck, well-maintained and with heavy suspension. Hauls of greater than 2 to 3 miles (3 to 5 km) should probably be avoided in planning unless the roads are good. The cost of hauling water falls most heavily upon the herd owner.

- Development of a spring, reservoir, or well in the area to be worked is a preferable method if a suitable site exists, access for needed equipment is available, and the area is planned for yearly use, or the water developed can be used for other purposes on a continuing basis. The cost of this method could be shared between the herd owner and the benefiting landowner, by agreement. The inducement for the herd owner is the prospect of eliminating or greatly shortening the hauling job.
- Piping water in from an existing source is an option that is controlled by several factors. The elevational difference between source and use area should allow water to be delivered by gravity or at least pumping costs should be low. Each change from upslope to downslope, or vice versa, requires expensive valves to either release air in the line or to allow draining of the system to prevent freezing. Funds for investment in engineering, materials, and a pumping mechanism (windmill or electric pump) must be available. And the need for the water must be on a continuing basis. The incentives for landowner and herd owner are about the same for this choice as for onsite development described earlier.

No one formula is available for determining which of three methods is best in any situation, nor are there any "standard" costs for each method because of the many variables involved. Detailed analysis of alternatives and their costs and benefits should be made while the goat project is in its earliest stage, because water availability is often the most expensive and limiting factor.

Another important consideration in maintaining a goat herd is supplemental feeding. Supplementing the annual range type has long been practiced during fall and winter when feed was not nutritionally adequate for livestock. It appears to be a desirable practice for goats on chaparral ranges. Pregnant animals particularly need to have supplemental feeding. Feeding before kidding increases the mothering instinct, the kid size at birth, the milk supply for the kid, and the size of the kid crop (Spurlock and others 1978).

Feeds used as supplements can be any livestock feed available, such as alfalfa hay, or whatever can be purchased most advantageously. Alfalfa cubes at about 3/8 pound (0.17 kg) per day per head, or 1/4 pound (0.11 kg) cottonseed meal, or grains at 1/4 to 1/3 pound (0.11 to 0.15 kg) per day can be fed (Groff 1973, Spurlock and others 1978). Cottonseed cake and whole corn were fed at times to goats on the Cleveland National Forest during 1978-79.

We do not recommend using goats to control mature brush but if the goats are supplemented while browsing mature brush, they are less inclined to break through fences in search of better feed.

Other Considerations

In addition to the problems of herding, fencing, and supplying water, other problems associated with managing goats in mountainous areas include these:

- Roads are usually not good, and can be rendered impassable by snowfall or heavy rains. Scheduling of mountain operations in southern California should usually be set for the period April 15 to November 15. At other times, uncertainty increases as to road conditions. In northern California, the dates may be May 15 to October 15, and shorter at the higher elevations.
- Rough, steep, rocky terrain takes a toll on herders, dogs, and horses that is unknown in lowland agricultural areas. The herding efficiency may be greatly reduced because of the difficulty of traversing steep slopes. Dogs, horses, and people have become injured or lame for various periods due to these terrain conditions. Herders must learn to adjust their methods and approaches to the job in order to succeed in the mountains. Strategic fencing is often part of the success formula, allowing less legwork for all.
- Wide diurnal temperature fluctuations (15° to 85° F [−10° to 29° C]) or low temperatures associated with storm fronts may occur in spring and fall, causing hardship or death to kids (when chill factors are too low) and discomfort to herders.
- The general remoteness of most fuelbreak areas from people, stores, and the amenities of life imposes a strong psychological burden to most people who try goat herding. These conditions will continue to severely limit the number of people available for managing goats in the mountains. Yet, there are people who have a cultural background consistent with both the work required and the remote conditions in which it is done.

GOATS AND THE ENVIRONMENT

Competition with Wildlife

Much has been made in some quarters about the prospect of goats out-competing native wildlife species for food and territory. While it is true that goats and mule deer (for instance) have similar diet preferences, several factors tend to mitigate the effects of this competition:

- Few wildland goat operations are active in the State. We estimate that less than 2000 goats are on public land in California. This small number is due primarily to marginal economics caused by high interest rates, mountain conditions, and uncertain markets. This situation will change gradually. Consequently, there is time—in our judgment—to determine desirable areas and carrying-capacity relationships for a planned approach to greater use of goats.
- The use of goats to control brush regrowth, in areas where there are insufficient populations of browsing wildlife species to do so (anywhere in the chaparral), actually benefits the wildlife in two ways: (a) Brush areas, rather than reverting to closed brush stands, are kept open so desirable forbs, grasses, and brush sprouts can grow. (b) Water developments for seasonal goat use become sources of water for wildlife.

Although further research is needed on competition between goats and wildlife, we have concluded that a well-managed operation can contribute to the attainment of wildlife habitat objectives as well as range and fire control objectives. The habits and diet of the goat *per se* are not a threat to wildlife. Intelligent management, or the lack of it, is the factor that determines whether the results reflect an ecosystem improved for wildlife.

Damage to Native Plants

Concern has been expressed that goats will decimate native plant species—particularly rare plants. On the Cleveland National Forest, rare plants were inventoried before goats were brought in. Where such plants were found, goats were excluded by fencing or herding. Another concern expressed has to do with shifts in species composition resulting from the use of goats. Shifts are inevitable but the key point is whether they are desirable within the context of land management objectives, or whether they are uncontrolled. Goats on the Cleveland National Forest have contributed to a change, as an area was converted from brush to a brush-grass or to grass association. This species shift is clearly desirable and, having been well managed, allows all uses to proceed in relative harmony.

Losses to Cold Weather

Goats in southern California have been lost to cold, stormy weather, flooding, predators, and accidents. Losses during unfavorable weather have been most damaging. Goats cannot withstand wet weather that is accompanied by freezing or near freezing temperatures. Such losses started in our goats even before they came to the Cleveland National Forest. The goats had been held on a small ranch near Goleta, California. Brush was mostly too high for the goats to browse, and they were thin, emaciated, and in no condition to withstand stress. The kids were born during January, and 250 were lost to cold weather (Hughes 1976).

On March 12, 1976, 435 nannies, billies, and kids from the Goleta ranch arrived on the Descanso Ranger District, Cleveland National Forest, at about 4000 ft (1220 m) elevation. During the second week of April, on Monday, a storm dropped snow and rain, and the cold continued over 4 days. Nineteen kids and 8 nannies died even though the herder's trailer home was filled with kids. On Friday, there was snow and sleet for 1/2 hour, and 20 to 30 kids whose mothers had died or had left them had to be bottle fed. Some of these died.

A tropical storm caused intense rainstorms in Mexico and into San Diego County on August 13, 1976. Ten goats drowned in a flooded creek, and 24 carcasses were found in the brush later. In early October, three more goats died during stormy weather. The total 1976 weather-related death loss on the Cleveland National Forest stood at not less than 30 adults and 61 kids when the goats were moved to a lower elevation off-forest wintering area.

Later, in 1979, the second owner of goats on the Cleveland National Forest had a kid crop reduced to about 70 percent, mostly by cold weather-related losses.

In 1975, a prospective permittee for the Bureau of Land Management, U.S. Department of Interior, near Redding, California, imported 500 Angora goats. They arrived during a cold October storm and were trailed 3 or 4 miles (4.8 or 6.4 km) through the brush. A few died during the trailing, but around 100 died from pneumonia or other respiratory disease during the next few days (Walker 1975).

An especially critical time for Angoras is immediately after shearing. This is normally done twice yearly, so there is a hazardous period in both spring and fall. The newborn kids are always sensitive to cold, and shelter must be provided for them.

On the Cleveland National Forest, it was necessary to establish a low elevation wintering area. The site selected contained a brushy canyon with large rock outcrops that would help protect against wind. About 200 open, 50 gallon (190 *l*) oil drums were dug in slightly among the brush and rocks so that mothers with kids could escape wind and rain. This appeared to be a simple, effective way to protect young goats from adverse weather. The goats were herded and bedded outside this area during good weather, and the special protection was used only during severe storms.

Losses to Predators

Predators of sheep and goats include coyotes, dogs, bobcats, and mountain lions. Coyotes were the primary predators of sheep and accounted for 82 percent of predator losses; dogs caused 14 percent of the losses; and all other predators, including eagles, lions, and bobcats, accounted for 4 percent (Anonymous 1976). No such figures for goats are available, but goat losses due to predators are probably similar to those of sheep (Pearson and Caroline 1981).

Coyotes in south Texas were primarily responsible for reducing an Angora kid crop to 13.5 percent, even with partial predator control. Coyotes selected the youngest, smallest kids before older kids, and older kids before nannies. Predation on nannies in pastures with no predator control began immediately after kids were eliminated (Guthery and Beasom 1978). Lambs were taken first by coyotes in a California study, then the ewes (Connolly and others 1976).

Predator losses in southern California were not excessive as long as the goats were guarded by dogs and a herder who had access to a gun. One nanny was killed by a bear which was then shot by the herder. Coyotes were always around. We could often hear them as the goats were taken out to graze during the morning or afternoon, and the coyotes sometimes vocalized at night. Herders told of individual coyotes stalking the herd for 2 or 3 days at a time. One goat, tethered near a herder's trailer, was killed by a coyote during the day. Two or three goats that managed to stray away from the main herd when a new truckload was being unloaded were killed by coyotes before they could be rounded up. Goats occasionally got caught in the net wire fence, and if not released soon, were preyed upon by bobcats as well as coyotes. A young nanny, 1 of 15 in a flock, was attacked by a coyote and killed while rounding a corner on a jeep trail in midday. A herder, but no dogs, was in attendance.

Mountain lions were a vexing problem near Goleta, California, where they killed about 100 goats during a 3½-month period (Hughes 1976). Personnel at the Kern River Wildlife Sanctuary, Onyx, California, scared away a lion after it had killed one nanny. Domestic dogs were reported by herders to be more and more of a problem as they were closer to population centers. On the north central Texas Grand Prairie rangelands, death losses after weaning were 8 to 13 percent. A large part of the losses was credited to dogs (MaGee 1957). Goats in southern California were occasionally bitten by rattlesnakes, and there were infrequent losses from snake bites.

Losses to Poisonous Plants

Goats are much less common on the Western Range than are sheep or cattle, consequently, information about the reaction of goats to poison plants is scant. Poison plants are generally less palatable than other plant species and are usually eaten only when livestock are hungry. But with goats sometimes forced to eat shrub species of low palatability, poison plants could cause losses.

While checking a Los Angeles County canyon as a possible site for goat browsing, we found five plants that have caused livestock losses—tree tobacco (*Nicotiana glauca* Grah.), Jimsen weed (*Datura meteloides* A. DC.), cocklebur (*Xanthium strumarium* L. var. *canadensis* [Mill.] T. & G.), a shrubby nightshade (*Solanum* sp.), and groundsel or senecio (*Senecio* sp.).

Tree tobacco has long been recognized as a plant potentially poisonous to all classes of livestock (Los Angeles County Livestock Department 1938, Sampson and Malmsten 1942). Tree tobacco has also caused congenital deformities in calves when the mothers were fed dried, ground tree tobacco during the first third of gestation (Keeler 1979). The young leaves and stems are the most dangerous parts of the plant, and they are readily available in canyon bottoms and disturbed sites in southern California. Fortunately, they are distasteful to goats. On parts of Catalina Island that are heavily browsed by goats, tree tobacco was utilized only when other forage was severely depleted, and then only sparingly (Coblentz 1977).

Seeds and young leaves of Jimsen weed usually do the poisoning if this plant is eaten to excess, but all parts of the plant are dangerous. The burs or seeds of the cocklebur are highly toxic, and the poisonous alkaloids are concentrated in the cotyledons and first true leaves as the seed germinates (Los Angeles County Livestock Department 1938, Sampson and Malmsten 1942).

The woody nightshade we observed, probably Douglas black nightshade (*Solanum douglasii* Dunal), is suspected of poisoning livestock, but this may be partly because of its close botanical relationship with the annual black nightshade (*Solanum nigrum* L.). *Senecios* have been troublesome on the Western Range, and species growing east of the Sierra Nevada Mountains are more frequently reported as causing losses than Senecios growing in California.

Plants that Sampson and Malmsten (1942) report as having caused goat losses in California are black nightshade, laurels and azaleas (*Leucothroe, Rhododendron, Kalmia,* and *Menziesia*), loco weeds (*Astragalus* sp.), and poison hemlock (*Conium maculatum* L.).

Death camas (*Zygadenus* sp.) grows from a bulb, to a height of 2 ft, and has been a serious cause of range sheep losses during early spring. The onion-like leaves of star or chaparral death camas (*Z. fremontii* Torr.) often appear on burned-over chaparral areas before other herbaceous plants. It should be considered poisonous to goats.

In Texas, goats were reported to eat some plants with impunity that cause illness or economic loss to cattle. For example, goats there appeared unsusceptible to most of the nightshades, and they were less susceptible than cattle to *Senecio*, oak, and larkspur (*Delphenium*) (Dollahite 1972).

ECONOMIC RETURNS FROM GOAT MANAGEMENT

The main obstacle to general use of goats on fuelbreaks has been the inability of herd owners to show an economic return. Several reasons account for this condition:

- Operators have been livestock traders rather than local ranchers, and have made some mistakes that ranchers experienced in the area would not have made. Examples of these errors include insufficient supplementing during the winter, insufficient protection during cold, wet weather, and insufficient protection against disease.
- The inability to get financing for an economic unit. Bankers are reluctant to loan money on an operation that they do not understand, especially when potential profits do not appear great enough to pay the current high interest rates. However, many of the costs of running a few hundred goats are not much greater if the flock is 1500 or more, a flock size we believe should be minimum.
- The market for goat meat is somewhat uncertain, seasonal, and decentralized, although for several years, mohair has sold for $4 to $7 per pound ($8.80 to $15.40/kg), depending on hair quality and current demand.

Subsidizing Herd Owners

Despite these obstacles, both land managers with fuelbreaks to maintain and herd owners with goats to feed continue to seek ways to make the idea work. From the land manager's standpoint, fuelbreak maintenance costs of from $20 to $200 per acre ($50 to $500/ha) for other methods are too high. Many managers feel that a subsidy to the herd owner would be cheaper, and also be more environmentally acceptable than equipment or herbicides.

Subsidies can take several forms, including no charge for natural feed; developing water near areas to be worked; providing fencing material and labor; and paying a direct fee under contract for providing goats.

When considering the amount and kind of subsidy that can be afforded, the land manager must consider costs of alternatives and allow a factor for uncertainty. Thus, if the cheapest method were prescribed fire at $18 per acre ($45/ha), the manager might be able to justify an expenditure of $10 to $15 per acre ($25 to $37/ha) as a goat subsidy. The "hold-back" of $3 to $8 represents the cost of a risk that the goat operation will not meet objectives.

Marketing Goats

Several markets in Texas routinely handle goats (Groff 1973), but San Antonio and Los Angeles are the major markets (Dollahite 1972). In California, kids or adult goats can often be marketed on the ranch, or by consignment through local slaughterhouses. Advertisements in local papers and visits to labor camps will attract buyers (Spurlock and others 1978). In 1980, buyers from Mexico offered to purchase the goats being removed from San Clemente Island (Allen 1980).

Demand for young goats is considerable at Christmas and Easter, and a demand for goats is widespread among people of Hispanic and other Mediterranean origin. Goat for barbecuing is becoming more popular with other groups. Young goats are sold as "cabrito," and meat from more mature goats as "chevon." Meat from old animals is commonly used for sausage (Dollahite 1972).

In California, November and December is the best time to sell goats, and spring a good time to buy, according to the owner of goats on the Cleveland National Forest during 1978-79. Spotted or mottled goats are most sought after by buyers, whereas brown or white are the "worst sellers" (Beene 1979).

REFERENCES

Allen, Carl G. [Personal conversation with Lisle R. Green] 1980 August 3.

Anonymous. **Coyote is chief predator.** Calif. Agric. 30(7):11; 1976 July.

Askins, Gary D.; Turner, Everett E. **A behavioral study of Angora goats on west Texas range.** J. Range Manage. 25(2):82-87; 1972 March.

Aucamp, A. J. **Convert bush problem into meat production.** Die Boerbok. Supplement to Landbouweekblad 41:10-12; 1975 October 17. [Transl. from Afrikaans].

Batten, G. J. **Controlling scrubweeds with goats.** New Zealand J. Agric. 32(4);31-32. 1979 October.

Beasom, Samuel L. **Dietary overlap between cattle, domestic sheep, and pronghorns.** In: Sosebee, Ronald E.; Guthery, Fred S., eds. Noxious brush and weed control research highlights—1980. Vol. 11. Lubbock, TX: Texas Tech. Univ.; 1980:40-41.

Beene, Rocky [Personal conversation with Lisle R. Green] 1979 May 29.

Brotherhood of the Sun. **Goat grazing on the Caliente allotment.** Typewritten. 1974 February. 3 p. Located at Pacific Southwest Forest and Range Experiment Station, Riverside, CA.

Bryant, F. C.; Kothmann, M. M.; Merrill, L. B. **Diets of sheep, Angora goats, Spanish goats and white-tailed deer under excellent range conditions.** J. Range Manage. 32(6):412-417; 1979 November.

Calvopina, L. H.; De Vries, T. **Structure of the population of wild goats (*Capra hircus*) and damage caused to the vegetation on the Island of San Salvador, Galapagos.** For. Abstr. 40(7):2193; 1979 July.

Campbell, Q. P.; Ebersohn, J. P.; Von Broembsen, H. H. **Browsing by goats and its effect on the vegetation.** Herb. Abstr. 32(4):273-275; 1962 December.

Coblentz, Bruce E. **Wild goats of Santa Catalina.** Nat. Hist. 85(6):70-77; 1976 June-July.

Coblentz, Bruce E. **Some range relationships of feral goats on Santa Catalina Island, California.** J. Range Manage. 30(6):415-419; 1977 November.

Coblentz, Bruce E. **Effects of feral goats on the Santa Catalina Island ecosystem.** Power, Dennis M., ed. The California Islands: Proceedings of a multidisciplinary symposium; 1978 Feb 27-Mar 1, Santa Barbara, CA.: Santa Barbara Mus. Nat. Hist.; 1980:167-170.

Connolly, Guy E.; Timm, Robert M.; Howard, Walter E.; Longhurst, William M. **Sheep killing behavior of captive coyotes.** J. Wildl. Manage. 40(3):400-407; 1976 July.

Davis, Gary G.; Bartel, Laurence E.; Cook, C. Wayne. **Control of gambel oak sprouts by goats.** J. Range Manage. 28(3):216-218; 1975 May.

Dollahite, J. W. **Spanish goats have what it takes.** College Station, TX: Texas A&M Univ., Agric. Ext. Serv., Texas Agric. Progr. 18(3):21-23; 1972 Summer.

Dutoit, P. F. **The goat in a bush-grass community.** Proceedings of the 7th Grassl. Soc. of S. Africa. 1972; (44-50)

Elam, F. Leland. **Goats cleared our brush.** West. Livest. J. 30:37, 46, 51, 55; 1952 July 15.

Fraps, G. S.; Cory, V. L. **Composition and utilization of range vegetation of Sutton and Edwards Counties.** Bull. 586, College Station, TX. Texas Agric. Exp. Stn. 1940. 39 p.

Green, Lisle R.; Wagnon, K. A.; Bentley, J. R. **Diet and grazing habits of steers on foothill range fertilized with sulfur.** J. Range Manage. 11(5):221-227; 1958 September.

Green, Lisle R. **Fuelbreaks and other fuel modification for wildland fire control.** Agric. Handb. 499. Washington, DC: U.S. Department of Agriculture; 1977. 79 p.

Green, Lisle R.; Hughes, Catherine L.; Graves, Walter L. **Goat control of brush regrowth on southern California fuelbreaks.** Hyder, Donald N. ed. Proceedings of the 1st Int. Rangeland Congr; 1978 August 14-18; Denver, CO. Denver, Colorado Society for Range Management; 1978; 451-455.

Groff, Jack L. **Keys to meat-type goat production.** Fact Sheet L-934. College Station, TX: Texas Agric. Ext. Serv., 1973. 4 p.

Guthery, Fred S.; Beasom, Samuel L. **Effects of predator control on Angora goat survival in south Texas.** J. Range. Manage. 31(3):168-173; 1978 May.

Hatton, John H. **Eradication of chaparral by goat grazing.** In: Review of Forest Service Investigations, Vol. II Grazing Investigations. Susanville, CA: Lassen National Forest, Forest Service, U.S. Department of Agriculture; 1913; 25-28.

Hughes, Catherine L. **First annual report on using goats to control brush regrowth.** San Diego, CA: Cleveland National Forest, Forest Service, U.S. Department of Agriculture; 1976; 87 p.

Huss, Donald L. **Goat response to use of shrubs as forage.** In: Mckell, Cyrus M.; Blaisdell, James P.; Goodin, Joe R. eds. Wildland shrubs—their biology and utilization. Gen. Tech. Rep. INT-1. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972; 331-338.

Jones, Milton B.; Laude, Horton M. **Relationships between sprouting in chamise and the physiological condition of the plant.** J. Range Manage. 13(5):210-214; 1960 September.

Keeler, Richard F. **Congenital defects in calves from maternal ingestion of *Nicotiana glauca* of high anabasine content.** Clin. Toxicol. 15(4):417-426; 1979.

Larson, Jan, Staff Civil Engineer, Naval Air Station, San Diego, CA. [Telephone conversation with Lisle R. Green]. January 1981.

Los Angeles County Livestock Department. **Poisonous and injurious plants of Los Angeles County.** Los Angeles, CA: Los Angeles County Livestock Department; 1938. 27 p.

MaGee, A. C. **Goats pay for clearing Grand Prairie Rangelands.** MP-206. College Station, TX. Texas Agric. Exp. Stn.; 1957 May. 9 p.

Malechek, John C.; Leinweber, C. L. **Forage selectivity by goats on lightly and heavily grazed ranges.** J. Range Manage. 25(2):105-111; 1972 March.

Merrill, Leo B. **The role of goats in biological control of brush.** Beef Cattle Sci. Handb. 12:372-376; 1975.

Merrill, Leo B.; Taylor, Charles A. **Take note of the versatile goat.** Rangeman's J. 3(3):74-76; 1976 June.

Minnich, Richard A. **Vegetation of Santa Cruz and Santa Catalina Islands.** In: Power, Dennis M., ed. The California Islands: Proceedings of a multidisciplinary symposium; 1978, Feb 27-Mar 1. Santa Barbara, CA. Santa Barbara, CA: Santa Barbara Mus. Nat. Hist.; 1980; 123-137.

Murphy, Alfred H.; Leonard, Oliver A.; Torrell, Donald T. **Chaparral shrub control as influenced by grazing, herbicides, and fire.** Down to Earth 31(3):1-8; 1975 Winter.

Naveh, A. **The role of shrubs and shrub ecosystems in present and future Mediterranean land use.** In: Mckell, Cyrus M; Blaisdell, James

P; Goodin, Joe R. eds. Wildland shrubs—their biology and utilization. Gen. Tech. Rep. INT-1. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972; 414-427.

Pearson, Erwin W.; Caroline, Milton. **Predator control in relation to livestock losses in central Texas.** J. Range Manage. 34(6):435-441; 1981 November.

Plaister, Robert E.; Dal Porto, Norman. **Angora goats for foothill brush areas.** Amador County, CA: Calif. Agric. Ext. Serv.; 1973. 13 p.

Plumb, T. R. **Sprouting of chaparral by December after a wildfire in July.** Tech. Paper 57. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1961. 12 p.

Raven, Peter H. **A flora of San Clemente Island, California.** Aliso 5(3):289-347; 1963 April 15.

Sampson, Arthur W. **Plant succession on burned chaparral lands in northern California.** Bull. 685. Berkeley, CA: Calif. Agric. Exp. Stn.; 1944. 143 p.

Sampson, Arthur W.; Malmsten, Harry E. **Stock-poisoning plants of California.** Bull. 593. Berkeley, CA: Calif. Agric. Exp. Stn. 1942. 90 p.

Sidahmed, Ahmed E.; Morris, J. G.; Radosevich, S. R. **Summer diet of Spanish goats grazing chaparral.** J. Range Manage. 34(1):33-35; 1981 January.

Sidahmed, Ahmed E.; Radosevich, Steven R.; Morris, James G.; Koong, Ling J. **Nutritive value of chaparral for goats grazing in fuelbreaks.** Calif. Agric. 36 (5 and 6): 12-14, 24; 1982 May-June.

Spatz, Gunter; Mueller-Dombois, Dieter. **The influence of feral goats on Koa tree reproduction in Hawaii.** Volcanoes National Park. Ecology 54(4):870-876; 1973 August.

Spurlock, G. M.; Plaister, Robert; Graves, Walter L.; Adams, Theodore E.; Bushnell, Robert. **Goats for California brushland.** Coop. Agric. Ext., Univ. of Calif. CP-321-100. Berkeley, CA. Cooperative Extension, Univ. of Calif. 1978. 24 p.

Taylor, Charles, Jr. **Spanish versus Angora in controlling brush.** Presentation at the Spanish Goat Conference, San Angelo, TX. Texas A&M Res. and Ext. Center. 1975 September.

Trollope, W. S. W. **Role of fire in preventing bush encroachment in the eastern Cape.** Proceedings of the 9th Grassl. Soc. of South Africa; 1974; 67-72.

Van Dyne, G. M.; Heady, H. F. **Botanical composition of sheep and cattle diets on a mature annual range.** Hilgardia 36(13):465-492; 1965 September.

Vries, T. De. **How the hunting of goats affected the vegetation on the islands of Santa Fe and Pinta, Galapagos.** For. Abstr. 40(7):2195; July 1979.

Vries, T. De.; Calvopina, L. H. **Role of goats in vegetation changes on the island of San Salvador, Galapagos.** For. Abstr. 40(7):2194; July 1979.

Wagnon, Kenneth A. **Behavior of beef cows on a California Range.** Bull. 799. Berkeley CA: Calif. Agric. Exp. Stn. 1963. 58 p.

Walker, Robert [Telephone conversation with Lisle R. Green] 1975 December.

Wilson, A. D. **A review of browse in the nutrition of grazing animals.** J. Range Manage. 22(1):23-28; 1969 January.

Wilson, A. D.; Weir, W. C.; Torell, D. T. **Evaluation of chamise (*Adenostoma fasciculatum*) and interior live oak (*Quercus wislizenii*) as feed for sheep.** J. Animal Sci. 32(5):1042-1045; 1971.

Green, Lisle R.; Newell, Leonard A. **Using goats to control brush regrowth on fuelbreaks.** Gen. Tech. Rep. PSW-59. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 13 p.

On fuelbreaks, herbicides have been the primary tool for controlling brush regrowth. Vegetation of low volume and low growth is maintained on these wide strips as an aid to firefighting safety. Goats are a promising alternative to herbicides, and may be the best tool available for controlling brush regrowth on fuelbreaks. They eat a wider variety of plants, and more woody plants, than other livestock. They are less selective on first-year brush regrowth, and more selective as brush is older. Goats should not be expected to control tall, mature brush. A good strategy is sufficient goats to eat all leaves from all brush species two or three times per year. Spanish goats are probably a better choice than Angoras for rough moutainous areas. Wethers have some advantages over a breeding herd, but may require more subsidy. Problems to solve when goats are acquired include road access during wet weather, fencing, herding, water and supplemental feeding, protection from predators, disease, and poison plants.

Retrieval Terms: Angora, brush control, chaparral management, diet of goats, fuelbreaks, goat losses, predators, Spanish goats, wethers

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

General Technical
Report PSW-60

A Meadow Site Classification for the Sierra Nevada, California

Raymond D. Ratliff

The Author:

RAYMOND D. RATLIFF, a range scientist, is assigned to the Station's range management research in California unit, headquartered in Fresno, Calif. He earned degrees in range management at the University of California (B.S., 1959; M.S., 1961) and at New Mexico State University (Ph.D., 1979). He joined the Station staff in 1961.

Acknowledgments

I thank all those who helped with this effort over the years. Special recognition, however, is due Stanley E. Westfall, range technician with the Station, and Roni J. Lavine, student aid, who were my mainstays.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

December 1982

A Meadow Site Classification for the Sierra Nevada, California

Raymond D. Ratliff

CONTENTS

Introduction 1
Methods 2
  Meadow Site Class 2
  Classification Criteria 2
  Sampling 2
  Cluster Analysis 3
Results 3
  Clusters 3
  Class Indicators 4
  Key to Meadow Classes 5
Meadow Class Descriptions 5
  Beaked Sedge 5
  Kentucky Bluegrass 6
  Ephemeral-Lake 6
  Hillside Bog 7
  Longstalk Clover 7
  Tufted Hairgrass 7
  Nebraska Sedge 8
  Fewflowered Spikerush 8
  Pullup Muhly 9
  Bentgrass 9
  Carpet Clover 10
  Shorthair 10
  Gentian-Aster 11
  Short-Hair Sedge 11
Classification of New Sites 11
Discussion 14
Appendix 14
  A. Species Index 14
  B. Glossary 14
References 15

Meadows are the most biologically active of the plant community types of the Sierra Nevada, California, and serve many purposes. They contribute a high proportion of the forage produced on many forest grazing allotments, park preserves, and wilderness areas. They supply habitats for wildlife populations. By providing scenic vistas, the meadows' timbered edges are favored campsites of forest, park, and wilderness visitors. The meadows also help to filter sediments from water of surrounding slopes, thereby assuring clean streams and lakes. Because of these multipurposes, land managers face a special challenge to maintain, restore, and manage all meadows.

Meadows comprise less than 10 percent of the Sierra Nevada, and they are generally smaller than those of other mountain ranges (Smiley 1921). Because of these features, meadow (as commonly used in the area) includes open grasslands, marshes, bogs, and meadows as usually defined (California Region 1969, Range Term Glossary Committee 1974).

A meadow site is an area of homogeneous species composition, having a general species composition visually different from that of adjacent areas (Ratliff 1979). Although vegetation is a continuum, when a site is delimited, it occupies space. The space is limited, and no two meadow sites are exactly alike. Meadow sites are discrete entities and each site has characteristics peculiar to it. Meadow sites, therefore, are individual units to be classified.

Classification of meadow sites of the Sierra Nevada and of other mountain ranges have been attempted over the years. But a better classification system than now exists for mountain meadows is needed. To assist land managers, applicable cultural treatments—reseeding, weed control, gully stabilization, and grazing management—need to be developed for the *varying kinds of meadow sites* rather than for meadows in general. Standards for the healthy condition of the vegetation, for trends to potential or stable-state vegetation, and for grazing need to be more flexible to deal with variation between or within meadows. Requirements of most meadow plant species for growth and development, and for reproduction are either poorly known or known only generally. Interspecific relationships of meadow species are little understood. A classification system with classes, class descriptions, key, and classification functions can provide managers with a means for clearer communication of knowledge about meadows, a basis for grouping similar sites, and an opportunity for developing technical classifications, such as meadow fragility and condition. Class descriptions give some ideas of potential vegetations, and new sites can be placed into the classifications.

Meadows of the Sierra Nevada have been classified in various ways. Wet and dry or semiwet meadow range sites are recognized and classified by range type (California Region 1969). The range-type designation indicates the vegetation type and the dominant species. A single classification is usually applied to an entire meadow area with little, if any, recognition given to different sites.

Meadows are classed as midaltitudinal or montane and high altitudinal or subalpine and alpine (Sharsmith 1959). Kings Canyon National Park meadows are classified into wet, woodland, and shorthair (*Calamagrostis breweri*) types (Sumner 1941). The wet meadow type is broken into sphagnum, coarse-leaved sedge, fine-leaved sedge, and grass subtypes, and division of the woodland meadows into broad-leaved and coniferous subtypes is suggested (Bennett 1965). Three classes—level meadows, hanging meadows, and stringer meadows—are used along Rock Creek in Sequoia National Park (Harkin and Schultz 1967). Meadows of Gaylor Lake Basin in Yosemite National Park are classed as wet, moist, and dry (Klikoff 1965). The wet type is the shorthair type of Sumner (1941), and the dry type corresponds to the short-hair sedge (*Carex exserta*) type described by Bennett (1965).

Four kinds of meadow soils on the Sierra National Forest are described by the U.S. Department of Agriculture, Soil Conservation Service (1962). They are normal meadow, drained meadow, alluvial timber, and peat meadow soils. All have effective depths of 3 to 5 feet.

Meadows outside the Sierra Nevada have been classified in various ways. A hydric series of developmental stages leads to climax forest in the Black Hills of South Dakota (Hayward 1928). Streamside meadow communities of the Wasatch Plateau can be separated into types on the basis of dominant species (Ellison 1954). Northeastern California meadows are classed as well-drained, open-basin; poorly drained, closed-basin; or moderately drained, closed-basin (Hormay 1943). Three kinds of meadow or marsh associated with "fen peat" are separated from sphagnum bog and aquatic stands on the presence or absence of *Carex rostrata* (beaked sedge) (Dirschl and Coupland 1972). Eight subalpine meadow community types are described for the Olympic Mountains of Washington (Kuramoto and Bliss 1970). Six Rocky Mountain National Park, Colorado, meadow types are defined and divided into montane and subalpine successional sequences (Wilson 1969). Dry, moist, subalpine or alpine moist-to-wet, tule, and wet meadows are the five subformations of the meadow formation (Hall 1979). Within the subformations are 28 series that can be divided into associations—groups of sites having closely similar vegetation. Sedge (*Carex*) and wiregrass (*Juncus*) series are included in the graminoid subformation of the herbaceous formation in southern California (Paysen and others 1980).

Some of the meadow sites in some other areas are similar to those found in the Sierra Nevada. The pond stage of Hayward (1928) and the rostrata sedge marsh and spikerush (*Heleocharis pauciflora*, fewflowered spikerush) bog of Wilson (1969) are examples. Many of the series of Hall (1979) have their counterparts here.

This report describes an initial effort to classify quantitatively the meadows of the Sierra Nevada, California. From 1973 through 1978, 90 meadow sites in the Stanislaus, Sierra, and Sequoia National Forests and in the Yosemite and Sequoia-Kings Canyon National Parks were sampled (*fig. 1*). The first 72 sites were used to develop the classifications, and the other 18 were used to evaluate them.

METHODS

A classification is a summary and an organization (Major 1958). "The purpose of any classification is to so organize our knowledge that the properties of objects may be remembered and their relationships may be understood most easily for a specific objective" (Cline 1967).

Meadow Site Class

Similar meadow sites can be grouped or clustered into a class—an abstract grouping of meadow sites at any categorical level in a classification system. At the lowest level a class of meadow sites would approximate an association (Braun-Blanquet 1932, Hall 1979).

Figure 1—National Forests and National Parks in the Sierra Nevada, California, where meadow sites were sampled.

Classification Criteria

The potential vegetation of a site is preferred for classification purposes to existing vegetation. Because of inadequate knowledge of potentials, however, vegetation as it exists is a criterion of classification.

Dominance is a major criterion for describing vegetation (Noy-Meir and others 1975). Livestock grazing on many of the sites studied, however, prevented use of weight or foliar cover as dominance measures. Because of the grazing factor, frequency was used as an index to dominance.

More than 200 species were found on the sites studied. To include them all in the analyses seemed both unnecessary and unwise. By introducing covariances and interactions, inclusion of nondiagnostic species reduces the effectiveness of clustering techniques (Jancey 1974), and not all species need to be included (Bray and Curtis 1957). SCREEN, a FORTRAN program described by Grigal and Ohmann (1975), provided seven criteria and was the basis for species selection. As a result, 71 species were selected for developing the classification.

Sampling

I assessed frequency on the nearest shoot-to-point basis—the shoot nearest where the point contacts the soil. Fifteen 5-point quadrats were taken in each quadrant of a site for a total of 60 quadrats or 300 points.

Actual basal hits (point contacts with shoot bases or with moss, soil, litter, gravel, rock or wood) were used to express cover and surface conditions, and selected soil properties were determined for each site. Use of these data and shoot frequency as criteria for classification was discussed earlier (Ratliff 1979). Other criteria used in this study to describe the classes derived are elevation, slope, aspect, and drainage.

Cluster Analysis

Techniques of cluster analysis offer the best hope for meaningful grouping of sites. To provide a number of alternatives to select from, I tried three agglomerative and one divisive cluster analyses (Ratliff 1979). Agglomerative analysis starts with the individual sites and progressively combines them. Divisive analysis starts with all sites as one group and progressively divides the group(s). The analysis selected was agglomerative.

Because of interest in sites rather than in species, data were site-standardized. Site standardization equalizes the influence or weight of all sites while stressing dominant species (Noy-Meir and others 1975). The matrix of intersite relationships was formed with standard Euclidean distance as the "resemblance function" (Orloci 1978). The flexible clustering procedure (Clifford and Stephenson 1975, Everitt 1974, and Lance and Williams 1967) was used to recompute distances after each fusion of sites or site groups. A value of −0.25 was assigned the parameter controlling clustering by that procedure; that value is appropriate for most purposes (Williams 1971).

With the structure derived from cluster analysis, the number of final clusters was determined divisively. The method (Ratliff and Pieper 1981) compares the intercluster distances and intracluster distances of each of the two possible clusters in an analysis of variance. Each cluster and the intercluster space are thought of as treatments, with $n(n-1)/2$ intersite Euclidean distances being response measurements. Each division indicated by the dendrogram is separately tested. A cluster is accepted as final when the F-ratio does not justify its division or when a single site can be split off.

Stepwise discriminant analysis, BMDP program P7M (Dixon 1977), was used to help evaluate the resulting classification. Thirty-eight of the 71 species used in the cluster analysis were selected as having the most indicator value for the final clusters. The 38 species, therefore, were used in the discriminant analysis. Objectives of the analysis were to determine if reallocation of sites among clusters was needed, to assess the viability of the final 14 clusters, to further identify indicator species, and to derive functions for classifying new sites.

The method of Edwards and Cavalli-Sforza (1965) was used to determine whether (over all clusters) significant clustering was indicated. Although the F-ratio as used here and to decide the final clusters (Ratliff and Pieper 1981) will serve to indicate significance, in practice, statements of statistical significance should be avoided.

Classification efficiency was assessed by the method of Orloci (1978). Only at the individual site level, or if all individuals in the clusters are identical, will classification efficiency be 100 percent. Classification efficiency reflects the number of clusters and the within-cluster variations.

RESULTS

Clusters

The 72 sites fell into 14 final clusters. Clusters and corresponding names for classes of Sierra Nevada meadow sites are:

Cluster	Class
A	*Carex rostrata* (beaked sedge)
B	*Poa* (Kentucky bluegrass)
C	*Heleocharis/Heleocharis* (ephemeral-lake)
D	*Hypericum/Polygonum/Viola* (hillside bog)
E	*Trifolium/Muhlenbergia* (longstalk clover)
F	*Deschampsia/Aster* (tufted hairgrass)
G	*Carex nebrascensis* (Nebraska sedge)
H	*Heleocharis/Muhlenbergia* (fewflowered spikerush)
I	*Muhlenbergia/Heleocharis* (pullup muhly)
J	*Agrostis* (bentgrass)
K	*Trifolium/Mimulus* (carpet clover)
L	*Calamagrostis/Oryzopsis* (shorthair)
M	*Gentiana/Aster* (gentian-aster)
N	*Carex exserta* (short-hair sedge)

These final clusters were derived on the basis of cluster analysis and divisive testing of the dichotomous structure of the resulting dendrogram (*fig. 2*). Significant clustering was indicated (*table 1*), and classification efficiency was 51.4 percent.

Discriminant analysis placed 66 (91.7 percent) of the 72 sites into the clusters derived by cluster analysis. Reallocating the remaining six sites slightly increased classification

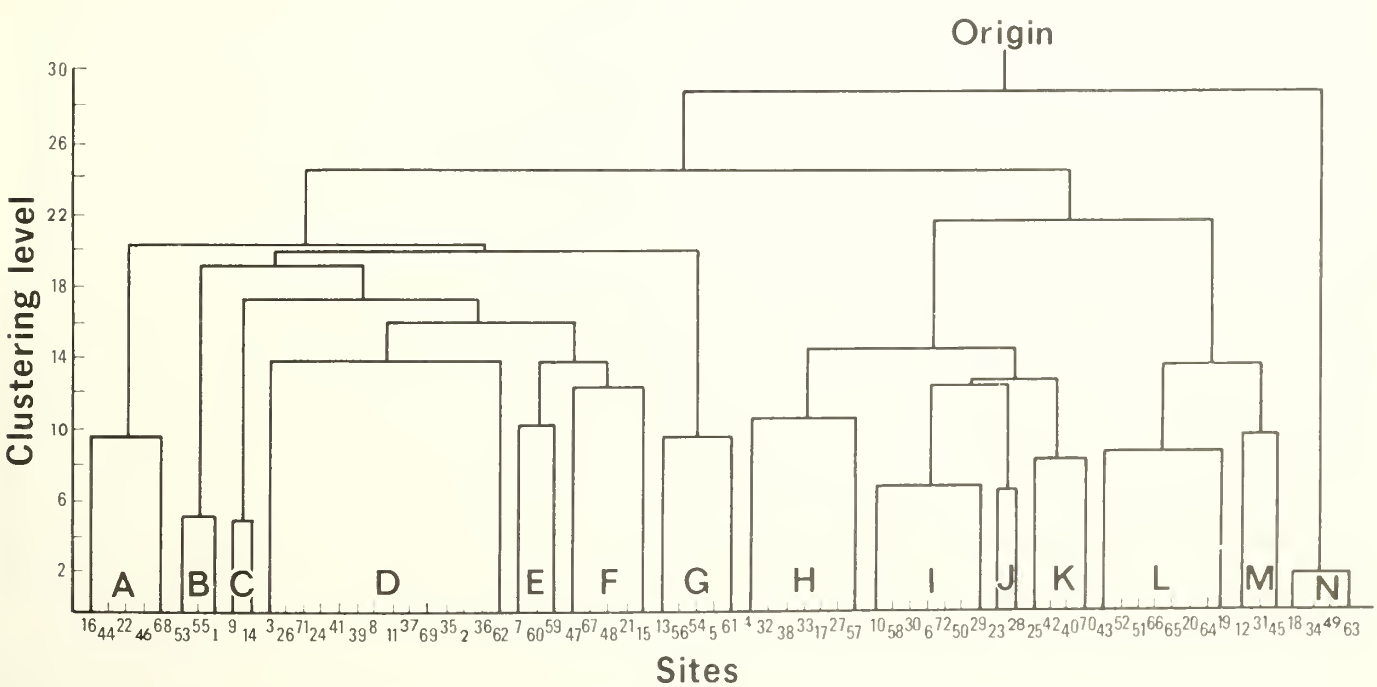


Figure 2—Agglomerative cluster analysis of 72 meadow sites of the Sierra Nevada, California, based upon nearest shoot-to-point species composition. (Standard Euclidean distance, flexible with $\beta = -0.25$ procedure, and site-standard deviates standardization)

Table 1—*Analysis of variance of meadow site clustering*

Source	df	Sum of squares	Variance	F[1]
Between clusters	13	2364.37	181.87	4.72
Within clusters	58	2236.16	38.55	
Total	71	4600.53		

[1] $F_{0.99}(13,58) = 2.45$

efficiency (51.8 percent as well as the F-value 4.8) in the analysis of variance.

Two of the clusters (H and I) could not be clearly distinguished by discriminant analysis. Their F-value (1.85) was not significant at the 0.05 level. If these two clusters were combined, 68 sites would be placed the same as by cluster analysis. The dichotomous structure, however, would be altered, and the classification efficiency would be 1 percent lower—because of having one less cluster.

Combining the two clusters with reallocation of sites reduces the classification efficiency by 2 percent. In this situation, site reallocation accentuates the negative effect of combining clusters.

The sites, therefore, were reallocated among the clusters as indicated by discriminant analysis, and 14 clusters were retained. The two questionable clusters were kept separate because of differences in variables other than vegetation (drainage, for example), and to maintain the dichotomous structure.

Class Indicators

Among the 38 species used in the discriminant analysis, none was restricted to a given cluster (*table 2*). Therefore, no species could be considered "faithful" (Braun-Blanquet

Table 2—*Average nearest shoot-to-point compositions of 38 selected species by cluster*

Species	Cluster													
	A	B	C	D[1]	E	F	G	H[1]	I[1]	J[1]	K[1]	L	M	N
	Percent													
Aster alpigenus[2]	0.01	—	—	2.52	—	5.27	—	8.86	7.17	2.00	—	12.88	13.11	0.01
Aster occidentalis[2]	0.02	—	—	—	4.45	7.47	0.07	1.38	1.67	0.68	0.01	—	—	—
Carex rostrata[2]	78.50	—	0.52	2.19	0.56	—	3.93	2.10	0.06		0.01	—	—	—
Carex abrupta	2.00	—	—	7.55	5.57	2.93	1.33	2.15	0.22	11.00	2.13	0.40	—	—
Dodecatheon jeffreyi	0.01	—	—	3.36	—	0.21	0.01	0.01	0.39	1.89	0.08	0.42	0.01	—
Gentiana newberryi[2]	1.67	—	—	—	—	1.60	—	—	0.67	—	—	2.17	10.55	—
Heleocharis pauciflora[2]	0.25	—	—	2.52	3.56	4.40	4.27	33.81	20.17	4.56	12.06	1.71	5.78	—
Juncus nevadensis	1.50	—	—	1.10	—	5.53	—	4.15	2.33	0.01	—	—	—	—
Mimulus primuloides[2]	1.33	0.89	—	6.48	0.22	4.21	0.78	7.05	9.06	5.22	19.73	1.38	4.00	—
Muhlenbergia filiformis[2]	2.58	—	—	6.12	21.89	3.00	15.27	10.86	21.94	7.89	5.67	0.96	9.00	1.08
Polygonum bistortoides[2]	2.76	0.67	—	1.15	0.11	1.35	1.41	0.16	1.46	1.00	0.14	0.05	0.12	—
Viola macloskeyi[2]	0.01	—	—	5.15	—	1.27	0.13	0.05	1.78	10.33	9.87	0.54	—	—
Carex jonesii		0.22	—	1.91	—	0.20	—	—	0.89	0.01	0.80	—	—	—
Danthonia californica		1.78	—	1.20	1.78	1.13	0.01	1.95	2.23	1.45	5.53	—	0.01	—
Hordeum brachyantherum		0.67	—	—	6.11	—	0.01	—	—	—	—	—	—	—
Juncus balticus		1.89	—	0.12	6.73	—	—	0.19	1.45	—	0.07	0.38	—	2.50
Juncus oxymeris		0.78	—	3.67	—	1.53	0.67	—	0.01	0.11	0.73	—	—	—
Poa pratensis[2]		48.33	—	0.36	5.67	0.13	0.27	0.01	—	1.00	0.27	0.04	—	—
Trifolium wormskioldii		2.45	—	0.71	—	—	4.27	0.48	—	—	—	—	—	—
Heleocharis acicularis[2]			58.67	0.83	—	—	2.33	—	0.72	0.34	0.01	—	—	—
Heleocharis palustris[2]			16.00	1.26	—	—	5.87	2.05	—	—	0.13	0.04	—	—
Agrostis scabra[2]				1.48	0.01	0.07	0.21	0.10	1.45	22.34	1.07	—	—	—
Carex ormantha				1.12	—	—	—	2.53	0.78	2.55	0.40	—	—	—
Deschampsia caespitosa[2]				0.98	—	14.20	0.13	0.90	1.78	—	0.01	0.01	0.01	
Deschampsia danthonoides				0.67	8.68	1.60	—	0.15	—	—	0.54	—	—	—
Hypericum anagalloides[2]				9.41	1.00	1.47	0.61	3.52	1.89	4.23	3.73	0.05	5.00	—
Mimulus tilingii				3.05	—	—	0.21	—	—	0.01	1.20	—	—	—
Oxypolis occidentalis				4.07	—	—	—	—	—	—	0.33	—	—	—
Phalacroseris bolanderi				2.05	—	1.34	0.01	0.10	0.28	1.11	1.40	—	—	—
Scirpus microcarpus				4.48	0.11	—	1.74	0.01	1.00	2.89	7.60	—	—	—
Trifolium longipes[2]				0.81	23.55	2.00	0.87	2.19	1.11		—	—	—	—
Trifolium monanthum[2]				0.93	—	1.01	—	0.33	1.07	2.22	11.27	1.21	—	—
Veronica species[2]				0.56	—	—	0.60	—	—	1.44	0.41	—	—	—
Calamagrostis breweri[2,3]						0.93	—	—	0.01	—	—	39.33	9.01	0.25
Carex nebrascensis[2]						0.80	38.20	0.76	1.50	—	—	—	—	—
Scirpus clementis						0.01	—	0.33	—	—	—	2.37	9.11	—
Vaccinium nivictum						0.47	—	—	—	—	—	12.17	13.56	—
Carex exserta[2]						—	—	—	—	—	—	0.17	—	86.00

[1]Contains sites reallocated by the discriminant analysis.

[2]Species used to name the meadow classes.

[3]Includes *Oryzopsis kingii.*

1932). One or more species, however, had sufficient affinity for each cluster to allow naming of the meadow classes.

Thirteen of the species used to name classes (*table 2*) were also selected by discriminant anlysis as best for distinguishing between the classes. In order of their entry into the analysis, they were: short-hair sedge, shorthair, slender spikerush (*Heleocharis acicularis*), Kentucky bluegrass (*Poa pratensis*), Nebraska sedge (*Carex nebrascensis*), fewflowered spikerush, beaked sedge, rough bentgrass (*Agrostis scabra*), longstalk clover (*Trifolium longipes*), Newberry gentian (*Gentiana newberryi*), tufted hairgrass (*Deschampsia caespitosa*), western aster (*Aster occidentalis*), and carpet clover (*Trifolium monanthum*). These 13 species are most significant in the class key and are the ones for which classification functions are provided.

Key to Meadow Classes

The pattern for this key is the dichotomous structure of the dendrogram (*fig. 2*). Percentages are nearest shoot frequencies (> = greater than, ≤ = less than or equal to).

1a. *Carex exserta* > 5 pct. .... Short-hair sedge.
1b. *Carex exserta* ≤ 5 pct.
2a. (A) *Calamagrostis breweri* > 10 pct.
(B) *Calamagrostis breweri* > 0, ≤ 10 pct. and *Gentiana newberryi* > 5 pct.
(C) *Heleocharis pauciflora* > 5 pct. and exceeding species in 2b.
(D) *Agrostis scabra* > 10 pct.
3a. Sites as in 2a (A or B).
4a. *Calamagrostis breweri* > 25 pct. .... Shorthair.
4b. *Calamagrostis breweri* ≤ 25 pct. .... Gentian-aster.
3b. Sites not as in 2a (A or B).
4a. *Heleocharis pauciflora* > 25 pct. .... Fewflowered spikerush.
4b. *Heleocharis pauciflora* ≤ 25 pct.
5a. *Trifolium monanthum* > 5 pct. .... Carpet clover.
5b. *Trifolium monanthum* ≤ 5 pct.
6a. *Agrostis scabra* > 10 pct......... Bentgrass.
6b. *Agrostis scabra* ≤ 10 pct..... Pullup muhly.
2b. Sites with species in 2a not as indicated and/or the amount of *Heleocharis pauciflora* exceded by *Aster occidentalis, Carex nebrascensis, Carex rostrata, Deschampsia caespitosa, Heleocharis aricularis, Poa pratensis*, or *Trifolium longipes*.
3a. *Carex rostrata* > 50 pct. .... Beaked sedge.
3b. *Carex rostrata* ≤ 50 pct.
4a. *Carex nebrascensis* > 25 pct. ....Nebraska sedge.
4b. *Carex nebrascensis* ≤ 25 pct.
5a. *Poa pratensis* > 25 pct. .... Kentucky bluegrass.
5b. *Poa pratensis* ≤ 25 pct.
6a. *Heleocharis acicularis* > 25 pct. .... Ephemeral-lake.
6b. *Helocharis acicularis* ≤ 25 pct.
7a. *Trifolium longipes, Deschampsia caespitosa*, and/or *Aster occidentalis* > 10 pct.
8a. *Trifolium longipes* > 10 pct. ....Longstalk clover.
8b. *Trifolium longipes* ≤ 10 pct. .... Tufted hairgrass.
7b. *Trifolium longipes, Deschampsia caespitosa*, and *Aster occidentalis* ≤ 10 pct. A grasslike or forb not given in 2b will usually be more abundant than *Heleocharis pauciflora* ....Hillside bog.

MEADOW CLASS DESCRIPTIONS

It is not possible to describe adequately all possible variations that may be found within a given class. The following descriptions, therefore, aim to provide modal class concepts on the basis of data used in developing the classification.

In the descriptions, species abundance terms relate to nearest shoot frequencies as follows: few ≤ 5 percent; frequent > 5 percent ≤ 10 percent; plentiful > 10 percent ≤ 25 percent; abundant > 25 percent ≤ 50 percent; and luxuriant > 50 percent. Unless otherwise stated, soil properties referred to are for the 10- to 20-cm depth layer. References to surface variables relate to basal cover derived from the frequency of basal hits. Texture, slope, and reaction classes follow those of the U.S. Department of Agriculture, Soil Survey Staff (1951). Drainage classes are intended to reflect conditions of relative wetness found among meadow sites; however, they are subjective and without quantitative basis. Statements pertaining to management considerations are made on the basis of acquaintance with meadows of the Sierra Nevada.

Beaked Sedge

Site characteristics: The sites are level, poorly and imperfectly drained, but surface water usually is not stagnant (*fig. 3*). Little, if any, moss is present. The soil contains about 20 percent organic matter, with pH about 5.0, and average soil texture is a loam. Beaked sedge may grow as a nearly pure stand and is luxuriant on sites of this class. Few other species are in abundance.

Comments: Sites of this class were identified in Colorado (Wilson 1969). Three distinct types of beaked sedge meadow were distinguished from meadows without beaked sedge. (Dirschl and Coupland 1972).

Beaked sedge is considered by some to be a secondary or increaser species in wet meadows (California Region 1969), and should be in 40 to 60 cm of water at flowering (Hormay

Figure 3—Beaked Sedge Class, Sky Parlor Meadow, Chagoopa Plateau, Sequoia National Park. (Typical coarse stems in a nearly pure stand, Tule Meadow, Sierra National Forest)

1943). Draining the meadows should result in a decrease of beaked sedge. The wetter portions of a meadow, therefore, are the normal habitat of this species. And, at least in wet meadows, beaked sedge must be considered a primary species.

Beaked sedge may provide good spring forage and, in some countries, it is considered excellent forage for cattle (Hermann 1970). In California, however, it has usually not been well thought of as a forage species. Cattle will use it as the water recedes but not before significant growth has occurred. Beaked sedge sites, therefore, should withstand grazing well. And the manager need not be too concerned about the health of the sedge.

Kentucky Bluegrass

Site Characteristics: Abundant Kentucky bluegrass (*fig. 4*) characterizes this class; however, one or two other species are usually found in some abundance. *Carex* species are present, but do not contribute greatly to the composition.

The sites are nearly level to gently sloping and well-drained. Bare soil comprises about 25 percent and litter about 70 percent of the surface. Moss is absent. Soils are sandy loam to sandy clay loams with pH about 5.5 and are relatively low in organic matter.

Comments: A Kentucky bluegrass association for Northwestern United States has been identified (Hall 1979). Kentucky bluegrass has become the dominant species on what had been bunchgrass meadows in central Oregon (Volland 1978). It increased from less than 1 percent to more than 5 percent of the composition (foliar cover basis) on good to poor condition meadows, respectively (Reid and Pickford 1946). On very poor condition meadows its percentage again was less than 1 percent. Kentucky bluegrass, therefore, must be considered an increaser or secondary species, even though it is excellent forage. And sites of the Kentucky bluegrass class in the Sierra Nevada cannot be considered to be in good condition. Because it is well established, however, management to replace Kentucky bluegrass likely would prove futile.

Ephemeral-Lake

Site Characteristics: The ephemeral-lake sites (*fig. 5*) have very poor drainage and are usually ponded until midsummer. Although slender spikerush is luxuriant here, creeping spikerush (*Heleocharis palustris*) usually dominates the appearance and is plentiful. Microtopographic differences of a few centimeters, altering the depth of water, can markedly alter the composition. Pepperwort (*Marsilea vestita*) is common where water depth is less than 30 cm. Shortawn foxtail (*Alopecurus aequalis*) and ladysthumb knotweed (*Polygonum amphibium*) are common where standing water is a few centimeters deeper.

Ephemeral-lake sites occupy depressed areas with re-

Figure 4—Kentucky Bluegrass Class, Redwood Meadow, Hot Springs Ranger District, Sequoia National Forest. (A dense bluegrass stand, Crane Flat, Yosemite National Park)

Figure 5—Ephemeral-Lake Class, Minarets Ranger District, Sierra National Forest. (Creeping spikerush [tall], with slender spikerush [short])

stricted surface and subsurface drainage. Moss is generally absent, and bare soil may be in considerable amount. The soils are high in clay, and pH is about 6.0.

Comments: The sites studied and others observed are similar to ephemeral-lake sites in northeastern California and to the pond stage as described by Hayward (1928).

Except where excessive use continues year-after-year, the manager need not be greatly concerned about the condition of ephemeral-lake sites. They are subject to grazing as the water recedes, but the species are able to grow and store reserves before the site is used much.

Hillside Bog

Site Characteristics: Various species may dominate the composition of sites in this class (*fig. 6*). Tinkers penny (*Hypericum anagalloides*), American bistort knotweed (*Polygonum bistortoides*), and species of violet (*Viola*) are all present. The combination is not restricted to this class; however, violets and tinkers penny reach their maximum abundance on these sites.

The sites are mostly sloping to moderately steep, poorly or imperfectly drained, and seep-watered. Moss comprises at least 20 percent of the surface cover. Soils are loams to loamy sands. Amount of organic matter in the surface is usually near or above 20 percent but, at 10 to 20 cm, it is usually much less. Soil reaction is strongly acid, with pH 5.2.

Comments: This class has been recognized and called "hanging meadows" (Harkin and Schultz 1967).

Grazing may contribute to the abundance of violets and tinkers penny. They are low-growing species and their frequencies should be reduced by an increase of taller-growing species. Two such species, which grow on hillside bogs, are tufted hairgrass and bluejoint (*Calamagrostis canadensis*). There are, however, sites ungrazed for some time on which violets and tinkers penny are abundant. Several different associations, therefore, are possible within the hillside bog class. In fact, a reanalysis indicates that there are at least five associations.

Figure 6—Hillside Bog Class, Willow Meadow, Minarets Ranger District, Sierra National Forest. (Abundant moss, primrose monkeyflower, and American bistort knotweed)

Figure 7—Longstalk Clover Class, near Clover Meadow, Minarets Ranger District, Sierra National Forest. (Abundant clover with western aster)

The steeper, more organic hillside bogs appear to be fragile. Some such sites have been trampled severely, and it is likely best to not graze them, or to permit only light use.

Longstalk Clover

Site Characteristics: Longstalk clover sites (*fig. 7*) vary in appearance in relation to the perennial grasses and grasslikes present. Longstalk clover is plentiful on these sites. It is more abundant than fewflowered spikerush, but pullup muhly (*Muhlenbergia filiformis*) and various other species may individually be more abundant than the clover. The class, therefore, contains a number of associations.

Soils are mostly well-drained sandy loams, loams, or clay loams with pH 5.0 or a little higher. Soil organic matter is less than 10 percent and gravel content is high (16 percent). The sites are level, or nearly level, and moss may be prevalent on some sites.

Comments: These sites are among the best for grazing of livestock, and deer apparently make some use of the clover in spring and early summer. The clover has high forage value. Ecologically, longstalk clover is a secondary species. As taller grass and grasslike plants are reduced under grazing, the clover increases. But under continued heavy use, the clover decreases and annual hairgrass (*Deschampsia danthonoides*) increases.

Tufted Hairgrass

Site Characteristics: Tufted hairgrass (*fig. 8*) is usually plentiful and one or more asters (usually western aster), sedges (*Carex*) or rushes (*Juncus*) generally will be frequent or plentiful. Fewflowered spikerush, pullup muhly, and primrose monkeyflower (*Mimulus primuloides*) may all be present, but are less abundant than tufted hairgrass. Species diversity is usually high. Litter covers between 60 and 70 percent of the surface. Soil, moss, or both, make up most of the remainder. Soil pH is slightly less than 5.0. Soil

Figure 8—Tufted Hairgrass Class, Crane Flat, Yosemite National Park. (Large size plants of tufted hairgrass in excellent health)

textures are sandy loams and organic matter is relatively low. The sites are level to gently sloping and are moderately well- to well-drained. Variations relate mainly to the amounts of tufted hairgrass and other species. On some sites tufted hairgrass shoots may be few and other species may dominate.

Comments: Two tufted hairgrass associations have been identified in moist meadows, and a tufted hairgrass series recognized in dry meadows (Hall 1979). On good condition meadows the composition of tufted hairgrass was reported to be about 70 percent (Reid and Pickford 1946). Poor condition meadows, in contrast, had only 5 percent of that species. Proper grazing management is necessary to maintain tufted hairgrass sites.

The tufted hairgrass class is found extensively in the Sierra Nevada, and some of the other classes derived in this study may represent stages of degeneration from a tufted hairgrass climax. Bluejoint may be found on some tufted hairgrass sites of better condition. Studies have indicated that western aster is an increaser on these sites (Reid and Pickford 1946). It and mat muhly (*Muhlenbergia richardsonis*) may increase on drier sites of the class as grazing reduces tufted hairgrass. On more moist sites fewflowered spikerush and primrose monkeyflower, along with certain rushes and sedges, may be the increasers.

Nebraska Sedge

Site Characteristics: Although other species may be more abundant in this class, Nebraska sedge (*fig. 9*) is the ecological dominant and is abundant. Typically, the sites are level or nearly level and are imperfectly to moderately well-drained. The class is expressed best where water flows over the surface but does not pond. Nebraska sedge is found as a nearly pure stand where overflow water is about 10 cm deep. In deeper water it mixes with beaked sedge, and on drier sites it can be found with tufted hairgrass and a host of other species.

Texture of the soil ranges from clay loam to sandy loam. Soil organic matter is above 20 percent and pH is about 5.3. The surface is generally well-covered with litter. Little moss is present.

Comments: Sites of this class are common in the Western United States, and Hall (1979) recognized Nebraska sedge series in his moist and wet subformations.

Nebraska sedge has been rated as a primary species (California Region 1969). It has also been considered valuable as late-season forage (Hermann 1970). In the Sierra Nevada, Nebraska sedge frequently is grazed season-long and seems to tolerate repeated grazing. Drying of a site as a result of erosion is the most likely cause of reductions in Nebraska sedge.

The next four classes described do not represent potential vegetations. Each class is comprised of sites having similar current vegetations, and the vegetations of the four classes differ. But rather careful study of vegetation is needed to decide to which one of these four classes a site belongs.

Almost all sites of these classes are grazed. The vegetations, therefore, may reflect more the regimes of grazing than any differences in potentials. The main species—those used to name the classes—are not primary or decreaser species. The sites would benefit from improved grazing management. Various caespitose sedges and grasses, such as Star of David sedge (*Carex ormantha*), abruptbeak sedge (*C. abrupta*), Jones sedge (*C. jonesii*), tufted hairgrass, and California oatgrass (*Danthonia californica*) are probably the potential dominants.

Fewflowered Spikerush

Site Characteristics: Fewflowered spikerush (*fig. 10*) may form early pure stands especially in very wet places at high elevations. Sites of the class have more fewflowered spikerush than pullup muhly and primrose monkeyflower combined. And fewflowered spikerush will be abundant and may be luxuriant.

The sites are mostly poorly and imperfectly drained and

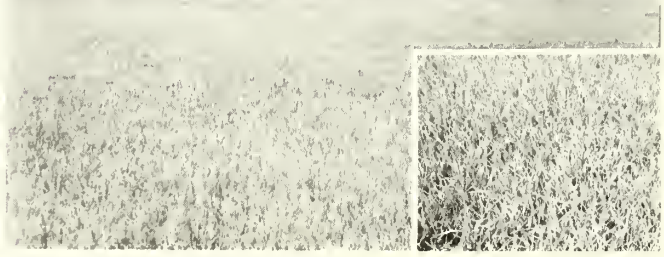


Figure 9—Nebraska Sedge Class, Jackass Meadow, Minarets Ranger District, Sierra National Forest. (Healthy, dense stand of Nebraska sedge)

Figure 10—Fewflowered Spikerush Class, upper Bone Yard Meadow, Pine Ridge Ranger District, Sierra National Forest. Site is well grazed. (Typical short growth of fewflowered spikerush on an ungrazed site)

are kept wet by seeps and springs. They are similar, therefore, to the hillside bog sites. But they are mostly level to gently sloping and some sites are well-drained. Abundant moss characterizes the surface. Soils range in texture from silt loams to sandy loams. Reaction is very strongly acid, with pH about 4.9. The surface 10 cm is generally organic, averaging more than 20 percent and the 10- to 20-cm layer has, on the average, about 15 percent organic matter.

Comments: The "spikerush bog" of Wilson (1969) appears to be similar to this class.

Longstalk clover, alpine aster, and California oatgrass may be frequent or more abundant on some sites. And at lower elevations, at least, the abundance of fewflowered spikerush appears to be related to livestock grazing. Taller growing species would be expected to comprise more and fewflowered spikerush less of the composition in the absence of grazing, or on sites in good condition.

Pullup Muhly

Site Characteristics: Pullup muhly sites (*fig. 11*) appear to vary little from those of the fewflowered spikerush class. The main difference is a higher composition of pullup muhly and a correspondingly lower composition of rush.

The sites are level to nearly level and mostly moderately well- or well-drained. Some imperfectly drained sites can be found. Soil textures range from silt loams to sandy loams; reaction is mostly very strongly acid, but ranges to neutral. Although usually above 20 percent in the surface 10 cm, soil organic matter averages about 15 percent between 10 and 20 cm. Moss is a prominent surface characteristic. The similarity and overlap in characteristics of pullup muhly and fewflowered spikerush sites is the apparent reason for the lack of distinction by the discriminant analysis.

Comments: Pullup muhly has been rated as a low value or invader species (California Region 1969). Except for the Kentucky bluegrass and ephemeral-lake sites, it has grown on at least one site of each class. Pullup muhly, therefore, has a broad ecological amplitude, and some of the sites where it was found had not been grazed for many years. My study suggests, therefore, that ecologically, pullup muhly is an increaser rather than an invader species.

In the climax stand, pullup muhly occurs in a somewhat reduced amount. It appears to be able to tolerate considerable shade and may comprise a fairly high percentage of the composition on sites in good or excellent condition. One should not assume that a high amount of this species always indicates poor condition.

Bentgrass

Site Characteristics: Rough bentgrass and Idaho redtop (*Agrostis idahoensis*) typify this class and are plentiful (*fig. 12*). Various speedwells (*Veronica*) and sedges are present. Pullup muhly and primrose monkeyflower may occur in some abundance. Moss is a prominent surface characteristic, and the sites are watered by seeps. Slopes vary from nearly level to gently sloping, and the sites are likely to be poorly and imperfectly drained. Soils are sandy loams, low in organic matter. In the upper 10 cm of soil, however, organic matter may exceed 20 percent. Soil reaction is very strongly acid, with pH about 4.9.

Comments: A series dominated by *Agrostis* species was recognized by Hall (1979).

Taxonomically, rough bentgrass is similar to Idaho redtop (Hitchcock 1950, Munz and Keck 1959). Generally it is rated low in palatability, but it may be grazed well early in the season (U.S. Department of Agriculture, Forest Service 1937). Rough bentgrass can grow in wet to fairly dry situations and has been considered to be a low value or invader species of meadows (California Region 1969). A tufted or caespitose species with culms of medium height (somewhat over 30 cm), rough bentgrass occurs naturally in meadows. I think, therefore, that this species is better considered a secondary or increaser species in the Sierra Nevada.

Figure 11—Pullup Muhly Class, an ungrazed meadow, Kings River Ranger District, Sierra National Forest. (Dense stand of pullup muhly with western aster and American Bistort knotweed)

Figure 12—Bentgrass Class, Willow Meadow, Kings River Ranger District, Sierra National Forest. (Tufts of bentgrass with tinkers penny and violet)

Figure 13—Carpet Clover Class, Brush Meadow, Kings River Ranger District, Sierra National Forest. (Small white flowers of carpet clover and basal leaves of western aster)

Carpet Clover

Site Characteristics: Although it does not grow exclusively on sites of this class, carpet clover (*fig. 13*) is frequent or plentiful here. There is much less pullup muhly than on sites of the pullup muhly class; and, relative to the bentgrass class, primrose monkeyflower is more abundant. Violets, panicled bullrush (*Scirpus microcarpus*), and *Carex lemmonii* are all present in some abundance.

The sites are sloping or strongly sloping, watered by seeps, and imperfectly to moderately well-drained. The better-drained sites have little moss and much bare soil. Texture of the soil is a loam or sandy loam. Soil reaction is strongly to medium acid (average pH 5.4) and organic matter is less than 20 percent in the surface as well as between 10 and 20 cm. Variations are mainly related to abundance of the main species and to presence or absence of California oatgrass.

Comments: A low-growing, mat-forming, creeping species, carpet clover prefers moist to wet habitats and has been rated as good to excellent forage (Hermann 1966). Although it is not specifically listed, carpet clover would evidently be considered a primary or decreaser species (California Region 1969). The species will withstand shade from trees bordering a site, but its abundance will be few where taller species are abundant and vigorous. I believe, therefore, that carpet clover, like longstalk clover, should be considered an increaser species.

Most species of monkeyflower are neither sufficiently palatable nor abundant to be valued as forage (U.S. Department of Agriculture, Forest Service 1937). They are all rated as low value or invaders in meadows (California Region 1969). Primrose monkeyflower is plentiful on carpet clover sites, and it is found on sites of every class, except those of the ephemeral-lake and short-hair sedge classes. It is not found away from the meadows. Therefore, I think primrose monkeyflower should be considered a secondary or increaser species, also.

Shorthair

Site Characteristics: Sites of the shorthair class (*fig. 14*) represent an important forage resource in wilderness and backcountry areas. In 1971, sites of the class produced about 121 g per m^2 (1080 lbs/acre).[1]

Shorthair and Sierra ricegrass (*Oryzopsis kingii*) are the dominant species. Slender club-rush (*Scirpus clementis*), Sierra bilberry (*Vaccinium nivictum*), and Newberry gentian are usually present in some abundance. Main variations in the class appear related to amounts of Sierra bilberry and alpine aster (*Aster alpigenus*) present.

Sites of the shorthair class are found in subalpine meadows. The average elevation of the sites studied was 2930 m. Amounts of moss are generally low, and litter makes up more than 50 percent of the surface. Soil textures are mostly sandy loams, with pH 5.0. Organic matter content of the soil is usually less than 10 percent. The sites are nearly level or gently sloping and moderately well- to well-drained.

Comments: The shorthair class was recognized in the Sierra Nevada (Klikoff 1965 and Sumner 1941). As the name indicates, the vegetation is short. Height growth seldom reaches 15 cm, and it is frequently less than 10 cm, even on sites ungrazed for many years. This naturally short growth should not be interpreted to mean that a shorthair site is overused.

Dominants of the climax communities are, I believe, shorthair and Sierra ricegrass. On drier sites, Sierra ricegrass may be more abundant, although shorthair may be so on more moist sites. When together and in vegetative phenological stages, however, these species are most difficult to distinguish. Alpine aster and slender club-rush appear to be increaser species.

[1] Unpublished data on file at the Pacific Southwest Forest and Range Experiment Station, Fresno, Calif.

Figure 14—Shorthair Class, Delaney Meadow, Yosemite National Park. (Abundant litter and healthy tufts of grass—here mostly Sierra ricegrass)

Gentian-Aster

Site Characteristics: Except for having smaller amounts of shorthair and larger amounts of bare soil, gentian-aster sites (*fig. 15*) would fall into the shorthair class. Species diversities, amounts of moss, soil organic matter and gravel content, soil texture, pH, slope, and drainage are generally the same as for the shorthair class. Here, however, shorthair is replaced largely by Newberry gentian, fewflowered spikerush, pullup muhly, tinkers penny, and slender clubrush. And there is about 36 percent bare soil as compared with 14 percent bare soil on shorthair sites. Newberry gentian has its greatest abundance on these sites and is about as abundant as alpine aster.

Comments: The three sites representing the gentian-aster class were grazed by livestock. Those of the shorthair class were not. Fewflowered spikerush and slender clubrush appear to be successional species of the sere (Ratliff 1973). It seems likely, therefore, that gentian-aster sites are disturbances of the climax shorthair vegetation.

Short-Hair Sedge

Site Characteristics: Short-hair sedge (*fig. 16*) is clearly the dominant species of this class. On the four sites in this study it comprised an average of 86 percent of the shoot frequency. In an earlier study (Ratliff 1974), the same composition was found for 10 sites by using foliar cover estimated from stereo prints. Species diversity is low. There is little if any moss, and bare soil (48 percent) is the most prominent surface feature. The sites are somewhat excessively or excessively drained and vary from level to strongly sloping. Elevation is usually above 2500 m. Soils are low in organic matter and high in sand. Textures are sandy loams, with gravel making up about 10 percent of the soil mass, and the soils are strongly acid, with pH about 5.1.

Variations in the class appear associated with presence or absence of a tree overstory. Trees may adversely influence the abundance of short-hair sedge and alter the species of forbs present.

Comments: Short-hair sedge sites were recognized (Bennett 1965), and the class is the dry type, as described by Klikoff (1965).

Short-hair sedge is considered to be a secondary species (California Region 1969). It becomes dormant by early August (apparently in response to rapid drying of the soil), but its palatability is equal to that of the similar threadleaf sedge (*Carex filifolia*) (U.S. Department of Agriculture, Forest Service 1937). On the study and similar sites, short-hair sedge is the climax dominant of the herb layer and is a primary species.

Short-hair sedge sod responds well to limited grazing. But because of its short growing period, grazing that is too early, too heavy, or both will reduce vigor of the sedge and lead to deterioration of the sod. Deterioration resulting from continued trampling of the sod by people and stock is evident on trails. Once the sod is broken, much time is required for it to rebuild.

CLASSIFICATION OF NEW SITES

The classification functions (*table 3*) were used in a modification of program CONDIT (Jameson and others 1970) to assign the 18 additional sites to classes. CONDIT computes the probabilities of class membership. A simple example will help the reader to understand the procedure (*table 4*).

Each function (F_{ij}) is multiplied by the percentage of composition (X_i) of the corresponding species to derive the score of species i for class j. To the sum of the species scores, the constant (C_j) for the class is added (here subtracted) to obtain the site score (S_j) for the class. Thus, $S_j = C_j + X_1F_{1j} + X_2F_{2j} + X_3F_{3j}$. The maximum score is found and

Figure 15—Gentian-Aster Class, Shorthair Meadow, Kings River Ranger District, Sierra National Forest. (Small tufts of shorthair, alpine aster, Newberry gentian, slender club-rush, and Sierra bilberry)

Table 3—*Species site classification functions for meadows of the Sierra Nevada*

Species	Cluster A	B	C	D	E	F	G	H	I	J	K	L	M	N
Agrostis scabra	0.05	-0.52	-0.57	-0.48	-0.24	0.31	0.21	0.48	0.51	3.81	0.26	0.14	0.06	0.00
Aster occidentalis	.57	.74	.01	.11	1.86	3.77	.50	.15	.69	.02	-.32	-.56	-.04	-.02
Calamagrostis breweri	-.07	.02	-.25	.01	-.14	.11	.00	.33	.16	.15	.10	5.08	1.04	.15
Carex exserta	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.01	.08	.04	9.83
Carex nebrascensis	.22	-.14	.85	.04	.01	.35	2.81	.01	.20	.10	.04	.00	.07	.00
Carex rostrata	.83	.06	.03	.02	.09	.20	.16	.04	.04	.02	.00	-.01	.06	.00
Deschampsia caespitosa	.89	.51	.32	.26	1.22	4.84	.66	.38	.87	.42	-.03	-.34	.06	-.01
Gentiana newberryi	.99	.37	.07	.08	.40	.92	.33	.02	.25	-.17	-.44	.15	4.30	.17
Heleocharis acicularis	.03	.31	8.38	.09	-.47	.00	.80	-.55	-.21	-.24	.01	-.17	-.14	-.01
Heleocharis pauciflora	.00	.00	.95	.08	-.29	.14	.13	1.46	.92	.64	.42	.49	.36	.02
Poa pratensis	.10	5.15	-.38	.04	1.40	.34	.06	.09	.05	.27	-.08	.02	.08	.00
Trifolium longipes	.18	1.51	.93	.03	2.50	.69	.05	-.36	-.18	-.38	-.20	-.20	-.02	.00
Trifolium monanthum	.07	.48	1.30	.45	.14	.19	.11	.56	.22	.07	2.18	.00	.56	.03
Constant	31.56	127.06	248.51	4.12	39.71	52.87	57.89	25.98	13.84	49.88	17.14	-103.16	-31.06	425.29

subtracted from each S_j to give the ln N_j. Corresponding numbers are determined and divided by their sum to give the probabilities.

With low amounts of fewflowered spikerush and moderate amounts of other species, sites with low composition of pullup muhly can be assigned to that class. To be in the pullup muhly class, a site should have about as much or more of that species as it has of fewflowered spikerush. But neither of the two sites assigned to the pullup muhly class (*table 5*) had that condition. Amounts of other discriminating species (*table 6*) offset the influence of fewflowered spikerush.

Fewflowered spikerush and pullup muhly on site 79 are in about the same proportion as on the sites referred to earlier. But absence of other discriminating species gave a higher probability for the fewflowered spikerush class (*table 5*). Changes in amounts of other species, therefore, will determine the class assignment, and the close relation between the fewflowered spikerush and pullup muhly classes will become more apparent.

Figure 16—Short-hair Sedge Class, Dana Meadow, Yosemite National Park. (Typical patchiness, but good production, in an excellent condition stand)

The influence of other species is also evident for site 86. More than 40 percent of the composition was fewflowered spikerush, but probability of membership was highest for the tufted hairgrass class. Only a trace amount of tufted hairgrass grew on the site. Western aster, however, was in significant amount and was responsible for the class assignment. Western aster also resulted in site 84 being assigned to the tufted hairgrass class. About 20 percent of western aster appears to indicate a tufted hairgrass potential.

Pullup muhly and fewflowered spikerush sites may have a tufted hairgrass potential. Variables other than current vegetation are about the same at sites 83 and 84 and at sites 85 and 86, and all four are similar. Potential vegetations of these sites should, therefore, be similar. On the basis of data presented, sites 73, 87, and 88 have a tufted hairgrass potential as well. Presence of more shorthair than tufted hairgrass suggests an increaser status for shorthair on these three sites.

The last two sites studied are in the elevational range of shorthair sites. Both have about 27 percent alpine aster. Although they currently fall into the fewflowered spikerush class, their potential vegetation is probably shorthair.

Table 4—*An example of class assignment through calculation of the probabilities of class membership (P_j)*

Species (i)	Percent composition (X)	Classes (j) 1	2
		Classification functions (F)	
1	5	0.74	0.05
2	10	.89	.25
3	25	.10	.70
Sum of species scores		15.10	20.25
Constants (C_j)		-3.00	-7.00
Score for class (S_j)		12.10	13.25
ln N_j		-1.15	.00
N_j		.32	1.00
$P_j = N_j/1.32$		.24	.76

Table 5—*Class membership for 18 meadow sites of the Sierra Nevada as given by the classification functions (values) and the key (K's)*

Class[2]	Sequential site number[1] 73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
Beaked sedge	[3]	1.000 K																
Hillside bog			1.000 K	0.998	0.875		T	0.989 K	0.971 K		T							
Longstalk clover					T K	1.000 K												
Tufted hairgrass										1.000 K		1.000 K		0.762				
Nebraska sedge					0.079													
Fewflowered spikerush	0.023 K						0.561						0.957 K	0.006 K	0.997 K	0.983 K	1.000 K	0.930 K
Pullup muhly	0.975		T	0.002 K	0.045		0.439 K	0.011	0.029		1.000		0.043	0.232	0.003	0.017	T	0.070
Carpet clover				T							K							
Gentian-aster	0.002																	

[1]These are the last 18 sites sampled for this study.

[2]Only those classes with positive probabilities are included.

[3]Values are probabilities of class membership. T indicates a probability of less than 0.001 and a blank a probability of 0.0.

These sites may possibly progress through the gentian-aster class.

Tinkers penny, American bistort knotweed, and violet are present on the five sites assigned to the hillside bog class. In that respect they each agree with other sites of the class. Site 77 had too little Nebraska sedge and too little longstalk clover to classify as one of those classes. Sites 80 and 81 are similar to a site reallocated to the hillside bog from the beaked sedge class. Those three sites—68, 80, and 81—may form one of the indicated divisions within the hillside bogs.

Classifications given by the key (*table 5*) agree with those given by the functions for 12 of the 18 sites. Amounts of the 13 species are integrated by the classification functions. Except as the amount of one species leads to the next species to be considered, the key does not integrate the species. Discrepancies are expected. For a particular application, either the functions or the key, but not both, should be used.

Table 6—*Species compositions for computing probabilities of class membership for 18 meadow sites of the Sierra Nevada*

Species	Sequential site number[1] 73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
Agrostis scabra	1.33	—	1.33	0.67	6.33	3.00	—	4.00	7.00	—	1.67	3.33	0.03	0.03		—	—	
Aster occidentalis	6.33	—	—	0.03	—	5.33	—	1.00	—	3.00	11.69	22.00	13.00	22.00	2.06	2.42	0.03	0.03
Calamagrostis breweri	4.00	—	—	—	—	—	—	—	—	—	—	—	—	—	2.36	2.06		
Carex exserta	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
Carex nebrascensis	—	—	0.03	—	19.33	0.33	—	—	—	—	—	—	—	—	—	—	—	
Carex rostrata	0.33	61.00	—	—	0.33	—	—	17.00	18.67	0.03	—	—	1.67	0.03	0.03	0.03	0.03	0.03
Deschampsia caespitosa	0.33	—	—	—	0.33	0.03	—	1.00	0.03	20.00	0.03	0.03	0.33	0.03	1.03	0.67		
Gentiana newberryi	6.67	—	—	—	—	—	—	—	—		3.03	0.33	2.00	6.67	1.69	1.00	0.03	2.67
Heleocharis acicularis	—	—	—	3.67	0.33	0.33	—	—	—	—	0.03	0.03	7.33	2.33	0.03	0.03		
Heleocharis pauciflora	24.33	19.67	—	6.00	7.67	11.00	22.67	5.33	6.67	11.00	20.11	1.67	47.67	42.00	35.75	32.43	41.58	28.10
Muhlenbergia filiformis[2]	8.33	1.00	2.00	3.33	21.33	12.00	7.67	2.33	9.67	6.67	7.68	5.00	16.00	12.67	4.11	8.88	26.55	26.42
Poa pratensis	—	—	0.33	0.33	—	—	—	0.03	—		0.03	0.03	—				—	
Trifolium longipes	—	—	—	0.33	14.33	25.33	—	2.00	—		—	—	—	—		—	—	—
Trifolium monanthum	1.33	—	0.33	0.33	—	—	—	0.67	—	2.33	5.35	3.33	2.00	0.67	0.33	0.03	—	—

[1]These are the last 18 sites sampled for this study.

[2]Pullup muhly is not required for computing the probabilities; it is included here for comparison with other species and because it names one of the classes.

DISCUSSION

The present meadow site classes appear to be at least two levels above the individual site. That is, at least one additional division is needed to reduce the residual heterogeneity so that the classes of the lowest category correspond to associations (Braun-Blanquet 1932). Presence of this heterogeneity means that some quite-different-looking sites may be assigned to the same class, and a particular site may not fit its class concept particularly well. The opportunity to classify new sites, however, gives new insights into successional relationships and helps in determining site potentials and defining associations.

Best use of the current classification is in conjunction with range types and ecoclasses (Hall 1979). With range types the classes may replace the wet and dry site types and, thereby, expand that categorical level. Within the ecoclass concept the classes may be taken as approximations of series quantitatively derived. Hall's (1979) series, however, are based upon climax or stable-state species, although these meadow site classes are based upon current vegetation. In that respect, the meadow site classes more closely correspond to series as defined in southern California (Paysen and others 1980).

According to the general scheme of Hall (1979), and the altitudinal scheme used by Sharsmith (1959), meadow subformations and series of the Sierra Nevada are as follows:

Subformations	Series or class
Montane dry meadow	Kentucky bluegrass
	Tufted hairgrass
Montane moist meadow	Kentucky bluegrass
	Tufted hairgrass
	Longstalk clover
	Nebraska sedge
	Pullup muhly
	Bentgrass
	Carpet clover
	Fewflowered spikerush
Montane wet meadow	Nebraska sedge
	Fewflowered spikerush
	Beaked sedge
	Ephemeral-lake
	Hillside bog
Montane tule meadow	As given by Hall (1979)
Subalpine alpine dry meadow	Short-hair sedge
Subalpine alpine moist to wet meadow	Shorthair
	Gentian-aster

Presence of a class under more than one subformation indicates that individual sites of the class (as derived in this study) had different moisture conditions. The suggestion is that more than one series having the same major species will eventually be found.

The current meadow site classes and the classification functions provide a basic system from which, as new information is added, a revised classification system will result. A natural system (Cline 1967) of meadow site classification that has associations at the lowest level and a category to represent potential vegetations may evolve. Any classification system, however, is only an approximation of reality. And no classification should be considered final. As a summary a classification "advances," but as an organization it "ossifies" scientific thought (Major 1958). Classification of meadow sites of the Sierra Nevada, therefore, must be a dynamic, continuing process.

APPENDIX

A. Species Index

Scientific name	Common name	Pages
1. *Agrostis idahoensis*	Idaho redtop	9
2. *Agrostis scabra*	Rough bentgrass	9
3. *Alopecurus aequalis*	Shortawn foxtail	6
4. *Aster alpigenus*	Alpine aster	9-11
5. *Aster occidentalis*	Western aster	7, 8
6. *Calamagrostis breweri*	Shorthair	10, 11
7. *Calamagrostis canadensis*	Bluejoint	7, 8
8. *Carex abrupta*	Abruptbeak sedge	8
9. *Carex exserta*	Short-hair sedge	11
10. *Carex filifolia*	Threadleaf sedge	11
11. *Carex jonesii*	Jones sedge	8
12. *Carex lemmonii*	— —	10
13. *Carex nebrascensis*	Nebraska sedge	8
14. *Carex ormantha*	Star of David sedge	8
15. *Carex rostrata*	Beaked sedge	5, 8
16. *Carex* species	Sedge	6-9
17. *Danthonia californica*	California oatgrass	8, 9
18. *Deschampsia caespitosa*	Tufted hairgrass	7, 8
19. *Deschampsia danthonoides*	Annual hairgrass	7
20. *Gentiana newberryi*	Newberry gentian	10, 11
21. *Heleocharis acicularis*	Slender spikerush	6
22. *Heleocharis palustris*	Creeping spikerush	6
23. *Heleocharis pauciflora*	Fewflowered spikerush	7-9, 11
24. *Hypericum anagalloides*	Tinkers penny	7, 11
25. *Juncus* species	Rush or wiregrass	7-9
26. *Marsilea vestita*	Pepperwort	6
27. *Mimulus primuloides*	Primrose monkeyflower	7-10
28. *Muhlenbergia filiformis*	Pullup muhly	7-11
29. *Muhlenbergia richardsonis*	Mat muhly	8
30. *Oryzopsis kingii*	Sierra ricegrass	10
31. *Poa pratensis*	Kentucky bluegrass	6
32. *Polygonum amphibium*	Ladysthumb knotweed	6
33. *Polygonum bistortoides*	American bistort knotweed	7
34. *Scirpus clementis*	Slender club-rush	10-11
35. *Scirpus microcarpus*	Panicled bullrush	10
36. *Trifolium longipes*	Longstalk clover	7, 9, 10
37. *Trifolium monanthum*	Carpet clover	10
38. *Vaccinium nivictum*	Sierra bilberry	10
39. *Veronica* species	Speedwell	9
40. *Viola* species	Violet	7, 10

B. Glossary

Agglomerative cluster analysis—a type of cluster analysis that starts with individual units and progressively combines them until all are in a single group.

Association—a cluster of similar individuals, it is the lowest categorical level.

Basal hit—a point contact with a shoot base or a surface variable at ground level.

Categorical level—all groupings of the same degree of abstraction in a classification (all associations or all series).

Class—an abstract group of individuals or groups within a particular categorical level (an association or a series).

Class indicator—a species or factor that is diagnostic of a particular class or that discriminates between classes.

Classification—the process of combining or partitioning individuals into groups.

Classification efficiency—the extent to which variation between individuals is accounted for by the groups derived.

Classification function—a species coefficient derived by discriminant analysis.

Cluster analysis—any of several techniques used to combine or divide a number of items into groups of similar individuals.

Decreaser—a species of the climax vegetation that will decrease with overgrazing.

Dendrogram—a classification structure that indicates dichotomous hierarchical relationships.

Dichotomous structure—a structure which, throughout, is successively divided into two parts.

Discriminant analysis—a method for finding the most likely class to which an individual belongs.

Divisive cluster analysis—a type of cluster analysis that starts with individuals as a single group and progressively divides them into small-size groups of similar individuals.

Dominance—as used here, those species having high shoot-to-point frequencies. In general, the degree of control exerted by a particular species on the community.

Ecoclass—a uniform coding system in which vegetation of a site is identified by subformation (potential vegetation), series (dominant climax species), and association.

Increaser—a species of the climax vegetation that will (for a time) increase and then decrease with overgrazing.

Invader—a species not of climax vegetation that will invade with overgrazing. (Sometimes species present in small amounts that increase with overgrazing are considered invaders.)

Individual—one of the items (sites) to be classified.

Meadow—wetland or semiwetland that supports a herbaceous cover of emergent hydrophytes, mesophytes, and/or intermediate species, and dry herbland of the subalpine and alpine types. Except for some dry herblands, herbaceous cover is continuous, unless interrupted by trees or rocks.

Meadow site—an area of meadow of homogeneous species composition, having a general species composition visually diffrent from that of adjacent areas; an individual unit to be classified.

Series—a class composed of similar associations.

Shoot-to-point frequency—the proportion of shoot-to-point hits on a species.

Shoot-to-point hit—the live shoot nearest to the basal hit.

Site class—a grouping of individual sites or groups of sites at any categorical level; as used here, a site class is a series or an approximation thereof.

REFERENCES

Bennett, Peter S. **An investigation of the impact of grazing on ten meadows in Sequoia and Kings Canyon National Parks.** San Jose, CA: San Jose State College; 1965. 164 p. Dissertation.

Braun-Blanquet, J. **Plant sociology, the study of plant communities.** New York: McGraw-Hill Book Co.; 1932. 439 p.

Bray, J. Rodger; Curtis, J. T. **An ordination of the upland forest communities of southern Wisconsin.** Ecol. Monogr. 27:325-349; 1957 October.

California Region, Forest Service. **Range environmental analysis handbook.** San Francisco, CA; 1969. Chapters 000 and 100.

Clifford, H. T.; Stephenson, W. **An introduction to numerical classification.** New York: Academic Press; 1975. 229 p.

Cline, Marlin G. **Basic principles of soil classification.** In Spec. Publ 1. Madison, WI: Soil Sci. Soc. Amer.; 1967:381-392.

Dirschl, Herman J.; Coupland, Robert T. **Vegetation patterns and site relationships in the Saskatchewan River delta.** Can. J. Bot. 50:647-675; 1972 March.

Dixon, W. J., ed. **BMDP-77. Biomedical computer programs P-Series.** Berkeley, CA: Univ. of California Press; 1977. 880 p.

Edwards, A.W.F.; Cavalli-Sforza, L. L. **A method for cluster analysis.** Biometrics 21:362-375; 1965 June.

Ellison, Lincoln. **Subalpine vegetation of the Wasatch Plateau, Utah.** Ecol. Monogr. 24:89-184; 1954 April.

Everitt, Brian. **Cluster analysis.** New York: John Wiley and Sons; 1974. 122 p.

Grigal, D. F.; Ohmann, Lewis F. **Classification, description, and dynamics of upland plant communities within a Minnesota wilderness area.** Ecol. Monogr. 45:389-407; 1975 Autumn.

Hall, Frederic C. **Codes for Pacific Northwest ecoclass vegetation classification.** R6, Ecol. 79-002. Portland, OR: Pacific Northwest Region, Forest Service, U.S. Department of Agriculture; 1979. 62 p.

Harkin, Donald W.; Schultz, Arnold M. **Ecological study of meadows in lower Rock Creek, Sequoia National Park: progress report for 1966.** 1967. Unpublished report on file at Sequoia and Kings Canyon National Parks, Three Rivers, CA.

Hayward, Herman E. **Studies of plants in the Black Hills of South Dakota.** Bot. Gazette. 85:353-412; 1928 June.

Hermann, F. J. **Notes on western range forbs: Cruciferae through Compositae.** Agric. Handbook 293. Washington, DC: U.S. Department of Agriculture; 1966. 365 p.

Hermann, Frederick J. **Manual of the Carices of the Rocky Mountains and Colorado Basin.** Agric. Handbook 374. Washington, DC: U.S. Department of Agriculture; 1970. 397 p.

Hitchcock, A. S. **Manual of the grasses of the United States.** 2d ed., revised by Agnes Chase. Misc. Publ. 200. Washington DC: U.S. Department of Agriculture; 1950. 1050 p.

Hormay, A. L. **Observations on species composition in northeastern California meadows as influenced by moisture supply.** Berkeley, CA: California Forest and Range Experiment Station; 1943; 6 p.

Jameson, Donald A.; Gierisch, Ralph K.; Wallace, Stanton; Robinson, Robert. **Range condition evaluation by discriminant analysis.** Range Sci. Dep. Sci. Series 8. Fort Collins, CO: Colorado State Univ.; 1970. 25 p.

Jancey, Robert C. **Algorithm for detection of discontinuities in data sets.** Vegetatio 29:131-133; 1974 November.

Klikoff, Lionel G. **Microenvironmental influence on vegetational pattern near timberline in the central Sierra Nevada.** Ecol. Monogr. 35:187-211; 1965 Spring.

Kuramoto, Richard T.; Bliss, Lawrence C. **Ecology of subalpine meadows in the Olympic Mountains, Washington.** Ecol. Monogr. 40:317-347; 1970 Summer.

Lance, G. N.; Williams, W. T. **A general theory of classificatory sorting strategies. I. Hierarchical systems.** Computer J. 9:373-380; 1967 February.

Major, Jack. **Plant ecology as a branch of botany.** Ecology 39:352-362; 1958 April.

Munz, Philip A.; Keck, David D. **A California flora.** Berkeley: Univ. of California Press; 1959. 1681 p.

Noy-Meir, I.; Walker, D.; Williams, W. T. **Data transformations in ecological ordination. II. On the meaning of data standardization.** J. Ecol. 63:779-800; 1975 November.

Orloci, Laszlo. **Multivariate analysis in vegetation research.** 2d ed. The Hague: Dr. W. Junk, b.v., Publishers; 1978. 451 p.

Paysen, Timothy E.; Derby, Jeanine A.; Black, Hugh Jr.; Bleich, Vernon C.; Mincks, John W. **A vegetation classification system applied to southern California.** Gen. Tech. Rep. PSW-45. Berkeley, CA: Pacific

Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 33 p.

Ratliff, Raymond D. **Shorthair meadows in the high Sierra Nevada . . . an hypothesis of their development.** Res. Note PSW-281. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1973. 4 p.

Ratliff, Raymond D. **Short-hair sedge . . . its condition in the high Sierra Nevada of California.** Res. Note PSW-293. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1974. 5 p.

Ratliff, Raymond D. **Meadow sites of the Sierra Nevada, California: classification and species relationships.** Las Cruces, NM: New Mexico State Univ.; 1979. 288 p. Dissertation.

Ratliff, R. D.; Pieper, R. D. **Deciding final clusters; an approach using intra- and intercluster distances.** Vegetatio 48:83-86; 1981 December.

Reid, Elbert H.; Pickford, G. D. **Judging mountain meadow range condition in eastern Oregon and eastern Washington.** Circular 748. Washington, DC: U.S. Department of Agriculture; 1946. 31 p.

Sharsmith, Carl W. **A report of the status, changes and ecology of back country meadows in Sequoia and Kings Canyon National Parks.** 1959. Unpublished draft on file at Sequoia and Kings Canyon National Parks, Three Rivers, CA.

Smiley, Frank J. **A report upon the boreal flora of the Sierra Nevada of California.** Publ. Bot. 9. Berkeley, CA: Univ. of California: 1921. 423 p.

Sumner, Lowell E. **Special report on range management and wildlife protection in Kings Canyon National Park.** 1941. Unpublished draft on file at Sequoia and Kings Canyon National Parks, Three Rivers, CA.

Volland, Leonard A. **Trends in standing crop and species composition of a rested Kentucky Bluegrass meadow over an 11-year period.** Proceedings of the first international rangeland congress; 1978 August 14-18; Denver, CO. Denver, CO: Soc. Range Manage.; 1978; 526-529.

U.S. Department of Agriculture, Forest Service. **Range plant handbook.** Revised Handbook PB168-589. Washington, DC: U.S. Department of Agriculture; 1937. Pagination varies.

U.S. Department of Agriculture, Soil Conservation Service. **Meadow soils.** 1962. Unpublished draft supplied to author by Morris A. Martin.

U.S. Department of Agriculture, Soil Survey Staff. **Soil survey manual.** Agric. Handbook 18. Washington, DC: U.S. Department of Agriculture; 1951. 503 p.

Williams, W. T. **Principles of clustering.** Ann. Rev. Ecol. & Syst. 2:303-326; 1971.

Wilson, Henry C. **Ecology and successional patterns of wet meadows, Rocky Mountain National Park, Colorado.** Salt Lake City, UT: Univ. of Utah; 1969. 99 p. Dissertation.

Ratliff, Raymond D. **A meadow site classification for the Sierra Nevada, California.** Gen. Tech. Rep. PSW-60. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 16 p.

This report describes 14 meadow site classes derived through techniques of agglomerative cluster analysis. The class names are: *Carex rostrata* (beaked sedge), *Poa* (Kentucky bluegrass), *Heleocharis/Heleocharis* (ephemeral-lake), *Hypericum/Polygonum/Viola* (hillside bog), *Trifolium/Muhlenbergia* (longstalk clover), *Deschampsia/Aster* (tufted hairgrass), *Carex nebrascensis* (Nebraska sedge), *Heleocharis/Muhlenbergia* (fewflowered spikerush), *Muhlenbergia/Heleocharis* (pullup muhly), *Agrostis* (bentgrass), *Trifolium/Mimulus* (carpet clover), *Calamagrostis/Oryzopsis* (shorthair), *Gentiana/Aster* (gentian-aster), and *Carex exserta* (short-hair sedge). Stepwise discriminant analysis is used to derive classification functions for quantitatively classifying new sites. A key to the classes is provided.

Retrieval Terms: meadow, meadow site, meadow ecology, meadow management, Sierra Nevada, classification

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

General Technical
Report PSW-62

Production Rates for Crews Using Hand Tools on Firelines

Lisa Haven T. Parkin Hunter Theodore G. Storey

The Authors

at the time of the study reported herein were assigned to the Station's fire management planning and economics research unit, headquartered at the Forest Fire Laboratory, Riverside, Calif. **LISA HAVEN**, a forester with the unit, attended Colorado State University, where she received a bachelor's degree in natural resources management (1978) and a master's degree in forest economics (1981). **T. PARKIN HUNTER**, a forest economist with the unit, earned bachelor's degrees in economics at the University of the South (1973) and in forestry at North Carolina State University (1975), where he also received a doctorate in forestry and economics (1980). **THEODORE G. STOREY**, until his retirement in 1980, was a research forester with the unit. He is a forestry graduate (1948) of the University of California, Berkeley.

Haven, Lisa; Hunter, T. Parkin; Storey, Theodore G. **Production rates for crews using hand tools on firelines.** Gen. Tech. Rep. PSW-62. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 8 p.

Reported rates at which hand crews construct firelines can vary widely because of differences in fuels, fire and measurement conditions, and fuel resistance-to-control classification schemes. Real-time fire dispatching and fire simulation planning models, however, require accurate estimates of hand crew productivity. Errors in estimating rate of fireline production affect estimates of fire size in simulation models predicting fire suppression effectiveness. Productivity rates, therefore, are crucial for such models and the high variability makes choices difficult. Studies of crews using hand tools to build firelines were compared. Wide variations in construction rates were found. The results suggest the need for future productivity studies to standardize procedures and to develop resistance-to-control classifications that can be identified with field measurements. Approaches showing the most promise are those that measure probability distributions of productivity.

Retrieval Terms: hand crews, initial attack simulation, fireline, resistance-to-control, fuels

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701
Publisher:

December 1982

Production Rates for Crews Using Hand Tools on Firelines

Lisa Haven T. Parkin Hunter Theodore G. Storey

CONTENTS

Introduction 1
Methods 1
Data Collection 1
Fuel Resistance-to-control Classes 1
Data Standardization 2
Results 2
Rates of Fireline Construction 2
Fire Size and Line Construction Rates 3
Summary and Conclusions 4
Appendix 5
References 8

Table 1—*Production rates of handcrews in building firelines, by fuel type, and crew experience*

Region	Rate of line construction (RLC)[1]	Samples	Classes[2]	Class range	Samples in each class	Class mean	Observations in each sample[3]	Fireline type[4]	Crew experience[5]
				Low resistance-to-control fuels					
Northern (1)	0.15 to 3.3	10	2	0.15 to 1.50	6	0.77	Many	C	IE
				1.96 to 3.30	4	2.44	N.D.	C	E
Rocky Mountain (2)	.62 to 2.70	7	2	.63 to .72	2	.66	Many	C	IE
				1.00 to 2.70	5	1.63	Many	CH	E
Southwestern (3)	3.00 to 7.00	2	1	3.00 to 7.00	2	5.00	N.D.	C/CH	IE
Intermountain (4)	1.14 to 6.00	2	1	1.14 to 6.00	2	3.57	N.D.	CH	IE
Pacific Southwest (5)	.40 to 4.97	3	2	.40	1	.40	Many	C	E
				3.75 to 4.97	2	4.36	N.D.	C	E/IE
Pacific Northwest (6)	4.35	1	1	4.35	1	4.35	N.D.	C	IE
Southern (8)	3.01	1	1	3.01	1	3.01	N.D.	CH	IE
Eastern (9)	2.50 to 5.30	2	1	2.50 to 5.30	2	3.90	Few/N.D.	CH	E/IE
Alaska (10)	4.00	1	1	4.00	1	4.00	N.D.	C	E
				Medium resistance-to-control fuels					
1	0.15 to 2.00	11	2	0.15 to 0.80	6	0.51	Many	C	IE
				1.00 to 2.00	5	1.40	N.D.	C	E
2	.20 to 2.00	5	2	.20 to 0.35	4	.28	Many	CH	E
				2.00	1	2.00	N.D.	C	E
3	4.00	1	1	4.00	1	4.00	N.D	CH	IE
4	.20 to 3.00	2	1	.20 to 3.00	2	1.60	N.D.	CH	IE
5	.28 to 3.18	6	2	.28 to 0.83	5	.52	Many	C	IE
				3.18	1	3.18	N.D.	C	IE
6	.32 to 3.15	4	2	.32 to 0.55	3	.44	Many	C	IE
				3.15	1	3.15	N.D.	C	IE
8	1.51 to 3.00	2	1	1.51 to 3.00	2	2.26	N.D.	CH	IE
9	2.10 to 2.70	2	1	2.10 to 2.70	2	2.40	N.D./few	CH	IE
10	1.30	1	1	1.30	1	1.30	N.D.	C	IE
				High resistance-to-control fuels					
1	0.05 to 0.80	11	2	0.05 to .39	7	0.25	Many	C	IE
				.45 to .80	4	.59	N.D.	C	E
2	.15 to 2.70	9	2	.15 to .30	4	.23	Many	CH	E
				1.00 to 2.70	5	1.92	Many	CH	E
3	.20 to 1.40	2	2	.20	1	.20	N.D.	C	IE
				1.40	1	1.40	N.D.	CH	IE
4	.14 to 1.20	2	1	.14 to 1.20	2	.67	N.D.	CH	IE
5	.12 to 1.25	7	2	.12 to .23	3	.18	Many	C	E
				.51 to 1.26	4	.86	N.D.	C	IE
6	.23 to 1.20	2	2	.23	1	.23	Many	C	IE
				1.20	1	1.20	Few	C	IE
8	.76 to 1.50	2	1	.76 to 1.50	2	1.13	N.D.	CH	IE
9	1.30 to 1.40	2	1	1.30 to 1.40	2	1.35	Few/N.D.	CH	IE
10	.70	1	1	.70	1	.70	N.D.	C	IE
				Extreme resistance-to-control fuels					
1	0.02 to 0.25	9	2	0.02 to 0.19	6	0.10	Many	C	IE
				.20 to .25	3	.23	N.D.	C	E
2	.05 to 1.30	8	2	.05 to .20	4	.13	Many	CH	E
				.60 to 1.30	4	.95	Many	CH	E
4	.08	1	1	.08	1	.08	N.D.	C	IE
5	.20 to .55	5	2	.20 to .35	3	.26	Many	C	E
				.52 to .55	2	.54	N.D.	C	IE
6	.25 to .46	2	1	.25 to .46	2	.36	N.D./many	C	IE
8	.75	1	1	.75	1	.75	N.D.	CH	IE
9	.68 to 1.00	2	1	.68 to 1.00	2	.84	Few/N.D.	CH	IE
10	.40	1	1	.40	1	.40	N.D.	C	IE

[1]Rate of fireline construction (RLC) was measured in lineal chains of fireline per person per hour.

[2]The classes refer to the number of distinct line construction rate changes classified by different studies under the same overall resistance-to-control class.

[3]RLC study results were based on few-many observations, where few = 1-9; many = 10-100. Often, however, the observations in each sample were not designated (N.D.).

[4]Fireline was either constructed (C) or constructed and held (CH).

[5]IE = Inexperienced fireline crews; E = experienced crews that may include smokejumpers.

Increasing costs of fire suppression have intensified the need to reevaluate all fire management practices to ensure that they are economically effective. One suppression activity, that of surrounding and containing a fire by building a fireline, has been studied in terms of rate of construction.

Estimates of fireline construction rates are used for real-time fire dispatching and in fire simulation planning models. The accuracy required for construction rate estimates depends on the purposes for which they are used. But because of differences in fuels, fire and management conditions, and fuel resistance-to-control classes, construction rate accuracy is difficult to obtain. And, because errors in construction rate estimates greatly affect estimates of fire size for simulation models of fire suppression effectiveness, accurate construction rates are crucial.

Fireline construction rates, however, have been found to vary by as much as 500 percent (Hanson and Abell 1941; Matthews 1940; Pirsko 1966; Stevenson 1951; U.S. Dep. Agric., Forest Serv. 1957, 1961, 1962, 1963, 1965a, 1965b, 1966a, 1966b, 1972a, 1972b, 1973, 1974). Such variability confounds even basic assessments and comparisons of suppression resource capabilities (Murphy and Quintilio 1978, Ramberg 1974, Storey 1969). The problem is accentuated when alternative suppression strategies are intensively analyzed by mathematical models (Davis and Irwin 1976; McMasters 1963, 1966; Parks and Jewell 1962; Quintilio and Anderson 1976; Simard and others 1978; Swersey 1963). Consequently, management decisions and justifications for fire suppression budgets are severely hindered at a time of increasing concern that costs of some suppression efforts may outweigh resultant benefits. Before current information on fireline construction rates from different studies can be reliably integrated into any mathematical analysis, additional information is needed as to what factors affect the high variability of construction rates.

This paper reports a comparison analysis of data on construction rates of crews using hand tools on firelines, and addresses the need for accurate production rates with a simple model for sensitivity analysis.

METHODS

Data Collection

Our compilation of line production rate data relied on the bibliography of Storey (1969) *(table 1)* and a current literature survey for studies after 1969. Although some works may have been overlooked, it is unlikely that additional studies would reduce the uncertainties involved with use of existing rate-of-line construction (RLC) estimates.

Fuel Resistance-to-control Classes

All production studies reviewed noted the general type of fuels in which firelines were constructed. Because certain fuels impede fireline construction more than others, fireline production rates vary among fuels. Grouping fuels into resistance-to-control classes (RTCC) has been the traditional means of classifying and comparing line construction rates. The RTCC broadly assesses the fuel size and structure so that the fireline construction job can be stratified by level of difficulty. Although the concept of resistance-to-control is the same in all Forest Service regions, standards for applying the classification system are needed.

A fuel's resistance-to-control rating—low, medium, high, or extreme—is determined by the rate at which fireline can be built in the fuel type. Specifically, RTCC is determined by dividing the relevant range of fireline production rates into four intervals and then classifying fuels by the interval into which they fall. Although this classification scheme is used by most Forest Service regions, it is inconsistently applied because of the lack of production rate range standardization between fireline production studies and throughout Forest Service regions. Much of the production range variability results from differences in fuels within each RTCC.

U.S. Department of Agriculture Forest Service Fireline Notebooks (U.S. Dep. Agric., Forest Serv. 1957, 1961, 1962, 1963, 1965a, 1965b, 1966a, 1966b, 1972a, 1972b, 1973, 1974) classify fuel type information by RTCC's for all Forest Service regions, except the Pacific Southwest and Pacific Northwest Regions. These two regions do not delineate RTCC's; they simply record fireline production information for each fuel type. Storey (1969) and Lindquist (1970) extrapolated on information from the Fireline Handbook by categorizing production rates given by fuel type into resistance-to-control classes.

To consistently interpret production rates for each RTCC, a description of fuel types within each RTCC must be known. Fuel type information rated by resistance-to-control class is listed in *table 3 (Appendix)* for all Forest Service regions, except the Pacific Northwest and Pacific Southwest. Productivity rates for specific fuel types in these Regions are summarized in *table 4 (Appendix)*.

An exception to the *ad hoc* determination of resistance-to-control is the procedure developed by Murphy and Quintilio

(1978). They quantitatively developed a fuel resistance-to-control classification by measuring the relative difficulty of clearing trees, clearing small trees and brush, building line through deadfall and slash, trenching, and building on slopes. Fuel can be given relative resistance-to-control rankings by measuring different associated stand variables.

Data Standardization

Production information from all sources was compared. Standard analysis of variance techniques could not be applied to the data because of the relatively small information base and wide range of possible influential variables. Instead, a classification scheme was developed to isolate and reduce possible sources of variability. Conclusions were drawn on the basis of simplified comparisons of point estimates. The data were inadequate for any further forms of analysis.

The data were grouped according to Forest Service region and RTCC. This grouping eliminated much of the variability resulting from different RTCC fuel classification schemes among regions. When only one production rate was given, it was recorded in the medium RTCC, unless otherwise specified. If three fuel classes were delineated, the production information was tallied in the low, medium, and high RTCC's.

All production information was standardized into similar units of production and conditions of measurement. Most studies recorded fireline production rates in lineal chains of fireline constructed per hour per person. When production rates were not recorded in these units, the rates reported in the studies were converted back to a per person and per chain basis. If, for example, a production rate was recorded as 165 ft per hour per person, it was converted to 2.5 chains per hour per person. If a production rate was recorded as 5 chains per 10 hours per person, it was converted to 0.5 chains per hour per person. If a production rate was recorded as 3 chains per hour per 3-person crew, it was converted into 1 chain per hour per person. The conversions ignore the possibility that the work produced by many individuals together is different from the total work of each individual working separately. The rate in these situations is the average rate per person for an interacting crew.

Some studies recorded production for a long period of time (Lindquist 1970; U.S. Dep. Agric., Forest Serv. 1980) to account for diminishing productivity as the work shift progressed; that is, fatigue allowance. When fatigue factors were given, their influence was incorporated as the average production rate for the time period reported.

Some studies measured production as a forward rate of progress with a stated or assumed fireline width (Hanson and Abell 1941; Pirsko 1966; Steele 1961; U.S. Dep. Agric., Forest Serv. 1957, 1961, 1962, 1963, 1965a, 1965b, 1966a, 1966b, 1972a, 1972b, 1973, 1974). Other studies measured production in areal units of fireline constructed (Lindquist 1970). To make production rates comparable, author-specified conversions were used to convert fireline area measurements to lineal measurements. If no width was recorded in the study, the standard U.S. Department of Agriculture Forest Service fireline widths were used (Lindquist 1970).

The widths used to convert lineal to area measures were 2.5 ft for light fuels, 3.5 ft for medium brush, 5.0 ft for heavy brush, and 6.0 ft for heaviest brush. The four categories listed were assumed to conform to low, medium, high, and extreme resistance-to-control classes.

For each region, the production data within each RTCC was ordinally ranked and inspected for trends by type of fireline, worker characteristics, and conditions of measurement. The resulting production rates were grouped according to study characteristics (*table 1*). Characteristics common to most studies were experience of the crew, number of observations used to estimate production, and quality of fireline production.

Crew experience was normally denoted by smokechasers and smokejumpers, high proficiency crew, medium proficiency crew, low proficiency crew, general crew, pickup firefighters, and trained or untrained woodsworkers. Characterizations classed as inexperienced were pickup firefighters, untrained woodsworkers, general crew, and low proficiency crew. Characterizations classed as experienced were smokechasers, smokejumpers, high proficiency crew, medium proficiency crew, and trained woodsworkers. Forest Service silviculture or inventory crews are sometimes called upon to assist in initial attack operations. Such crews are often classified as general handcrews. Although these crews have been instructed in firefighting techniques, their on-fire experience is infrequent. Because the term "general crew" has many interpretations, it was included in the inexperienced category.

RESULTS

Rates of Fireline Construction

The RLC estimates included in this report are based on many observations (10 to 100), few observations (1 to 9), or a nondesignated number of observations. Low production rates frequently resulted from studies that used large sample sizes; high production rates resulted from studies that used small or undesignated sample sizes.

Production rates should logically be greater for experienced as opposed to inexperienced hand crews. No consistent tendencies were found, however, when production rate was compared to level of crew experience.

The production rate results were not an obvious function of quality of fireline production. Some production rates only described constructed fireline (Biddison 1980; Buck 1938; Matthews 1940; Stevenson 1951; U.S. Dep. Agric., Forest Serv. 1966b); others described fireline constructed and held (Hanson and Abell 1941; U.S. Dep. Agric., Forest Serv. 1964, 1965a). No differences in rates of fireline constructed as against fireline constructed and held were apparent. A better indicator of fireline quality might be the width of fireline;

Table 2—*Effects of errors in estimates of line construction rates on final fire size predictions for a 20-man crew and a fire size of 1 acre at time of arrival*[1]

	Rate of spread (chains per hour)					
	4		8		12	
Estimation error	Final size	Fire size error	Final size	Fire size error	Final size	Fire size error
	Acres	*Percent*	*Acres*	*Percent*	*Acres*	*Percent*
50 percent underestimate	2.4	60	16.5	588	[2]	[2]
Correct	1.5	—	2.4	—	4.9	—
50 percent overestimate	1.3	−13	1.7	−29	2.4	−51

[1]Assumptions: two chains per person per hour is the correct line construction rate; the fire is represented by a 2:1 ellipse; suppression forces arrive simultaneously; the attack is a direct, rear attack with 10 people on each flank; percent fire size error = $\frac{\text{incorrect-correct}}{\text{(correct)}} \times 100$ percent.

[2]Fire cannot be controlled.

however, this information was usually unavailable in the production studies reviewed here so that the source of potential variability could not be tested.

Other variables may influence production rates. These include fireline grade, elevation, terrain, weather, hours workers spend on the job, worker's pulse, worker's perceived effort, smoke density, and others. Differences have been found in productivity for length of time spent on the fireline (Lindquist 1970). Variability of rates was measured so that probability distributions of RLC as a function of time could be derived. The effects of differences in fire intensity and rate-of-spread and crew fitness on fireline productivity were analyzed (Ramberg 1974). Although results were inconclusive, the analysis suggested that unmeasured variables such as skill, training, and supervision may have significant effects on productivity.

Fire Size and Line Construction Rates

Estimates of fireline construction rates are used for real-time fire dispatching and in fire simulation planning models. The accuracy required for production rate estimates depends on the purpose for which they are used and the effects of errors on fire size estimation.

Better estimates than those currently available may not be needed for real-time fire dispatching. Actual initial attack and suppression efforts are directed by regional experts who use professional judgments. These experts integrate the variables that affect productivity, and make management decisions accordingly.

But in planning models, where experienced fire bosses are not available for making localized (situation-specific) decisions, errors in productivity assumptions may be more crucial. Depending on the fire conditions simulated, errors in production values have the potential for radically biasing the simulated results.

The ranges of reported fireline construction rates for each RTCC per region are wide (*table 1*). The range of reported productivities in low resistance-to-control fuels for the Forest Service's Northern Region (Region 1) is 0.15 to 3.3 chains per person per hour (*table 1*). The upper boundary of the range is 22 times larger than the lower boundary. The effects of errors in productivity on fire size estimates must be known to assess the significance of range size.

An initial attack simulation is sensitive to errors in line construction rate estimates (*table 2, figs. 1, 2*). The examples were derived from a model (Bratten 1978) that relates ratios of final fire area to area at time of attack to different ratios of line construction rate to rate-of-spread. The effects of a 50 percent over- or underestimate of line construction capability for a 20-man crew with a fire spreading at three different rates have been delineated (*table 2*). A 50 percent overestimate in productivity results in a 13 percent underestimate of fire size for fires with rates of spread of 4 chains per hour and a 51 percent underestimate for fires spreading at 12 chains per hour. An underestimate in productivity results in a larger percentage error in final size prediction than an overestimate. For the conditions outlined (*table 2*) for a rate-of-spread of 8 chains per hour, a correct size at containment of 2.4 acres (0.97 ha) would be predicted as 16.5 acres (6.68 ha) with a 50 percent underestimate, and 1.7 acres (0.69 ha) with a 50 percent overestimate. The effects of errors in productivity estimation are asymmetrical.

Fire size predictions are related to production rate estimates. *Figure 1* gives the predicted ratio of final area to initial fire area as a function of the ratio of rate of line construction to rate-of-spread (ROS). Each curve is for a different percentage error in the ratio. The graph is interpreted as follows:

Point A: For a true RLC/ROS of 2.4, the ratio of final fire area to initial area is 2.5. This means a 1-acre (0.40-ha) fire initially attacked with a force size such that RLC/ROS = 2.4 would be 2.5 acres (1 ha) at containment.

Points B and C: For a true ratio of RLC/ROS of 2.4, a 50 percent underestimate of RLC results in a predicted ratio of final area to initial area of 22.7. A 50 percent overestimate of RLC results in a predicted area ratio of 1.8.

The shapes and positions of the curves further indicate the asymmetry of area error differences between equal percentage

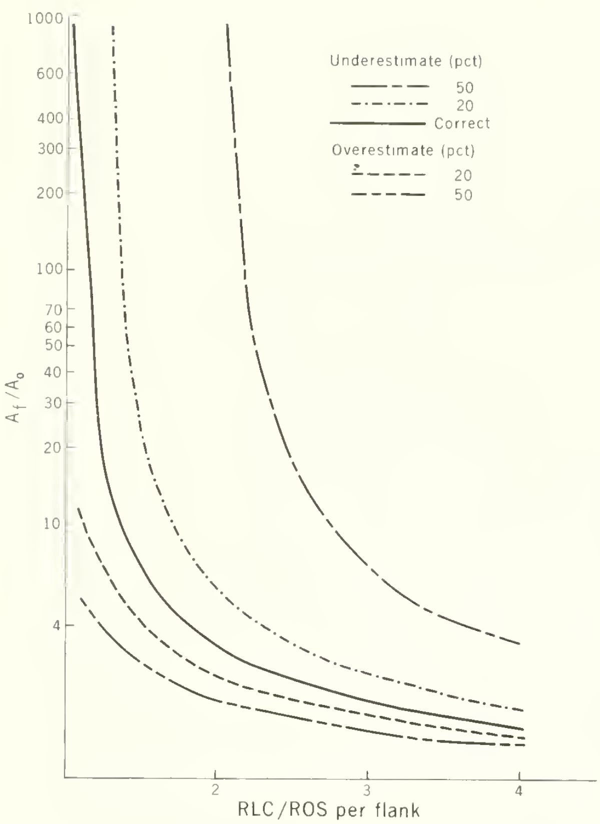


Figure 1—Sensitivity of final fire size to errors in the RLC/ROS ratio. Assumptions are (a) 2:1 fire ellipse, (b) simultaneous force arrival, and (c) direct, rear attack.

RLC overestimates and RLC underestimates. A 50 percent RLC underestimate results in more dramatic errors in the prediction of final fire size than does a 50 percent RLC overestimate. The difference is obvious for specific cases (*table 2*). Also, the error effect is large for RLC/ROS ratios near 1 and decreases as the ratio increases. A 50 percent RLC error is much smaller than the error magnitudes possible in the range of fireline construction rates historically reported (*table 1*).

Significant planning errors can be made by blind reliance on published rates. Different assessments of fire crew effectiveness are possible, depending on the rates chosen. A 20-person crew producing line at the rate of 1 chain per person per hour, for example, could not control a fire by direct rear attack if the fire was spreading at 10 chains per hour. If the productivity were 3 chains per person per hour, the same fire would only double in size between the time of initial attack and containment (*fig. 2*). Again, 1 to 3 chains per person per hour production rates are well within the range reported in the literature.

The examples cited show that reliance on the published rates of line construction for either planning or modeling purposes can bring about unexpected results. In some situations, the final fire size is fairly insensitive to sizable errors in production rate, but in others, fire size sensitivity is high. The sensitivity is also asymmetrical with respect to overestimates and underestimates. An underestimated production rate results in a larger percentage error in final fire size prediction than an overestimated rate. Size prediction sensitivity also decreases when RLC/ROS ratios are large.

SUMMARY AND CONCLUSIONS

Marked inconsistencies result from different fuels, fire and measurement conditions, and fuel resistance-to-control classification schemes. Substantial variability in production rates results from other variables that could not be identified by comparing results of previous studies. For example, crew supervision and team spirit may be major, yet difficult-to-measure, determinants. Recent and future production studies may attempt more detailed information coverage, but even with adequate accurate knowledge, some resulting variability in production rate may be a function of the type of production being measured.

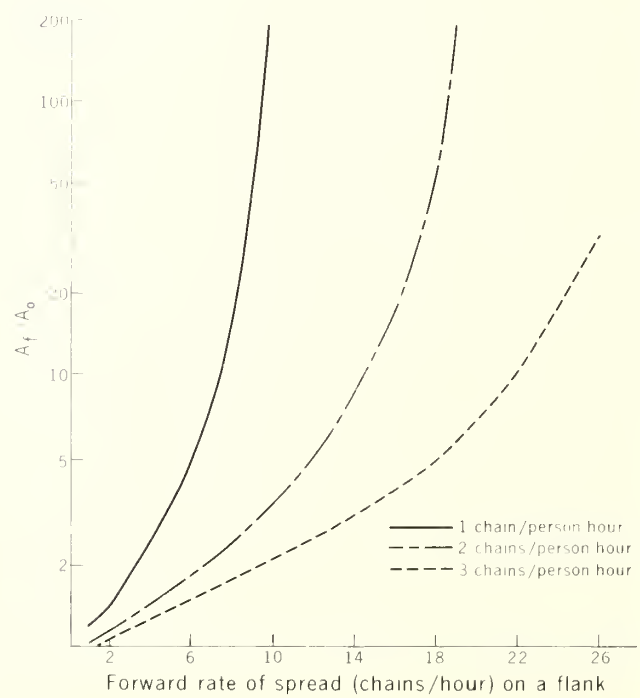


Figure 2—Effectiveness of a 20-man crew for different line construction rate assumptions. Assumptions are (a) 2:1 fire ellipse, (b) simultaneous force arrival, and (c) direct, rear attack.

Such inherent variability suggests that it is risky to rely on point estimates of production rates as a measure of estimating effectiveness of fire management activity. Production rate ranges, therefore, are provided for specific resistance-to-control classes. These ranges may be used in a variety of ways. They may be useful aids for helping fire managers assess the inherent risk in determining an adequate suppression force size. In certain instances, a fire manager may choose appropriate production rates by consistently selecting rates from the high or low ends of the given range, depending on fire site conditions and the manager's attitude toward risk.

The simplified sensitivity analysis shows the asymmetry of effects on fire size prediction resulting from errors in estimating production rates. A simulation model's percentage error of prediction is larger if crew production rates used are less than the real rate and smaller if production rates used are greater than the real rate. The effects of errors in productivity on real-time dispatching are equally severe. An assumption of high productivity results in too few forces being dispatched. Too few forces can have a dramatic impact on the final size of the fire. As the ratio of line construction rate to rate-of-spread increases, errors in production rates decline in importance for predicting final fire sizes.

Historically, studies on line production rates for hand crews show the difficulty of the research problem and the variability of the results. Point estimates and associated variances are needed for modern fire suppression modeling and planning decisions. Future studies need to assess probabilities of obtaining line production rates under different conditions. Any future studies of line production rate should be designed to measure variability so that probability distributions of rate of line construction can be derived. Probability distributions allow risk to be accounted for explicitly in fire analysis models. A methodology for obtaining the probability distributions required has been provided (Lindquist 1970). Productivity rates also need to be measured under actual fire rather than simulated conditions. Productivity under simulated conditions tends to be higher than productivity measured under actual conditions.

Another area of study needing attention is the development of resistance-to-control classes that can be determined by field analysis. Pioneering work on quantitatively determining resistance-to-control has already been done (Murphy and Quintilio 1978). Standardization of resistance-to-control measures and productivity probability distributions are required for future applications of line production rate measures.

APPENDIX

Table 3—*Fuels rated by resistance-to-control class, by Region within Forest Service*

Region	Low	Medium	High	Extreme
Northern (Region 1)[1]	Generally open with primarily grass cover.	Timber stands with minor amounts of dead branchwood, may contain some brush.	Timber stands with medium amounts of dead branchwood, tree stems, or rock. May contain heavy underbrush.	Timber stands with extensive dead tree stems, branchwood, brush, and rock
Rocky Mountain (Region 2)[2]	Open, park-like stands of: 1. Ponderosa pine 2. Spruce 3. Douglas-fir 4. Hardwoods Pinyon juniper Linden bristlecone Patchy oak Grass Patchy subalpine spruce and fir Patchy sagebrush	Light reproduction Uneven-aged stands Slash	Slash Heavy reproduction Mature stands Mixed aspen Dense oak Dense sagebrush	Slash (heavy)
Southwestern (Region 3)[3]	Woodland Grassland	Ponderosa pine Brush Spruce fir Aspen	Slash Chaparral	

[1]Source: Region 1 Supplement 1 to the Fireline Handbook (U.S. Dep. Agric., Forest Serv. 1974).

[2]The fuels listed are summarized from the fuels description in the Region 2 Supplement 1 to the Fireline Handbook (U.S. Dep. Agric., Forest Serv. 1972a). Twenty-one fuel classes with a total of 60 subclasses are listed in the supplement.

[3]Source: Region 3 Supplement to the Fire Fighting Overhead Notebook (U.S. Dep. Agric., Forest Serv. 1965a).

Table 3—*Fuels rated by resistance-to-control class, by Region within Forest Service* (continued)

Region	Low	Medium	High	Extreme
Intermountain (Region 4)[4]	Lodgepole pine 1. Light windfall, clear trees 2. Sapling stand	Lodgepole pine 1. Moderate windfalls with grass carpet 2. Open, pole stand 3. Scattered other species, some grass	Lodgepole pine 1. Mature with windthrow and bug kill	
	Subalpine 1. Protected NE slopes 2. Fully exposed ridgetops	Spruce 1. Snags, scattered brush, trees	Subalpine 1. Dense 2. Limbs thick to the ground	
	Spruce 1. Clean trees, no snags or windfall	Ponderosa pine 1. Dense, intermixed reproduction	Slash Old growth, Douglas-fir and white fir	
	Open, grassy stands of ponderosa pine, Douglas-fir, and subalpine fir Ceanothus brush Sagebrush Cheatgrass	Fir Mixed age, older trees Mixed brush Ceanothus brush		
Northeastern (Region 7)[5]	Grass, ferns, and weeds Unburnable	Northern and Appalachian hardwood, 3 inches d.b.h.	Northern conifers, 4 inches d.b.h.[7]	Conifer slash
		Southern pine 6 inches d.b.h.[6]	Northern conifers, cutover duff and no slash	
		Southern pine reproduction	Hardwood and hemlock Hardwood, cutover, no duff or slash Hardwood reproduction Hardwood and Southern pine slash[7] Laurel and rhododendron[7]	
Southern (Region 8)[8]		*Plains area except Florida*		
	Pine (except sand pine) Grass	Sand pine Bottomland hardwood	Pine and hardwood Scrub oak	Organic soil Pocosin
		Florida		
	Grass	Longleaf pine-scrub oak Sand pine Pine-hardwood	Loblolly pine-slash pine Palmetto flatwoods	Pond pine-titi Grass-tupelo
		Mountain area		
		Upland hardwood Conifers and hardwoods Pine (all except white pine) Pine-hardwood (all except white pine)	Brush (rhododendron, laurel) Scrub hardwood	
		Intermountain area		
	Grass	Pine (all) Pine-hardwood	Scrub hardwoods Pine-youpon	

[4]The fuels listed are summarized from the fuels description in Region 4 Supplement 1 to the Fireline Handbook (U.S. Dep. Agric., Forest Serv. 1972b). The Handbook lists 17 classes with a total of 48 subclasses.

[5]Sources: Banks and Frayer (1966) and Jemison and Keetch (1942). Region 7 no longer exists. Parts of it have been incorporated into Regions 8 and 9.

[6]Classified as low by Jemison and Keetch (1942).

[7]Classified as medium by Jemison and Keetch (1942).

[8]Source: Region 8 Fireline Notebook (U.S. Dep. Agric., Forest Serv. n.d.).

Table 3—*Fuels rated by resistance-to-control class, by Region within Forest Service* (continued)

Region	Low	Medium	High	Extreme
Eastern (Region 9)[9]	Short grass, weeds, and marshgrass	Wet brush, muskeg	Swamp conifers	Slash
		Lowland hardwoods	Slash	
		Upland hardwoods		
		Oak	1. Swamp conifers	1. Hardwoods and swamp conifers
		Aspen	2. White cedar	2. Upland conifers, oak, and white cedar
		Scrub oak	3. Oak	
		Upland conifers	4. Hardwoods	
		Understory upland conifers	5. Upland conifer and white cedar	
			6. Aspen	
		Understory upland conifers		
		Slash	Understory–upland conifers	
		1. Upland conifers		
		2. Oak and hardwoods	Oak	
		3. Aspen	Upland conifer plantations	
		Drybrush and muskeg		
		Broom sedge		

[9]Source: Region 9 Fire Overhead Notebook (U.S. Dep. Agric., Forest Serv. 1957). Duplicates in table result from size differences within a fuel type

Table 4—*Rates of construction of fireline for Forest Service Pacific Southwest and Pacific Northwest Regions, by fuel type and source of estimates (chains per hour per person)*[1]

Fuel type[2,3]	Fireline handbook: Basic rate	Fireline handbook: After 8 h	Scowcroft and others (1966)	Stevenson (1951)	Buck (1938)	U.S. Dep. Agric., Forest Serv. (1938)	Lindquist (1970)[4]: 1 h	Lindquist (1970)[4]: 8 h
1	4.0	2.1				2.9	1.2	0.6
2	3.6	1.8	1.0			1.8		
3	4.7	2.5				2.4	.8	
4	3.7	2.1				2.2		
5	2.7	1.4				1.5	.8	.5
6	1.4	.7	.5		1.1	1.5	.8	.5
7	2.7	1.4	.8			1.4	.8	.5
8	1.4	.7	.7			1.1	.8	.5
9	1.2	.6				1.0	.8	.5
10	1.1	.6			1.1	1.0		
11	.7	.4	.7	0.3		.6		
12	.7	.4		.5		.5		
13	.4	.2	.3	.22			.5	.2
14	.3	.2				.7	.3	.2
15	.5	.3						
16	1.2	.6						
17	6.2	3.1						
18	.7	.4						

[1]Regions 5 and 6 use the same fireline construction rates for each numbered fuel type. Region 5 information is from Region 5 Fireline Handbook (U.S. Dep. Agric., Forest Serv. 1973); Region 6 information is from Region 6 Fireline Notebook (U.S. Dep. Agric., Forest Serv. 1965b).

[2]Fuel types 4, 7, 8, 11, 12, and 17 are excluded from the Region 6 source; fuel type 18 is excluded from the Region 5 source.

[3]*Fuel descriptions:*

1. Grass
2. Grass and scattered sage
3. Mature timber—little chopping
4. Bear clover
5. Open manzanita—patchy brush
6. Timber—medium reproduction and brush
7. Light-to-medium chamise (southern California)
8. Brush mixtures with sage
9. Medium brush—in cutover or timber burn
10. Mixed Douglas-fir–white fir, with brush and reproduction
11. Medium brush and oak (southern California)
12. Heavy pure manzanita, chamise, or buckbrush
13. Heavy mixed brush
14. Heaviest mixed brush
15. Second growth—medium poles
16. Slash in cutovers
17. Woodland—little chopping
18. Mature timber (westside forests)

[4]The fuel groupings into regional fuel classes are the authors', based on descriptions given in the publications.

REFERENCES

Banks, W.G.; Frayer, H.C. **Rate of forest fire spread and resistance-to-control in the fuel types of the eastern region**. Fire Control Notes 27(2):1-13; 1966.

Biddison, L.R. [Letter to Parkin Hunter]. 1980, April. Forest Fire Laboratory, Forest Service, U.S. Department of Agriculture, Riverside, CA.

Bratten, F.W. **Containment tables for initial attack on forest fires**. Fire Technol. 14(4):297-303; 1978.

Buck, C.C. **Progress report on resistance-to-control study—1937**. Berkeley, CA: California Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1938. 28 p.

Davis, J.B.; Irwin, R.L. **FOCUS: A computerized approach to fire management planning**. J. For. 74:615-618; 1976.

Hanson, P.D.; Abell, C.A. **Determining the desirable size of suppression crews for the national forests of northern California**. Fire Control Notes 5(3):56-160; 1941.

Jemison, G.M.; Keetch, J.J. **Progress report**. Tech. Note 53. Asheville, NC: Appalachian Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 1942. 15 p.

Lindquist, J.L. **Building firelines—how fast do crews work?** Fire Technol. 6(2):126-134; 1970.

Matthews, D.N. **Crew size affects firefighting efficiency—a progress report on time studies of the firefighting job**. Res. Note 29. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1940. 10 p.

McMasters, A.W. **Preliminary analysis of the influence of handcrews on fire growth**. Oper. Res. Cent. Rep. ORC-63-7 (RR). Berkeley, CA: Univ. Calif. Inst. Eng. Res.; 1963. 29 p.

McMasters, A.W. **Wildland fire control with limited suppression forces**. Oper. Res. Cent. Rep. ORC-66-5 (RR). Berkeley, CA: Univ. Calif. Inst. Eng. Res.; 1966. 141 p.

Murphy, P.J.; Quintilio, D. **Handcrew fireline construction: a method of estimating production rates**. Inf. Rep. NOR-X-197. Edmonton, Alberta: North. For. Res. Cent., For. Serv., Environ. Canada; 1978. 28 p.

Parks, G.M.; Jewell, W.S. **Preliminary model for initial attack**. Oper. Res. Cent. Rep. F-1. Berkeley, CA: Univ. Calif., Inst. Eng. Res.; 1962. 29 p.

Pirsko, A.R. **How good are fire line construction rates?** 1966. Unpublished draft supplied to authors.

Quintilio, D.; Anderson, A.W. **Simulation study of initial attack fire operations in the Whitecourt Forest, Alberta**. Inf. Rep. NOR-X-166. Edmonton, Alberta: North. For. Res. Cent., For. Serv., Environ. Canada; 1976. 34 p.

Ramberg, R.G. **Firefighters physiological study—project record ED&T 2003—firefighting efficiency of man—the machine**. Missoula, MT: Equipment Development Center, Forest Service, U.S. Department of Agriculture; 1974. 33 p.

Scowcroft, P.G.; Murphy, J.C.; Pirsko, R. **How good are fireline production rates?** 1966. Unpublished draft supplied to authors.

Simard, A.J.; Young, A.; Redmond, R. **AIRPRO: An airtanker productivity computer simulator model**. Inf. Rep. FF-X-67. Ottawa, Ontario, Canada: Forest Fire Research Institute; 1978. 38 p.

Steele, R.W. **Use of bulldozers for fireline construction**. Missoula, MT: Montana State Univ. Bull. 19; 1961. 11 p.

Stevenson, S. **"Hot shot" crews**. Fire Control Notes 12(2):29-31; 1951.

Storey, T.G. **Productivity and rates of substitution of line building forces in fire suppression—a sumary of existing data**. 1969. Unpublished draft supplied to authors.

Swersey, F.S. **Parametric and dynamic programming in forest fire control methods**. Oper. Res. Cent. Rep. ORC 63-8 (RR); Berkeley, CA: Univ. Calif. Inst. Eng. Res.; 1963. 24 p.

U.S. Department of Agriculture, Forest Service. **Resistance to line construction 1938 tests, Region 5**. San Francisco, CA: Forest Service, U.S. Department of Agriculture; 1938. 20 p.

U.S. Department of Agriculture, Forest Service. **Fire overhead notebook**. Milwaukee, WI; Northcentral Region (R-5), Forest Service, U.S. Department of Agriculture; 1957. 92 p.

U.S. Department of Agriculture, Forest Service. **Fireline notebook**. FSH 2, 5135.7. Lakewood, CO: Rocky Mountain Region (R-2), Forest Service, U.S. Department of Agriculture; 1961. 108 p.

U.S. Department of Agriculture, Forest Service. **Firefighting overhead notebook**. FSH 2. Ogden, UT: Intermountain Region (R-4); Forest Service, U.S. Department of Agriculture; 1962. 216 p.

U.S. Department of Agriculture, Forest Service. **Fireline notebook**. FSH 2, 5135.7. San Francisco, CA: California Region (R-5), Forest Service, U.S. Department of Agriculture; 1963. 121 p.

U.S. Department of Agriculture, Forest Service. **Title 5100-fire control manual supplement 146**. Eastern Region (R-7), Forest Service, U.S. Department of Agriculture; 1964. 3 p.

U.S. Department of Agriculture, Forest Service. **Firefighting overhead notebook**. Albuquerque, NM: Southwestern Region (R-3), Forest Service, U.S. Department of Agriculture; 1965a. 187 p.

U.S. Department of Agriculture, Forest Service. **Fireline notebook.** FSH 4134.4 Portland, OR: Pacific Northwest Region (R-6), Forest Service, U.S. Department of Agriculture; 1965b. 200 p.

U.S. Department of Agriculture, Forest Service. **Fireline notebook**. FSM 5134.5 and FSH 5132.51. Missoula, MT: Northern Region (R-1), Forest Service, U.S. Department of Agriculture; 1966a. 160 p.

U.S. Department of Agriculture, Forest Service. **Fireline notebook**. Juneau, AK: Alaska Region (R-10), Forest Service, U.S. Department of Agriculture; 1966b. 150 p.

U.S. Department of Agriculture, Forest Service. **Fireline handbook**, Supp. 1. Lakewood, CO; Rocky Mountain Region (R-2), Forest Service, U.S. Department of Agriculture; 1972a. 5 p.

U.S. Department of Agriculture, Forest Service. **Fireline handbook**. R-4 Supplement No. 1. Ogden, UT: Intermountain Region (R-4), Forest Service, U.S. Department of Agriculture; 1972b. 9 p.

U.S. Department of Agriculture, Forest Service. **Forest Service Handbook**. FSH 5109.17. Region 5 Supplement No. 1. San Francisco, CA: California Region (R-5), Forest Service, U.S. Department of Agriculture; 1973. 39 p.

U.S. Department of Agriculture, Forest Service. **Fireline handbook**. Region 1 Supplement No. 1. Missoula, MT: Intermountain Region (R-1), Forest Service, U.S. Department of Agriculture; 1974. p. 23.4-1 to 23.4-2.

U.S. Department of Agriculture, Forest Service. **Fire management analysis for forest planning—Rocky Mountain Region (R-2) (Rev. 9/79)**. Washington, DC: Forest Service, U.S. Department of Agriculture; 1980.

U.S. Department of Agriculture, Forest Service. **Fireline handbook**. Atlanta, GA: Southern Region (R-8), Forest Service, U.S. Department of Agriculture; n.d. 90 p.

United States
Department of
Agriculture

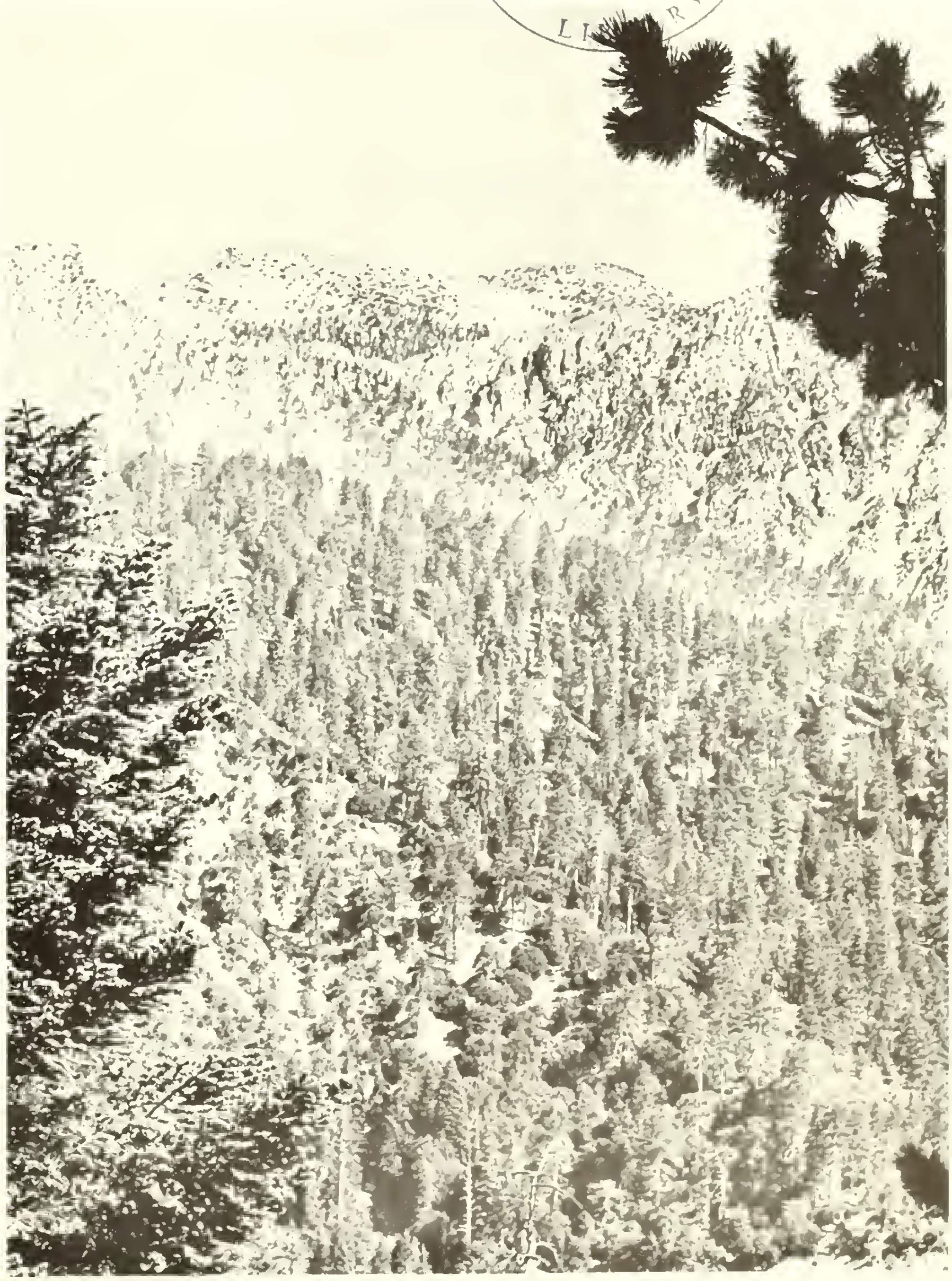
Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

General Technical
Report PSW-63

A Vegetation Classification System for Use in California: Its Conceptual Basis

Timothy E. Paysen Jeanine A. Derby C. Eugene Conrad



The Authors:

TIMOTHY E. PAYSEN, a research forester, is assigned to the Station's chaparral and related ecosystems research unit, with headquarters at Riverside, Calif. He earned a bachelor of science degree in forest management at Humboldt State College (1969) and a doctorate in applied statistics at the University of California, Riverside (1978). **JEANINE A. DERBY** is a forest botanist, San Bernardino National Forest, San Bernardino, Calif. She received a bachelor's degree in biology (1974) at the University of California, Riverside, and a master's degree in biology (1979) at California State University, San Bernardino. **C. EUGENE CONRAD** heads the Station's research unit studying the management of chaparral and related ecosystems, with headquarters at Riverside, Calif. He earned a bachelor's degree in agriculture (1956) and a master's degree in range management and plant ecology (1959) from Oregon State University. He joined the Forest Service and Station's research staff in 1961.

Acknowledgments:

We thank Ivan E. Parker of the Pacific Southwest Region's Land Management Planning Staff, Forest Service, U.S. Department of Agriculture, for his active participation in developing earlier manuscript drafts and for his pungent critique of concepts and philosophies that would have earned for him the right to coauthorship had time and priorities allowed him to become involved in developing the final draft. Responsibility for final content, concepts, and philosophies rests with us. We also thank members of the California Interagency Vegetation Task Group who provided technical review of this paper: Norden H. Cheatham, University of California Systemwide Administration; Harlan C. DeGarmo, Soil Conservation Service, U.S. Department of Agriculture; Don A. Duncan, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; E. Lee Fitzhugh, University of California Cooperative Extension; Glen Holstein, The Nature Conservancy; Nancy Tosta Miller, California Department of Forestry; Dale A. Thornburgh, Humboldt State University; and John W. Willoughby, Bureau of Land Management, U.S. Department of the Interior.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

December 1982

A Vegetation Classification System for Use in California: Its Conceptual Basis

Timothy E. Paysen Jeanine A. Derby C. Eugene Conrad

CONTENTS

Introduction 1
Vegetation Classification in California 2
Classification System for California 2
  Association: The Basic Unit 3
  Series: Overstory Species 3
  Subformation: Morphological Similarities 4
  Formation: Physiognomic Similarities 4
  Phase: Variability in Communities 4
  Nomenclature 5
Conceptual Basis of the System 6
  Performance Requirements 6
  Design Criteria 7
Concepts Useful in Field Application 9
  Plant Community Organization 9
  Succession and Development 10
  Potential Vegetation and Climax 10
  Apparent Instability in Stable Communities 10
Appendix: Classification System Correlations 11
References 13

A long-standing communication problem for people who manage resources is now entering a critical stage. In the past, different vegetation classification "languages" became current, in line with the emphasis on specific resource management responsibilities or functions, such as timber or wildlife. With the change in emphasis toward interdisciplinary management, the diversity of these languages hampers effective planning and coordination. Because each functional or technical vegetation classification system reflects a different viewpoint, no one system can be used by all disciplines or agencies.

The system described in this report solves the communication problem. It addresses only the vegetation component of ecosystems; it is a plant community taxonomy based on the fundamental concepts of classification. It can thus serve as a crosswalking mechanism, or general language, with common acceptance in resource management. Properly used, it is a consistent framework on which to build better languages adapted to specific resource functions.

The system addresses a basic plant community unit at five levels of descriptive detail, four of which are members of a formal hierarchy. Floristic criteria are used for the basic unit at the most precise level, the plant Association, and for the more generally descriptive unit, the Series. Physiognomic and morphological criteria are used to aggregate these basic units to the Subformation and Formation levels of the system. The fifth level, the Phase, which is outside of the hierarchy, provides a flexible tool for description of vegetation characteristics related to resource function or other specific objectives.

The development of the present system has taken place against a background of many attempts to classify vegetation. In the aggregate, existing systems reflect a variety of purposes and an assortment of descriptive scales, but each system meets a specific objective. Systems have been designed to organize vegetation according to functional resource management criteria, to describe vegetation associated with land units or ecological units, to distinguish structural types or floristic assemblages, or to stratify vegetation into recognizable areal units. Systems came into being to ease management activity (inventory, land allocation, planning), to illustrate ecological relationships, or to provide a framework for understanding vegetation dynamics. Systems can be designed to address a single level of plant assemblage organization, or a hierarchy of levels. Some classification schemes are designed for use in local areas (Critchfield 1971, Thorne 1976) and others for general application (Whittaker 1962). Each system performs its role well, when used as originally intended.

Many vegetation classification schemes are related to Clements' idea of stratifying the earth's vegetation into large-scale expressions of major climate zones (Clements 1916, 1920; Weaver and Clements 1938). Some of these schemes do not conform to Clements' exclusive use of climax vegetation in the definition of their basic unit (Cooper 1922). Most systems provide for recognition of both climax and seral vegetation. Although not as systematic as others in this group, the classification devised by Kuchler (1964) as a basis for mapping potential natural vegetation of the United States can be included. Kuchler's potential natural vegetation is defined as that which would exist if man were removed and subsequent plant succession telescoped into a single moment in time.

Many classification systems go beyond the mere description of vegetation. Some systems focus on the ecology of vegetation; these systems relate particular kinds of vegetation to the characteristics of the environments that they grow in. Thus, we find plant communities and vegetation types with such names as Alkali Sink Scrub, Alpine Cushion Plant, Palm Oasis Woodland, Foothill Oak, or Desert Transition Chaparral. Other systems focus specifically on ecosystems that are characterized by vegetation; these systems classify land units or ecosystems, but use names derived from vegetation classification schemes (see Daubenmire 1968, Hall 1976, Layser and Schubert 1979, Pfister and Arno 1980). A different use of vegetation nomenclature is found in systems for classifying land or ecological units that represent more general biological systems (Brown and others 1979, Dansereau 1951, Walter 1973). Included in this last group, and geared towards mapping vegetation on a global scale, are Fosberg's system (Fosberg 1967) and the UNESCO system (UNESCO 1973). The distinction between the kinds of systems described in this paragraph and those that classify vegetation alone is often missed by practitioners, and occasionally by the system developers themselves.

Vegetation classification systems have been a necessary by-product of inventory, mapping, land classification, or ecosystem classification systems. In timber and range management, for example, vegetation growing sites are placed in categories defined by management criteria (Eyre 1980; U.S. Dep. Agric., Forest Serv. 1979; U.S. Dep. Agric., Forest Serv. 1975). Some systems serve as a point of departure for understanding the structure and dynamics of vegetation (Braun-Blanquet 1932). Poulton (1972) developed a plant community classification system in order to complete a land cover map legend.

This report describes a Vegetation Classification System and its conceptual basis. It provides users of the System with information that will facilitate its consistent application in the field, clarifies the System's relevance to various classification problems, and suggests methods for its use. Application of the system was illustrated in an earlier report (Paysen and others 1980).

The theoretical and pragmatic needs that were considered in the development of the System, and the way that the System's final form meets both kinds of needs, provide the major topics for discussion. Given the understanding of the System's conceptual basis that this report provides, users with a resource management emphasis, and those with a theoretical ecology orientation, will understand the System's function as a framework for categorizing plant communities and as a vehicle for communication.

VEGETATION CLASSIFICATION IN CALIFORNIA

The dictum that form follows function is illustrated in the vegetation classification systems that have been applied to California vegetation. The goals of various practitioners have been met with a diverse collection of systems—not all of which classify vegetation in the strict sense.

Cooper (1922), following the approach of Clements (1920) with some modification, wanted to characterize broadly a community generally dominated by sclerophyllous-leafed shrubs. Addressing California's chaparral, he focused on a large zonal vegetation type and subdivided it into units that were distinctive strata within the general community. Because this (Clementsian) approach is a useful way of accounting for all vegetation from the start, and for dealing with more specific subdivisions as knowledge or awareness increases, it has been followed through the years by many practitioners who have extended Cooper's work. The approach is suitable for mapping and, in modified form, was used by Wieslander (1935) as the basis for his Vegetation Type Map Survey of California (Critchfield 1971).

The need for a practical framework for applying a statewide flora was the impetus for Munz' system for classifying California plant communities (Munz and Keck 1963). The intended use of his system is reflected in its form. The broad brush classes, in part zonal and in part based on dominant species or species groups, generally describe the environment of individual plant species. Because they operate at equivalent levels of precision, the Munzian and Clementsian approaches often provide similar descriptions of plant communities. Because these broad descriptions fill a common need, familiar nomenclature and concepts from Cooper, Munz, and Wieslander have often been combined to describe vegetation in general terms (see, for example, Hanes 1976).

Thorne's (1976) vascular plant communities of California also serve to describe the environment of plant species. His system is more detailed than that of Munz, but places less emphasis on vegetation and more on the character of the environment.

The need to describe vegetation characteristics of ecological units, landscape units, geographic zones, or climate zones has produced a set of contrasting classification systems. The precision of classification, and the successional status of the vegetation addressed by these systems vary with the author's goal (Brown and others 1979, Cheatham and Haller 1975, Sawyer and Thornburgh 1977). The heterogeneity of individual classes also varies with the goal, and must be evaluated according to the degree of precision in communities or types that is attempted. Compare, for example, the sytems of Wieslander (Critchfield 1971) and Kuchler (1977), disregarding differences in successional status being addressed by the two systems. The emphasis on particular kinds of vegetation often reflects an operational perspective, such as that of timber or range resource management (Beeson and others 1940; Eyre 1980; Jensen 1947; Show and Kotok 1929; Stoddart and Smith 1943; U.S. Dep. Agric., Forest Serv. 1969; Wieslander and Jensen 1946). A highly specialized system for characterizing vegetation on soil units—with emphasis on timber productivity—is used by the California Soil/Vegetation Survey (Colwell 1974).

A unique system developed by The Nature Conservancy is now being applied to California vegetation (Holstein 1980). The system is intended to provide a database framework designed to aid in ecosystem analysis by organizing information on all vegetation. The system identifies a homogeneous stand of plants, and characterizes the vegetation units strictly by cover dominance—without regard to visual or vertical dominance. The ecological significance attributed to cover dominance as defined by this system is based on the interception of solar radiation when the sun is at zenith position. Codominant community species are arranged in the community name in alphabetical order within a growth form hierarchy.

Interdisciplinary communication demands a way of bringing existing vegetation classification systems into common focus. Resource managers recognize that a well-designed basic classification system would solve the communication problem with a minimum of inconvenience to any single discipline or agency. Within the Forest Service, U.S. Department of Agriculture, the development of a basic reference language has been one concern of the Resources Evaluation Techniques Program of the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado (Driscoll and others 1982), and of the Pacific Southwest Region, San Francisco, California (Parker and Matyas 1979). A similar concern prompted the Chaparral Research and Development Program of the Pacific Southwest Forest and Range Experiment Station, Riverside, California, to accept a challenge to devise a general system that could be applied to southern California vegetation (Paysen and others 1980). Because of exchange of ideas, the general vegetation classification philosophies of the above groups have converged. The specific classification philosophy reported here has developed with the assistance of the California Interagency Vegetation Task Group. The system described is suited for local use within any of a variety of vegetation regimes and can be easily related to the kind of system that the Resources Evaluation Techniques Program is developing for use at the national level (see *appendix*).

CLASSIFICATION SYSTEM FOR CALIFORNIA

The focus and structure of the Vegetation Classification System allow the user to name plant communities in a single scale of community organization with the degree of precision warranted by a particular task.

A *plant community* is an aggregation of plants living in adjustment with one another in a relatively uniform environment, and has a distinct floristic and physiognomic character. This general definition applies to plant aggregations of any scale (Daubenmire 1968, Ecological Society of America 1952, Schwartz and others 1976). The plant community that the System is directed toward is site-specific; it is the most precise community that incorporates all layers of vegetation. The System's hierarachy is arranged along a dimension of descriptive precision—each level describes a given community in less detail than the level below it (*fig. 1*). The most detailed community description lies at the Association level. The Association is most appropriate for studying community dynamics and for carrying detailed project applications to completion. As resource management activities move from field units to higher levels in a management organization, more general levels of the System will come into use. To the level of detail in the initial data, the framework of the System can be used for aggregation and disaggregation of data and allocation of vegetation management activities. In *tables 1*, *2*, and *3*, the System levels, criteria, and rules for nomenclature are set forth.

Association: The Basic Unit

The plant Association is the basic unit of this classification system (*table 1*). The Association is an abstract classification category comprising stable plant communities that have a particular set of dominant species in common. Communities within an Association are relatively stable, and each has a distinctive stand physiognomy and characteristic species composition in each of its layers. The name given to an Association reflects the dominant species or set of codominant species (in terms of relative percent canopy cover) within each layer (*table 2*).

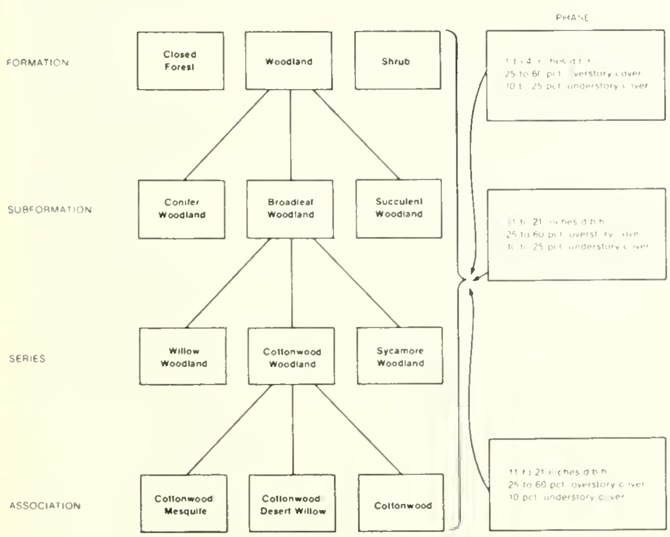


Figure 1—The relation between hierarchy levels of the classification system is shown in this example. In the diagram, the classification of a community becomes progressively more precise as it moves through the levels recognized in the classification (Formation, Subformation, and Series). The most specific level is the plant community (Association). The appropriate descriptive Phase is determined and applied to any level of the hierarchy.

The significance of an Association is due the Association's persistence in a given vegetation system. For this report, the plant communities and community dynamics that characterize a distinctive vegetation—and lend identity to an extensive ecosystem or floristic zone—constitute a vegetation system. An Association's persistence can find expression in one or more of the following ways: the Association can be the long-term occupant of a given site (although it need not be a climax community); it can often be found throughout a vegetation system, or it can recur in a vegetation system—perhaps as one stage of succession after disturbance. Length of occupance is not necessarily a criterion for naming or identifying an Association. Some authors reserve the term "Association" for plant communities that are climax or possess long-term stability in an ecosystem (Daubenmire 1952, Layser and Schubert 1979, Weaver and Clements 1938); however, this usage is not universal (Becking 1957, Brown and others 1979, Cooper 1922, Dansereau 1951, Whittaker 1962).

Because Associations have a degree of persistence, they can be incorporated into the formal management of resources. After some study, the dynamics of plant Associations can become sufficiently well known to be used as a management tool. Knowledge of Association dynamics is necessary in order for management specialists to determine the impacts of proposed management plans. Knowledge of plant Association dynamics is fundamental in directing land allocation for resource use and maintenance.

A feel for the variability within a plant Association can be gained from the identification criteria for the Formation and Subformation levels of the classification system (*table 3*), and from the overstory and understory species configurations that are possible within the limits of the criteria for each category. The Association is identified and named by the dominant species in the overstory and subordinate layers of the community.

Series: Overstory Species

In this classification system, all Associations with the same dominant species or set of species in the overstory are aggregated at the Series level (see *table 1*). For example, all Associations with red fir as the overstory dominant will belong to the Red Fir Series. Because they identify only the dominant species in the overstory, classes at the Series level provide a more general description of plant communities than is possible through use of the Association level. Series classes are therefore useful for general resource management planning, but have limited value in project applications where details of the vegetation and environment are important. For certain projects and in some ecosystems, Series may provide adequate detail.

Guidelines are necessary for developing Series names. Theoretically, every plant species in the world could have a unique Series associated with it; this would make an operational set of Series classes too cumbersome to use. It is reasonable, under some restrictions, to aggregate Associations dominated by *related* species into a single Series. The development of Series classes should be coordinated by responsible authorities within the body of classification system users. Inconsistencies that occur can thus be corrected as long as the information on community dominants, locale, and extent of occurrence is available.

Subformation: Morphological Similarities

The Subformation level of the System is most useful for general description of vegetation. Stem and leaf morphology of overstory dominants are key properties used to aggregate Series to this level of the System (*table 3, fig. 1*). In this paper, we identify 15 Subformations for California and specify identification criteria. Chaparral and Broadleaf Woodland are two such Subformations.

Formation: Physiognomic Similarities

The most general description of plant communities is made at the Formation level of the System (*table 3, fig. 2*). Overstory crown cover and growth form are used to aggregate Subformations to this level. We identify five Formations for California. Class names such as Closed Forest, Woodland, and Shrub imply the general structure of plant communities.

Phase: Variability in Communities

Qualified description of communities, at any level in the classification system, can be achieved with the Phase category. Phase allows us to deal with variability that exists within

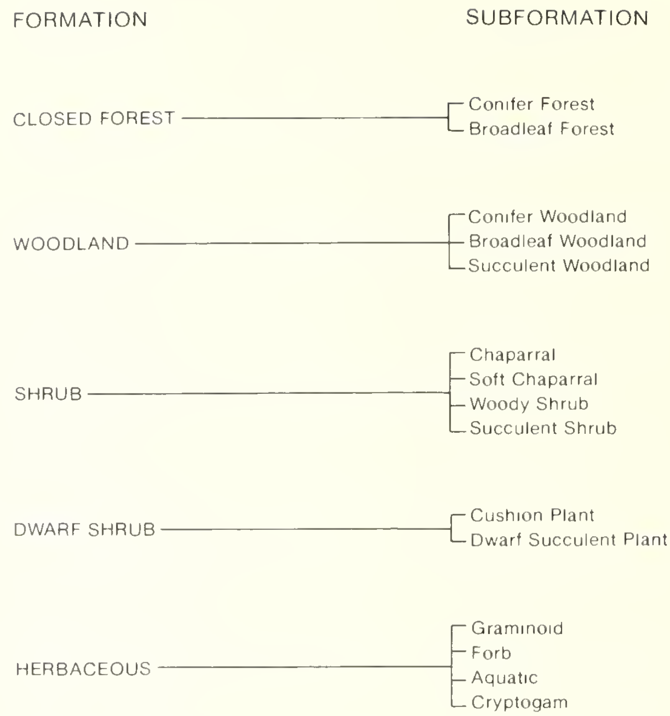


Figure 2—Within the Formation and Subformation levels of the classification system, classes such as these might be established if appropriate to California.

Table 1—*Classification system hierarchy, with identification factors and descriptions for each level*

Level	Level identification factors	Description
Formation (aggregate of Subformations)	Community physiognomy • Growth form of overstory layer • percent canopy cover of overstory	The Formation is a set of stable plant communities with a physiognomic profile bounded at the top by a vertical layer composed of species with a given growth form, and with an overstory crown cover that falls within a specific range of values
Subformation (aggregate of Series	Leaf and stem morphology of dominant species or set of species in overstory	The Subformation is a set of stable plant communities with a physiognomic profile bounded at the top by a vertical layer composed of species with a given growth form, with an overstory crown cover that falls within a specific range of values ,and with a characteristic stem and leaf morphology.
Series (aggregate of Associations)	Dominant[1] species or set of species in the overstory	The Series is a set of stable plant communities with a physiognomic profile bounded at the top by a vertical layer composed of species with a given growth form, and with the same dominant species or set of species in the overstory layer. The dominant species in the overstory characterize a group of taxonomically related Associations that are aggregated at the Series level.
Association (basic unit)	Dominant species or set of species in the overstory layer and in subordinate layers	The Association is a set of stable plant communities with a characteristic stand physiognomy and species composition in each of its layers. The same dominant species or set of species (in relative percent canopy cover) characterizes a given layer of each community.
Phase (qualifies all levels)	Flexible: age, density, stand vigor, mortality, development stage, etc.	The Phase addresses a dimension of the variability within a stable plant community or set of communities. The dimension addressed represents a particular technical or functional perspective.

[1]Defined by a measure of areal crown cover. The proportion of total areal cover allocated to a species determines its dominance status.

Associations. It can be used to specify growth stages, condition of vegetation, or some character within an Association that is especially noteworthy. Phase is a flexible category that can be used as a vehicle for management application of the system; such factors as age and density classes can be used to define Phases for specific functional applications.

Although it represents a break in the hierarchical nature of the system, the Phase category is necessary to the concept of the system as a crosswalking mechanism. A group of Phases defined to meet functional needs can be the link between the system and an existing functional resource management classification system.

Strict definition of all potentially relevant Phases of plant communities is not practical in this report; some examples can be found in *figure 1*, in Paysen and others (1980), and in Parker and Matyas (1979). Phases that are to be formally used within a resource management organization should be clearly defined, and accepted by members of the organization.

Nomenclature

The suggested guidelines for nomenclature in *table 2* are presented to give users a sense of the Vegetation Classification System's logic and structure. While these guidelines are tied strictly to the System's structure, certain details are subject to modification by a qualified body of user coordinators. The overstory/understory naming convention, with the use of dominants, is fixed. Specific percentages used to characterize mixed dominance, the number of layers to be considered, etc., are issues related to the transfer of ecologically significant information, and should be carefully evaluated by knowledgeable users.

Table 2—*Rules for naming plant Associations and Series*

System level and criteria	Nomenclature rule	Examples
Association		
A. Single-layered	Name by dominant species	Chamise Association; Red fir Association
Multilayered	Name by dominant species in each layer; start with overstory and end with herb layer if one exists. Separate layer names with a slash(/)	Jeffrey pine/Sagebrush/Squirreltail grass Association
B. Single species dominant in a layer	Name by dominant species in the layer	Jeffrey pine/Sagebrush Association (overstory dominated by Jeffrey pine; shrub layer dominated by Sagebrush)
Mixed species dominiant in a layer: proportion of layer cover allocated to each codominant species is within 10 percent of that of each of the other codominants	Name the layer by codominant species separated by hyphens. Where distinct synusia within a layer characterize an Association, treat as codominants	Jeffrey pine-White fir/Greenleaf Manzanita Association Chamise-Scrub oak Association
C. Sparse overstory layer: species is ecologically significant, but insufficient to define a Formation (10 to 25 percent cover)	Include sparse layer in parentheses	Foxtail fescue-Black mustard (Blue oak) Association Plicate coldenia/Desert dichoria (Creosote bush) Association
Series		
A. Association overstories dominated by a widespread species within an ecological zone or region, or by a species with distinct geographic/environmental affinities	Name by unique Series name for the dominant species	*Ceanothus leucodermis* Series Red fir Series
Association overstories dominated by a locally important species or a species that has ecological homologues within the same genus in adjacent ecological regions, zones, subregions, etc.	Name by genus of the dominat species	Ceanothus Series Manzanita Series Sagebrush Series Cypress Series
B. Mixed species dominant in overstory: proportion of overstory cover allocated to each codominate species is within 10 percent of that of each of the other codominants	Name the Series by codominant species separated by hyphens. Where distinct synusia within the overstory characterize a series, treat as codominants	Jeffrey pine-White fir Series Chamise-Scrub oak Series
Associations and Series		
Local usage	Use common names if available	Foxtail fescue-Black mustard (Blue oak) Association Manzanita Series
Official correspondence outside of administrative region, community documentation, scientific reports, etc.	Use Latin or scientific names	*Festuca megalura-Brassica nigra (Quercus douglasii)* Association *Arctostaphylos* Series

CONCEPTUAL BASIS OF THE SYSTEM

The new system proposed for use in California is different from others being used by resource management agencies in that it treats vegetation as an ecosystem component, and is neutral with respect to management function. Function neutrality is a necessary attribute of a vegetation classification system that serves as a basic reference language, because plant communities are used in one form or another in resource definition and description. Ecosystems with plant communities as identifying components (a plant community is used to name the ecosystem, or is of key importance in recognizing the system) can be defined at one or more levels of integration (for the theory of integrative levels, see Fiebleman 1954 and Rowe 1961). On the other hand, plant communities can be included with other biotic elements, and abiotic elements, as components that simply characterize a particular ecosystem. Also, ecosystems defined from various perspectives, each with a different center of emphasis, can have plant communities, or abstractions from them, as identifying components. Thus, the perception of animals, of land units that produce timber, and of land units that will someday produce particular climax plant communities, leads to the definition of wildlife habitats, timber types, and habitat types (Daubenmire 1968, Pfister and Arno 1980)—each of these being ecosystems that can be partially described by naming plant communities or some special aspect of plant communities. A basic reference classification system must be capable of consistent application within any of these contexts.

The development of a classification system proceeds against a background of information needs; these needs imply a set of performance requirements that are imposed upon the classification system. For a useful product to emerge, development should also be grounded in sound classification principles; these principles form the basis for specific system design criteria formulated in the light of the original information needs.

Performance Requirements

Information needs for a basic "language" system can be derived from a look at the system's potential use. Direct use would be in field classification of plant communities—which can provide information for resource management planning, for mapping, and for environmental description. Indirect use of the system would come about through its correlation with existing functional systems, such as timber-type or range-type classification systems; it would provide classifications from these systems with a common terminology. From these uses, the following performance requirements can be stated:

- The system should facilitate communication at local and regional levels of resource management; system information should be appropriate for direct input to national resource assessment systems.

Table 3—*Class identification criteria for the Formation and Subformation levels of the Classification System*

Formation	Subformation
Closed Forest—Overstory of deciduous or evergreen trees; 15 ft tall; crowns mostly interlocking; overstory crown cover 60 percent or greater	Conifer Forest—Overstory dominated by conifers Broadleaf Forest—Overstory dominated by broadleaf species
Woodland—Overstory of deciduous or evergreen trees; 15 ft tall; crowns not touching; overstory crown cover 25 to 60 percent	Conifer Woodland—Overstory dominated by conifers Broadleaf Woodland—Overstory dominated by broadleaf species Succulent Woodland—Overstory dominated by succulent-stemmed or succulent-leafed species
Shrub—Overstory of shrubs 1½ ft to 15 ft (0.5 to 5 m) tall at maturity (includes succulent stemmed species); overstory crown cover 25 percent or greater	Chaparral—Overstory dominated by plants that have sclerophyllous leaves and woody stems and twigs—such as chamise Soft Chaparral—Overstory dominated by plants that have softly sclerophyllous leaves and semiwoody stems—such as black sage Woody Shrub—Overstory dominated by plants that are as Chaparral but have membranous leaves—such as rose spp. Succulent Shrub—Overstory dominated by plants that have succulent leaves or succulent stems—such as *Opuntia* spp.
Dwarf Shrub—Overstory of shrubs 1½ ft (0.5 m) tall at maturity; overstory crown cover 25 percent or greater	Cushion Plant—Overstory dominants are nonsucculent dwarf shrubs Succulent Dwarf Shrub—Overstory dominants are succulent dwarf shrubs
Herbaceous—Overstory of grasses, sedges, rushes, forbs, and freshwater plants; herbaceous crown cover 2 percent or greater	Graminoid—Grasses and grasslike plants dominate Forb—Broadleafed herbaceous plants dominate Aquatic—Dominants require water for structural support Cryptogam—Dominated by Cryptogam species

- The system should be useful for classifying both existing and potential vegetation.
- For use at local resource management levels, the system should be flexible enough to allow site-specific description of plant communities and general description of vegetation in a management unit.

National Assessment and Communication

A resource language used locally and regionally must relate to communication problems at the national level. National assessment of renewable resources begins with basic, local, site-specific information. Site-specific information, when aggregated at the national level, provides an essential assessment of the nation's renewable resources. Management programs for these resources can be successful only if directives to local managers are issued within the framework that was used for aggregating the resource information. The new California system provides a framework that supports an assessment program for vegetation resources.

Classification of Existing and Potential Vegetation

The concepts of existing, potential, and climax vegetation relative to specific sites are of value to resource management. To identify current productivity, a management specialist must clearly recognize existing vegetation. A specialist must be able to identify and describe potential vegetation in order to predict the outcome of plant community changes that last only a few years. Knowledge of climax communities helps a resources manager know how much energy must be expended, or what management techniques are required, to modify the course of natural succession to a direction most suited to management needs. Knowledge of climax vegetation is useful in determining management alternatives that are in tune with the natural processes on specific land units or in specific resource systems.

A vegetation classification system is a naming tool that should be responsive to whatever information is given to it. A user should be able to describe the potential vegetation of a stand, and the system should be capable of responding with a community name.

Site Description and Data Aggregation

Various levels of planning intensity exists in the management of resource systems. Environmental analyses must be carried out at different levels of precision, depending on the perspective of the analysis and the precision of the impact in question. Aggregation of site-specific resource information to more general levels is necessary for management assessment and for allocation of resource systems to management treatment or resource production levels. Therefore, the need for detailed site descriptions can exist concurrently with the need for a general picture of resource status. The basic unit of a vegetation classification system should be site-specific, thereby facilitating detailed descriptions of plant communities; further, the system should allow the aggregation of community information for various management purposes.

Design Criteria

When a classification system is developed in a serious attempt to solve a problem (instead of an attempt to systematize a novel idea), a number of fundamental classification principles becomes apparent to the system developers:

- A classification system organizes a particular set of elements in a way that is useful, and provides a language for communicating information about these elements.
- A classification system should provide a unit that is fundamental to the needs expressed; within the realm of these needs, the unit should not overemphasize a particular specialized need or use—it should support all needs equally.
- A classification scheme should satisfy a single information requirement. Thus, if a complex set of classification needs is to be met, the system must focus on a common denominator among these needs.
- A classification system should be exhaustive, and limited to essentials. A system should classify any expression or realization of the elements that it is supposed to classify, but it should classify just those elements, and nothing more.

These principles provide a foundation for the system design.

The development of performance specifications is a necessary step early in the system development process. For a vegetation classification system to successfully serve as a basic communication vehicle, it should:

- Provide a framework for perceiving vegetation and a language for communicating information about vegetation (the role of vegetation classification in the resource communication process);
- Address a unit of vegetation that is common to the perception of users who represent a spectrum of management functions and research disciplines—each, conceivably, having a specialized technical system for classifying vegetation;
- Provide a common unit whose definition has utility in the identification of vegetation resource units and the vegetation component of ecosystems;
- Be organized in a way that allows it to be systematically applied to any kind of vegetation;
- Classify to the level of precision necessary to distinguish site-specific units on the basis of predominant physical and floristic characteristics;
- Classify vegetation and not technical interpretations of vegetation—but allow such interpretations;
- Provide for description of a unit with a range of precision levels

The rationale behind these specifications is summarized in the following paragraphs.

The Role of Classification in Resource Communication

Because classification is a key factor in the communication of resource data (*fig. 3*), a classification system should reflect the focus and perspective inherent in a set of information requirements. Information requirements, if clearly specified, center on a specific resource construct that reflects a functional or discipline-oriented viewpoint or bias. With regard to vegetation, the requirement may center on a zonal vegetation type defined from a range management point of view, or on a microcommunity defined from a wildlife biology viewpoint—to name only two examples.

If a classification system adequately addresses a set of resource information requirements, it becomes the primary vehicle of the information process. Classification has a direct role in inventory, mapping, database design, and resource management planning. The classification scheme provides the framework for the design of resource inventories. A map based on an inventory of the vegetation resource may be a direct areal representation of a classification system. Maps may depict resource aggregates, density patterns, interpretations, or any of numerous abstractions from components of the environment that are defined by classification systems. Classification also affects database design. A database may be a direct image of, or an abstraction from, the classification system. A classification system can be used both for direct communication of resource information, and for the formal description of environmental settings.

Common Vegetation Unit

The focus of a vegetation classification system should be plant communities or vegetation units. Many systems focus on abstractions from these (plant or animal habitats, functional vegetation types), or on communities or units that are qualified by successional status. To be useful as a general language, a system should have a neutral perspective, and it should have a common meaning to specific resource management functions. Timber or wildlife management should have the same perception of vegetation from data gathered by other functions as they would have from their own data sources; the system's basic unit should be common to the needs of all users. The scale of the system's basic unit should be site-specific, reflecting the most precise, commonly recognized community observable on a landscape.

All potential users of a classification system do not have a common perception of a basic plant community unit. Recognition of spatial patterns is subjective, and depends on an individual's background, training, and experience. In the planning stages of our development of the Vegetation Classification System, however, we determined that persons who deal with the management of vegetation do have a common perception of a basic plant community unit, and that it is sufficiently precise to be useful. The field studies leading to this conclusion sampled a variety of disciplines and resource management agencies. This commonly perceived basic unit is the Association.

A classification scheme should organize the system it addresses and should reflect the intended user's perception of the system. A classification scheme should satisfy a specific information requirement. The requirement may be common, and reflect many needs, or may be a single purpose requirement. The information requirement behind this system is the identification of a basic plant community unit.

The criteria used to classify a basic plant community should address the entire community—not just one aspect of it. They should distinguish communities that are distinct physical and biological units. The physical structure of the community and its floristic composition are major indicators of community character, and as such determine what use may be made of the community and how it can be recognized wherever it appears. Therefore, classification criteria based on physiognomy and floristics will be most generally useful.

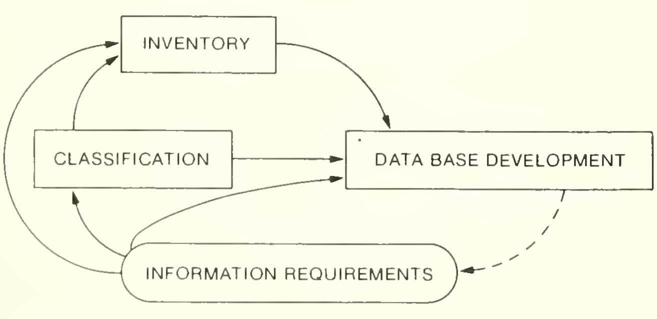


Figure 3—In the resource data communication process, information flows in the direction of the arrows; the broken arrow is feedback.

Logic and Elegance

The logic of a classification system should be completely developed, and consistently applied in the definition of categories and classes. A field practitioner should be able to correctly classify a unit of vegetation without resorting to "exceptions," "unusual cases," or descriptions of vegetation that "doesn't fit the mold." It follows that the definition of a unit in the classification system should allow for variability—but within specific limits.

A classification system should have as many categories and levels (if it is a hierarchical system) as are necessary to fulfill its role. Extraneous categories imply the use of classification criteria that do not specifically address the system's focus; too few categories imply a system that is incomplete. The system should strike a balance between complexity and simplicity. A complex system may address much useful information about a community's character, but may be too cumbersome to use operationally. An extremely simple system may be so ambiguous that attempts at explicit community distinctions are not possible within its bounds. An elegant system design should provide for simplicity without sacrificing the opportunity to elaborate or supplement with detailed information when needed. The variability implied by a class name should lie within acceptable bounds, or be reducible within the framework of the system.

Hierarchy and Language

A classification system is a language for the expression of commonly held concepts; the recognition criteria associated with these concepts should be clearly defined, so that the terms adopted really serve to communicate.

To be most useful for resource management, a basic component vegetation classification system should be designed around a hierarchy of descriptive precision. The hierarchy should be aggregative, with each hierarchical level describing the basic unit in more general terms that the preceding level.

CONCEPTS USEFUL IN FIELD APPLICATION

Once this classification system is understood, the problem of interpreting vegetation in the field still remains. Plant communities can be defined from various perspectives and at different levels of integration. Thus, a user must develop a feel for the particular range of variation in community organization that is addressed by the classification system. In addition, community structure and composition are not static, and their changes may in time require recognition of a new community. To know when a new community has evolved, and to interpret the dynamics of an existing plant community so as to visualize the potential community it represents, a user must evaluate many concepts of community dynamics, applying those compatible with the design of the classification system. The following discussion of these concepts should help assure consistent application of the classification system based on recognition of plant communities and on plant community dynamics.

Although a practitioner must recognize the distinction between the classification of vegetation and the science of ecology, the approaches and activities of ecology are important companions to the classification process. An ecological evaluation of an area often includes descriptions of both current vegetation and the vegetation that will occupy the site over a period of time, in the form of a succession of potential communities, with perhaps a climax community. The description of these communities and their dynamics is the business of ecology; naming them is classification.

Understanding of community dynamics is needed in classifying current vegetation that is changing rapidly. A stand may be developing from a pioneer stage, or may be at the point of succession from one community to another. A practitioner must determine the probable mature configuration of the *established* species in the stand and apply the rules of the classification system in order to name the community. For example, many chaparral sites are occupied by herbaceous communities immediately after a fire. For as long as herbaceous species dominate the site, the vegetation will be classified as a herbaceous community. When and if chaparral seedlings and sprouts become clearly established, however, and become an overstory, they should be considered in classification of the community. Thus, a practitioner must determine that the seedlings or sprouts are in fact established, and whether they will provide enough cover at maturity to form a chaparral community or will be simply a sparse overstory layer in a persistent herbaceous community.

Plant Community Organization

The concept implied in the definition of a plant community, that of a homogeneous or uniform environment, may be useful as a basic key to plant community recognition in the field, but must be applied with care. In its total effect, the interaction between individual plants and their immediate environments often helps us to define a unique cluster of microsites that is acceptable to an identifiable cluster of plants. The plant cluster may be an obvious discontinuity (*fig. 4*) or a loosely organized assemblage that is recognized only after study of distribution patterns. So, an organization of plants, identified as being drawn together by a collection of microsite conditions, is the community. This concept helps the practitioner avoid classifying microcommunities that are below the community scale of the system. If the concept is applied with an eye for overstory/understory patterns, the practitioner can also avoid classifying communities at too broad a scale; a significant shift in overstory/understory species composition patterns signals a distinction between communities. The community organization concept provides a logical means for expressing the view that floristically and physiognomically "pure" communities can be equivalent in classification status to those that have a degree of floristic and physiognomic diversity. For example, the fir communities in *figure 4* are equivalent, in the classification system, to the species-rich desert community in *figure 5*, and to the spare Jeffrey pine community in *figure 6*.

It is improper to state or imply an absolute, deterministic relation between an environmental unit and its associated plant community. A plant community is simply a perceived level of organization that expresses interaction between a cluster of plants and an environment. To some degree, at least, the perception of uniformity by an individual observer reflects the knowledge, experience, and concerns of that observer; the actual uniformity reflects the environmental requirements of the set of organisms. Biological communities are complex; consequently, the uniformity that exists is also complex. Dissection of a landscape by streams does not necessarily imply the presence of numerous communities. Neither can we assume that only one plant community is present in an environmental unit whose elements appear to be uniformity fixed.

The environmental uniformity we are concerned with in the field must be defined in relation to particular plant species aggregations. To plant species with a broad range of environmental tolerance, the environment of a given landscape unit may be sufficiently uniform, but to other species it may be intolerably nonuniform. Depending on the objectives of the classification project, a practitioner should evaluate the uniformity of an environmental unit with regard to either the plant community existing on the site, or another community that could potentially occupy the site.

Recognition of plant communities in the field does not demand total understanding of plant community dynamics for a particular site, but requires a general understanding aided by good sense. Cause-and-effect relationships between a community and its environment must be considered during the process of delineating plant communities. As much history as is available must be taken into account in the site analysis. Ultimately, though, pattern recognition and sound judgment in analyzing vegetation patterns are most important. A *bona fide* community exists in an environment that is relatively uniform, and the composition of the community is relatively stable. Interaction between a community and its environment, once the identification of the community has been established, can often be recognized and helps to solidify judgment on the status of a plant assemblage.

Succession and Development

There is an important distinction between community succession and plant community development. *Plant community succession* is the series of shifts in composition of plant cover on a site; by each shift, the aggregation changes from one community to another. In plant community succession, there is recruitment of new species and complete, or nearly complete, loss of others. *Plant community development* is also a shift in plant cover which results in a change in the character of a given plant community. But there is little, if any, recruitment of new species or loss of existing species, once the original composition has become established. As long as the identity of the community occupying a given piece of ground remains essentially unchanged, community processes such as growth and reproduction are part of plant community development. Changes in relative species composition that do not include significant recruitment are also a part of community development.

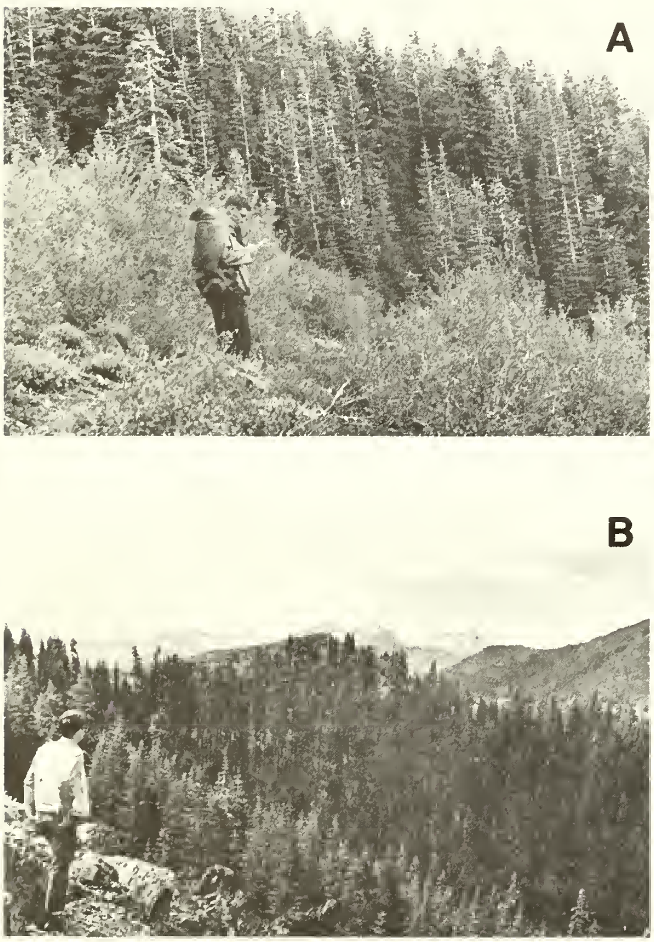


Figure 4—These easily distinguished plant communities in California's Salmon Mountains illustrate how the physical characteristics of species, the physical properties of the environment, and disturbance, often work—singly, or in concert—to provide distinct patterns on the landscape. (*A*) The physical contrasts between the shrub community in the foreground and the young white fir community in the background makes community recognition an easy matter. (*B*) Foliage color and species composition make the Shasta Red fir Association in the middle ground easy to distinguish from surrounding white fir communities. The Trinity Alps are seen in the background.

Potential Vegetation and Climax

It is often necessary to classify a unit according to a potential plant community, either climax or seral. The potential vegetation for a unit of land is any vegetation that could occupy that unit at some future time. Although juxtaposition and biogeographic history limit the possibilities, no one community can be cited as the "true" or "natural" unique occupant of a site—for any period of time. Chance events mitigate the effects of such deterministic processes as do exist. Only as part of the whole system can potential plant community expression be understood.

We can think of a climax community as one that represents the "end point" of an orderly, undisturbed process of succession. Climax vegetation is viewed as the ultimate potential of the site. The definition of end point determines the utility of the concept. Somewhat broadly interpreted, it provides at least a good baseline measure for evaluating the successional process, and understanding community dynamics. If defined as that point where all processes are effectively static, where mankind's influence is removed, and all perturbance is eliminated, the concept may have little value.

It is useful to reevaluate our approach to climax theory—or at least some operational aspects of our approach. Stability is a more effective indicator of climax than any specific stand configuration or such environmental factors as climate and soil. A climax stand is one that maintains itself indefinitely in a relatively stable environment. Such an environment has reached a plateau in its development, where its changes are below the sensitivity level of the associated plant community. Mortality of plants within a species is offset by regeneration. There are no clear signs of important changes in species composition. Normally, plants in a stand are of various ages unless the community is controlled by recurring perturbance—for example, by fire (Daubenmire 1968).

Apparent Instability in Stable Communities

Many ecologists have been perplexed by plant communities that refuse to fall into the classic pattern of plant succession and site occupancy. These communities change in appearance from year to year, from decade to decade, or from disturbance

Figure 5—This Desert apricot/Mojave yucca-Silver cholla Association is not as easily identified as the fir communities in *figure 4*. The species diversity and physiognomy of this community demand that we think in terms of a community organization, rather than a patchwork mosaic of vegetation, during the process of classification.

to disturbance, but do not seem to move toward any successional change. The major difficulty is that we rely, for our understanding of these communities, upon ecological theory, which is complex and in a rapid state of development.

Thus, the annual rangeland vegetation displays a relatively fixed set of species from year to year, but species dominance changes dramatically from year to year, influenced by annual rainfall. Over several years, the annual plant range seems to be stable. Over the long term, patterns of dominance are predictable, if knowledge of rainfall and grazing patterns is properly applied. Many chaparral communities display a fixed set of species after each disturbance by fire; yet the dominant species in these communities seems to be determined by the weather during the first years of seedling establishment after a fire. When viewed from a long-term perspective, these chaparral communities are stable in the same way as the annual plant rangelands.

Figure 6—This Jeffrey pine/Huckleberry oak/Rock spirea Association near Lake Tahoe illustrates how a community organization emerges from the intersection of the microsite pattern and the species occurrence pattern. If both patterns are not taken into account, the sparseness of the vegetation in the community could make recognition difficult.

Succession in the classical pattern is not taking place in such communities; instead, there is a dramatic form of community development. We maintain that stability, in these communities, does not lie strictly in the patterns of the aboveground vegetation; it resides in the pool of associated plant species that exists for each of these communities. This logical basis for the concepts of community stability and persistence should help the practitioner to identify stable communities, which can be properly classified once the species pool is understood. The sequence of developmental shifts in aboveground species cover composition can be described by means of Phase categories, a feature of the classification system which provides for a variety of special requirements.

The kind of stability we have described represents a specialized version of "pulse-stability" as discussed by Odum (1969). Odum's pulse-stable communities represent an intermediate stage of succession maintained by periodic ecosystem perturbations (as from fire or fluctuating water tables). Hanes (1971) coined the term "autosuccession" to describe the pulse-stable condition in chaparral. Pulse-stability and autosuccession, both represent the lack of true succession in some communities. By means of the Phase category, they can be adequately covered in their general application to plant community development.

APPENDIX: Classification System Correlations

This appendix describes the correlation between the system described in this report and that being proposed for use at the national level (Driscoll and others 1982). The information given here should be understood as subject to change in the course of system development.

The relationship between classes in the California system and the proposed national system is as follows:

California System	National System
Formation	Formation Class
	Formation Subclass
Subformation	Formation Group
	Formation
Series	Series
Association	Association
Phase	

Use of the proposed national system is limited to potential natural vegetation (as an approximation of climax) only; the California system may be applied to any vegetation, regardless of successional status.

The worldwide UNESCO system for vegetation classification includes vegetation-related criteria (*table 4*) which are the basis for the upper levels of the national system (UNESCO Formation Class down through UNESCO Formation). The national system will not necessarily make use of all UNESCO classes within each category—not, at least, without modification. The national system adds Series and Association categories to the UNESCO framework (Driscoll and others 1982).

For the purpose of comparison with the UNESCO framework, the criteria for class designations in the California system are shown in *table 5*. The important set of constants that exist in the System are the factors that form the basis for class criteria (for example, overstory growth form and percent crown cover at the Formation level, and overstory leaf and stem morphology at the Subformation level). Criteria are consistent in that classes in each hierarchical level are designated on the basis of the same factor or set of factors (for example, classes in the Subformation level, within all Formations, are all based on overstory leaf and stem morphology). However, class criteria differ between some portions of the Subformation level (compare, for example, criteria used to designate the Shrub Subformations, with those used to designate the Dwarf Shrub Subformations or the Woodland Subformations). The differences in class criteria between, for example, different Formations at the Subformation level simply represent the most useful adaptation of the basic System for use in California. In other parts of the world, it may be useful to distinguish between Conifer and Broadleaf Shrubs, or to designate more than one Broadleaf Woodland or Forest Subformation on the basis of leaf sclerophylly (as is done in the Shrub Formation).

The word "conifer" is used at the Subformation level to designate a specific *kind* of "needle-leaf" and thereby avoid lumping fine-leaf species from broadleaf genera together with spruces and firs. Grouping based solely on leaf shape would not designate useful classes from the standpoint of community classification. Our object is to provide an aggregation of Series based upon morphological characteristics, but comprehends *general* morphological and environmental relationships and concepts consistent with normal perception and thinking. For example, it would be uncomfortable—for many reasons—to aggregate palms, some acacias, some tamarix, and so on, into the same class as spruces and firs. We therefore use "conifer" in reference to species in the Order Coniferales; this order includes the families Pinaceae (pines, firs, spruces, etc.) Taxodiaceae (sequoias, baldcypress), Cupressacae (cedars, junipers, etc.), and Taxaceae (yew, California-nutmeg).

Table 4—*Vegetation-related factors and criteria used to designate levels and classes in the UNESCO system*

Level (criterion)[1]	Alternatives available for class designation					
Formation Class (growth form)	*Closed forest* Trees with interlocking crowns	*Woodland* Trees with crowns not touching	*Shrub* Woody caespitose phanerophytes	*Dwarf shrub* Shrubs less than 50 cm tall	*Herbaceous* Graminoids and forbs	*Tundra*[2]
Formation Subclass (Leaf drop)	Evergreen Deciduous	Evergreen Deciduous	Evergreen Deciduous	Evergreen Deciduous	Annual Perennial Species group	Evergreen Deciduous Bryophyte Lichen
Formation Group (leaf form)	Needle Broadleaf Succulent Thorn	Needle Broadleaf Succulent Thorn (Leaf shape)	Needle Broadleaf Succulent Thorn (Leaf size)	Needle Broadleaf Succulent Thorn (Plant density)	Grass Grass-like Forb Cryptogam (Associated species)	Bryophyte Lichen
Formation (Growth form mix)		Crown Shape	With trees Density	Vegetation mix with trees without trees with shrubs without shrubs	Associated species with trees without trees with shrubs without shrubs with dwarf shrubs without drawf shrubs	
Subformation (Various factors)	Leaf shape	Understory	Understory plus leaf shape			

[1]The most dominant factor that separates the classes at each level.

[2]A climate-geographic zone; vegetation criteria do not distinguish this. The vegetation in question is more logically allocated to the Herbaceous Formation Class. In the UNESCO System, Tundra is a subclass category within the Dwarf Shrub Formation Class. It is given a separate column in this table because the vegetation criteria are unique—not in keeping with the Dwarf Shrub criteria.

REFERENCES

Becking, Rudy W. **The Zurich-Montpellier school of phytosociology.** The Botanical Review 23(7):411-488; 1957 July.

Beeson, R.W.; Cronemiller, F. P.; Deering, R. L.; Fausett, A.; Meinecke, E. P.; Pitchlynn, P. P.; Show, S. B. **Handbook for range managers, Region 5.** Oakland, CA: California Region, Forest Service, U.S. Department of Agriculture, 1940. 212 p.

Braun-Blanquet, J. **Plant sociology.** New York: McGraw-Hill Book Co.; 1932. 439 p.

Brown, David E.; Lowe, Charles H.; Pase, Charles P. **A digitized classification system for the biotic communities of North America, with community (series) and association examples for the Southwest.** J. Ariz. Acad. Sci. 14(1):1-16; 1979 January.

Cheatham, Norden H.; Haller, J. Robert. **An annotated list of California habitat types.** 1975. Unpublished draft supplied to authors by Norden H. Cheatham.

Clements, Frederic E. **Plant succession.** Publ. 242. Washington, DC: Carnegie Inst. Wash. 1916; 512 p.

Clements, Frederic E. **Plant indicators.** Publ. 290. Washington, DC: Carnegie Inst. Wash. 1920; 512 p.

Colwell, Wilmer L., Jr. **Soil-vegetation maps of California.** Resour. Bull. PSW-13. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1974. 6 p.

Cooper, William S. **The broad-sclerophyll vegetation of California.** Publ. 319. Washington, D.C.: Carnegie Inst. Wash. 1922; 124 p.

Critchfield, William B. **Profiles of California vegetation.** Res. Paper PSW-76. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1971. 54 p.

Dansereau, Pierre. **Description and recording of vegetation upon a structural basis.** Ecology 32(2):172-229; 1951 February.

Daubenmire, R. **Forest vegetation of northern Idaho and adjacent Washington, and its bearing on concepts of vegetation classification.** Ecol. Monogr. 22(4):301-330; 1952 October.

Daubenmire, Rexford. **Plant communities.** New York: Harper and Row; 1968. 300 p.

Driscoll, Richard S.; Merkel, Daniel L.; Synder, Dale; Hagihara, James S. **An ecological land classification framework for the United States.** 1982. Unpublished draft supplied to authors by Richard S. Driscoll.

Ecological Society of America. **Report of the Committee on Nomenclature.** Durham, NC: Ecological Society of America and Duke University Press. 1952; 115 p.

Eyre, F. H., ed. **Forest cover types of the United States and Canada.** Washington, D.C.: Soc. Amer. For.; 1980. 148 p.

Feibleman, J. K. **Theory of integrative levels.** Brit. J. Philos. Sci. 5:59-66; 1954.

Fosberg, F. R. **Classification of vegetation for general purposes.** In: Peterkin, G. F., ed. Guide to checksheet for IBP areas. Oxford: Blackwell Sci. Publ.; 1967:73-120.

Hall, Frederick C. **Classification, designation, identification = confusion.** Regional Guide 4. Portland, OR: Pacific Northwest Region (R-6), Forest Service, U.S. Department of Agriculture; 1976. 11 p.

Hanes, Ted L. **Succession after fire in the chaparral of southern California.** Ecol. Monogr. 41(1):27-52; 1971 January.

Hanes, Ted L. **Vegetation types of the San Gabriel Mountains.** In: Latting, June, ed. Plant communities of southern California. Spec. Publ. 2. Berkeley, CA: Calif. Native Plant Soc.; 1976:65-76.

Holstein, Glen. **California vegetation cover types.** 1980. Unpublished draft supplied to author by Glen Holstein.

Jensen, Herbert A. **A system for classifying vegetation in California.** Calif. Fish and Game 33(4):266 p.; 1947 October.

Kuchler, A. W. **Potential natural vegetation of the conterminous United**

Table 5—*Factors and criteria used to designate levels and classes for California with the new system*

Level (criterion)	Alternatives available for class designation				
Formation (overstory growth form and percent crown cover)	**Closed Forest** Trees with closed canopy	**Woodland** Trees with open canopy	**Shrub** Shrubs	**Dwarf Shrub** Genetically dwarfed shrubs	**Herbaceous** Herbaceous plants as overstory
Subformation (overstory leaf and stem morphology)	Conifer Broadleaf Succulent	Conifer Broadleaf Succulent	Woody stems and membranous leaves Woody stems and sclerophyllous leaves Semiwoody stems and semisclerophyllous leaves Succulent stems or leaves	Woody stems Succulent stems or leaves	Grass or grass-like Forb Aquatic Cryptogam
Series (overstory dominant species)	Dominant species or group of species in overstory				
Associations (multiple layer-dominant species)	Dominant species or group of species in overstory and dominant species or groups of species in subordinate layers				

States. Spec. Publ. 36. New York, NY: Amer. Geogr. Soc.; 1964. 154 p.

Kuchler, A. W. **The map of the natural vegetation of California.** In: Barbour, Michael G.; Major, Jack, eds. Terrestrial vegetation of California. New York: John Wiley and Sons; 1977:909-938.

Layser, Earl F.; Schubert, Gilbert H. **Preliminary classification for the coniferous forest and woodland series of Arizona and New Mexico.** Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 27 p.

Munz, Philip A.; Keck, David D. **A California flora.** Berkeley, CA: Univ. Calif. Press; 1963. 1681 p.

Odum, Eugene P. **The strategy of ecosystem development.** Science 164:262-270; 1969 April.

Parker, Ike; Matyas, Wendy. **CALVEG: a classification of California vegetation.** San Francisco, CA: Pacific Southwest Region (R-5), Forest Service, U.S. Department of Agriculture; 1979. 159 p.

Paysen, Timothy E.; Derby, Jeanine A.; Black, Hugh, Jr.; Bleich, Vernon C.; Mincks, John W. **A vegetation classification system applied to Southern California.** Gen. Tech. Rep. PSW-45. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 33 p.

Pfister, Robert D.; Arno, Stephen F. **Classifying forest habitat types based on potential climax vegetation.** Forest Sci. 26(1):52-70; 1980 January.

Poulton, Charles E. **A comprehensive remote sensing legend system for the ecological characterization and annotation of natural and altered landscapes.** Proceedings of the eighth international symposium on remote sensing of the environment; 1972 October 2-6; Ann Arbor, MI. Ann Arbor, MI: Willow Run Laboratories, University of Michigan; 1972; 393-408.

Rowe, J. S. **The level-of-integration concept and ecology.** Ecology 42(2):420-427; 1961 February.

Sawyer, John O.; Thornburgh, Dale A. **Montane and subalpine vegetation of the Klamath Mountains.** In: Barbour, Michael G.; Major, Jack, eds. Terrestrial vegetation of California. New York: John Wiley and Sons; 1977:699-732.

Schwartz, Charles F.; Thor, Edward C.; Elsner, Gary H. **Wildland planning glossary.** Gen. Tech. Rep. PSW-13. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1976. 252 p.

Show, S. B.; Kotok, E. I. **Cover type and fire control in the National Forests of northern California.** Dep. Bull. 1495. Washington, D.C.: U.S. Department of Agriculture; 1929. 46 p.

Stoddart, Laurence A.; Smith, Arthur D. **Range management.** New York: McGraw-Hill Book Co.; 1943. 547 p.

Thorne, Robert F. **The vascular plant communities of California.** In: Latting, June, ed. Plant communities of Southern California. Spec. Publ. 2. Berkeley, CA: Calif. Native Plant Soc.; 1976:1-31.

UNESCO. **International classification mapping of vegetation.** Paris: Ecol. and Conserv. Serv., Educ., Sci., and Cult. Organ., United Nations; 6: 1973. 93 p.

U.S. Department of Agriculture, Forest Service. **Range environmental analysis handbook.** FSH 2209.21. San Francisco, CA: California Region (R-5), Forest Service, U.S. Department of Agriculture; 1969.

U.S. Department of Agriculture, Forest Service. **Forest survey handbook.** FSH 4809.11. Washington, D.C.: U.S. Department of Agriculture, Forest Service; 1975.

Walter, Heinrich. **Vegetation of the earth.** New York: Springer-Verlag; 1973. 237 p.

Weaver, John E.; Clements, Frederick E. **Plant ecology.** New York: McGraw-Hill Book Co.; 1938. 601 p.

Whittaker, Robert H. **Classification of natural communities.** The Bot. Rev. 28(1):1-239; 1962 January-March.

Wieslander, Albert E. **First steps of the forest survey in California.** J. For. 33:877-884; 1935 October.

Wieslander, Albert E.; Jensen, Herbert A. **Forest areas, timber volumes and vegetation types in California.** Forest Sur. Release 4. Berkeley, CA: California Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1946. 66 p.

Paysen, Timothy E.; Derby, Jeanine A.; Conrad, C. Eugene. **A Vegetation Classification System for use in California: its conceptual basis.** Gen. Tech. Rep. PSW-63. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 14 p.

A taxonomic Vegetation Classification System proposed for use in California is designed to simplify interdisciplinary communication about vegetation. The system structure is an aggregative plant community hierarchy at four levels of precision—the Association, Series, Subformation, and Formation. A flexible Phase category links specific resource management concerns to the system. The System is based on the concept of vegetation as an ecological component, and is neutral with respect to management function; design criteria stem from performance needs and principals of classification. The System is useful as a basic language and as an information framework for vegetation management activities.

Retrieval Terms: vegetation classification, plant community classification, vegetation types, plant communities, classification, resource classification

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

General Technical
Report PSW-64

Starch Gel Electrophoresis of Conifer Seeds: a laboratory manual

M. Thompson Conkle Paul D. Hodgskiss Lucy B. Nunnally Serena C. Hunter

The Authors:

M. THOMPSON CONKLE, a geneticist, is assigned to the Station's research unit studying the genetics of western forest trees, with headquarters in Berkeley, Calif. He earned a bachelor's degree in forestry at Michigan State University, a master's degree in forest genetics at North Carolina State University, and a doctorate in forestry and genetics at the University of California, Berkeley. **PAUL D. HODGSKISS**, a biological technician with the genetics research unit, is a forestry graduate of the University of California, Berkeley. **LUCY B. NUNNALLY**, a biological technician at the Southeastern Forest Experiment Station, Raleigh, N.C., earned a bachelor's degree in biology at Vanderbilt University. **SERENA C. HUNTER** received a bachelor's degree in forestry at the University of the South. At the time of this study, she was a graduate student at North Carolina State University, where she received a master's degree in forestry.

Foreword

The procedures described in this manual were adapted from starch gel techniques in use at the University of California, Davis. Alex Kahler, now plant geneticist, Northern Grain Insects Research Laboratory, Agriculture Research Service, U.S. Department of Agriculture, Brookings, S.D., provided information on electrophoresis that led to the establishment of an isozyme laboratory in 1970 at the Pacific Southwest Forest and Range Experiment Station under the direction of M. Thompson Conkle and to the development of a user's manual. The first draft of the manual was prepared by Lucy B. Nunnally and Serena C. Hunter. Recent modifications of techniques and additions of stain systems prompted Paul D. Hodgskiss to revise and enlarge the manual. Demand for copies of the first draft and requests for details about the procedures encouraged this publication. Because these procedures are constantly being modified, the authors would appreciate receiving suggestions for the improvement of this manual.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

December 1982

Starch Gel Electrophoresis of Conifer Seeds: a laboratory manual

M. Thompson Conkle   Paul D. Hodgskiss   Lucy B. Nunnally   Serena C. Hunter

CONTENTS

Introduction 1
Seed Preparation 1
Collection, Extraction, and Storage 1
Stratification 2
Germination 2
Sample Preparation 2
Gel Preparation 2
Molding the Starch 3
Starch Preparation 3
Gel Loading 3
Gel and Tray Setup 4
Electrophoresis 4
Electrical Requirements 4
Dewicking and Running Gels 5
Slicing and Staining 5
Slicing the Gel 5
Mixing the Stains 5
Storing the Gels 6
Safety and Procedural Cautions 6
Safety 6
Procedural Cautions 6
Troubleshooting 7
Appendix 12
A. Extraction Buffer 12
B. Gel and Tray Buffer Formulations and Electrode Tray Dimensions 13
C. Stains 14
D. Chemicals Needed for Processes Described 17
References 18

The identification of different forms of enzymes by the process of electrophoresis is a powerful research tool for the genetic analysis of forest trees (Feret and Bergmann 1976). Electrophoresis is the movement of enzymes in a gel, under the influence of an electric current. Dissimilar enzymes and the alternative forms of similar enzymes migrate at different rates when direct current is applied to macerated seed samples in a buffered starch gel. Enzyme migration in gels and the separation of enzymes with different charges results from the interaction of the electric current, the pH in the gel, and the pH in the electrode tray (gel system). The direction—anodal or cathodal—and rate of enzyme migration depend on the kind of electric charge—plus or minus—and the charge strength.

Several gel systems are needed to analyze maximum numbers of enzymes. After gels have been held for a sufficient time in the electric field, gel slabs are sliced and thin gel slices are stained for different enzymes. Stain solutions contain specific substrates, and enzymes from the seed samples act on these substances to produce reaction products. Reaction products are stained or are the bases of stain processes. The locations of visible bands on the gels mark the migration distances of specific enzymes. Different bands on a gel that has been stained for one reaction denote functionally related molecules that differ in electrical charge—isozymes. Isozymes, tested by determining Mendelian segregation ratios and found to be phenotypic expressions of alleles of a single genetic locus, are allozymes.

The electrophoresis of conifer seeds has many useful applications. Conifer seeds are excellent for genetic studies because gene products are present in haploid and diploid tissues. The nutrient material surrounding the embryo is haploid. Electrophoresis of this tissue resolves enzyme alleles identical with the female gamete of the seed. Analysis of gametophytes from several seeds of one tree provides an accurate evaluation of that tree's genotype. Electrophoresis of embryos resolves diploid banding patterns. The pollen contribution to individual embryos can be deduced by subtracting the allele carried by the gametophyte from the pair of alleles carried by the embryo.

This manual provides detailed information on seed preparation techniques, equipment, and chemical formulas, including how to prepare tissue and gel, supply electric current, and stain gel slices to produce visible bands marking the location of enzymes. It outlines proven procedures for obtaining isozyme phenotypes in 23 enzyme systems, for resolving genotypes at about 45 loci. The procedures for conifer seed electrophoresis are presented in sections in the order they are performed during day-to-day laboratory operation. This manual, which updates and supersedes an earlier publication (Conkle 1972), does not cover genetic interpretation of the bands on the gels.

SEED PREPARATION

Seed processing—collection, extraction, storage, stratification, and germination—varies by species (consult Agriculture Handbook 450 [U.S. Dep. Agric., Forest Serv. 1974] for species information). The methods we describe provide satisfactory results for a wide range of conifers and are suited for small quantities of seed.

Seeds, once collected and dried, should be frozen for storage. In this state they remain viable for many years and retain high levels of enzyme activity. The efficient scheduling of studies using stored seed tissues permits a constant output from the laboratory and support staff, without breaks caused by seasonal lack of research material.

The seeds should be germinated under uniform conditions and sampled at uniform growth stages. This procedure guarantees that a specific set of enzymes will be active in all seed of the test, and bypasses problems encountered with tissues sampled from field trees—differences arising from microsites, seasons and years, and difficulties of collection, transportation, storage, and processing.

It is advisable to analyze seed at the stage of germination when the emerging radicle of the embryo extends 2 to 5 mm beyond the seed coat. Enzymes are present from dry seed stage through the shedding of the seed coat (Conkle 1971), but female gametophytes and embryos in the early stages of germination are superior to dry seed for most species. Additionally, germination simplifies removal of the seed coat and separation of the embryo from the gametophyte.

Collection, Extraction, and Storage

Collect mature cones, while still closed, from the tree. Air dry or warm the cones in a circulating air oven or kiln (32° C for 24 to 48 hours). Shake or tumble the open cones to release the seeds.

Remove the seed wings by gently rubbing a small quantity of seed within a folded cloth. Separate the seed from the wing particles by

a. Shaking the seed on a wire mesh. Small wing pieces will sift through the mesh; larger pieces can be removed from the seeds by a quick downward motion of the mesh.

b. Placing the seed material in a variable-flow air column. Place the seeds and wing fragments on a wire mesh inside an air tube and increase the air flow until the wing pieces are blown into the collector. This procedure is also useful for separating filled from hollow seed.

Store dry seeds in labeled envelopes in a freezer (−15° C).

Stratification

Withdraw from cold storage the seed samples to be included in a study. Place seeds of each sample in plastic bags labeled with identifying codes. Pour enough Captan fungicide solution (2.5 g Captan 50-W/liter of water) into each bag to cover the seeds.[1] Soak seeds for 24 hours in a refrigerator (throughout this manual, refrigeration implies a temperature of 4° C). Drain the Captan solution and refrigerate the moist seed 90 days for white pines and 45 days for all other species.

Prepare petri dishes by adding a cellulose pad or sterile sand. Overlay the pad or sand with a filter paper labeled indelibly with identifying codes. Wet the pad and filter paper with Captan solution. The filter paper should be saturated but the dish should not have freestanding solution. Transfer the seeds into the petri dishes and place in a germinator. Throughout the subsequent germination period add distilled water as needed to maintain moisture on the seeds and paper.

Germination

Germinate seeds at 20° to 22° C with 12 hours of light. Most seed lots begin to germinate in 3 to 7 days. When the radicle of a seed extends beyond the seed coat 2 to 5 mm, place the germinant in a second petri dish (prepared with moist pad or sand and filter paper) and refrigerate. Refrigeration halts the growth of seeds while maintaining enzyme activity 6 to 8 weeks and longer, and allows you to accumulate seeds at the same stage of development.

Sample Preparation

Prepare a record sheet (*fig. 1*) listing in order the identifying codes and tissue types for samples to be analyzed. Recommendation: In addition to the seeds that are being tested, stratify, germinate, and include seeds of alternative species or particular families as standards for comparing the mobility of enzyme bands on different gels. Label grinding plates (*fig. 1*) with sample identities corresponding with the record sheet.[2]

[1]Trade names and commercial enterprises or products are mentioned solely for information. No endorsement by the U.S. Department of Agriculture is implied.

[2]Figures are found on pages 8 to 11 of this manual.

Each sample consists of a paper wick (12 × 3.5 mm, Whatman chromatography paper, no. 3MM) saturated with liquid derived from macerated tissue combined with extraction buffer solution. To obtain the liquid from the germinated seeds, proceed as follows:

a. For each seed, split and remove the seed coat and peel off the brown papery tissue surrounding the gametophyte. Split the gametophyte on one side and remove the embryo.

b. Place the gametophyte tissue and embryo in separate labeled wells of a frozen grinding block (*fig. 1*). The amount of tissue to process depends on seed size and enzyme activity. Use the entire gametophyte or embryo of species with small seeds but subsample the tissues from species with large seeds.

c. Process the samples loaded in the grinding block immediately if electrophoresis run will be made that day. Otherwise, store them frozen overnight so as to reduce the workload on the day of the run.

d. On the day of the run, remove the samples from the freezer. Add one or two drops of extraction buffer (*app. A*) to the tissue in each well. Use the minimum quantity necessary to just saturate paper wicks; too much extraction buffer dilutes the enzyme solution and diminishes the resolution of isozyme bands. Note that in *appendix A* there are suggestions for additives that improve resolution of specific enzymes, and of enzymes of seeds with large amounts of resins.

e. Grind thawed, cold tissues in the extraction buffer with a glass rod or blunt-tipped electric engraver. Macerate each sample thoroughly—the macerate in each well should be opaque and contain no sample chunks. After grinding each sample, clean the grinding tip with absorbent tissue paper. Once a sample is homogenized, enzymes begin to break down. Work rapidly once you begin the grinding step.

f. Insert paper wicks in the wells containing the macerated tissue. Use one wick per well for each gel system to be run; if, for example, each sample is to be used in four different gels, use four wicks per well. Keep the saturated wicks cold. You can also include on a gel one or more wicks with dye marker (0.1% solution bromophenyl blue, 0.1 mg/100 ml of water) to monitor freely migrating molecules during the electrophoresis run.

GEL PREPARATION

Four gel systems, with pH values from 6.2 to 8.8, are useful for resolving different enzymes. The specific chemical formulations for gel and tray buffers are given in *appendix B*. Instructions call for preparing two gels of each gel system. Two gels provide analyses for numerous tissue samples each day and make efficient use of space and materials by allowing staining of two slices in each stain tray. You may wish to adjust the formulations to meet different experimental design goals.

Starch, when cooked with a buffer solution and cooled, forms a gel. The proportion of starch to buffer determines the consistency of the gel. Gels that are 12.5 percent starch appear to work well, but the proportions may need adjusting to produce gels with good characteristics. A major variable is the brand of starch. Other factors—the quality of distilled or deionized water, starch lot, laboratory and refrigerator temperatures, and the length of time that gels are vacuum degassed—contribute to gel quality. There is an art to producing consistently good quality gels; a visit to an electrophoresis laboratory is highly recommended to anyone planning to establish a new laboratory.

Molding the Starch

Form the gel in a mold consisting of plastic bars secured to single-strength glass with rubber bands (*fig. 2*). This mold forms a gel slab, 18.5 × 15.5 × 1.2 cm, capable of yielding up to 10 gel slices. Lines on the side bars serve as guides for cutting the gel where the wicks will be inserted—a location on the gel called the origin because enzyme migration starts from this point. Lines on side bars also mark locations for folding the plastic wrap cover, placing electrode sponges, and determining the 8-cm migration distance for gels that develop a visible front as electrophoresis proceeds.

Starch Preparation

Prepare and level two molds for each batch of starch. Weigh out 94 g of starch. If necessary, remove any small, hard-to-suspend aggregates by sifting or screening the dry starch. Measure out 750 ml of gel buffer solution from laboratory stock bottles (*app. B*). Of the 750 ml of solution, reserve 160 ml for suspending the starch, and heat the remaining 590 ml to boiling in a 1000-ml long-necked volumetric flask (Pyrex no. 5600). While the solution is heating, use a 400-ml beaker to combine 150 ml of the reserved buffer solution with the starch. Mix the starch and buffer thoroughly with a stirring rod to eliminate all lumps. Pour the starch suspension into a 2000-ml thick-walled vacuum flask (Pyrex no. 5340). Wash the remaining starch from the beaker into the vacuum flask with the remaining 10 ml of buffer. Swirl the mixture to keep the starch well suspended. Here and elsewhere in the text, the word *swirl* is used to describe the required motion for the flask containing the starch suspension. Hold your forearm stationary and use wrist action to produce a circular motion of the base of the vacuum flask. The starch suspension should circle the bottom of the flask; it should not break up and splash against the wall.

Put on insulated gloves to handle hot glassware and wear eye protection. Shortly after the 590 ml of solution comes to a rapid boil, grasp the vacuum flask in one hand and the volumetric flask in the other. Swirl the starch in the vacuum flask until the starch is again thoroughly suspended. Then carefully invert the volumetric flask containing the boiling buffer, sliding its neck deep into the vacuum flask (*fig. 3*). Point the neck of the vacuum flask away from you. *CAUTION: Failure to insert the flask with boiling buffer deep into the vacuum flask may result in a violent kickback of steam and boiling buffer.* Swirl the vacuum flask as the buffer solution empties into the starch suspension. Remove the volumetric flask, when empty, and continue swirling the starch and buffer for 10 to 15 seconds.

If gels are consistently weak and difficult to work with, you may need to heat briefly the suspended starch after the boiling buffer is added to further cook the mixture. Such further cooking may be required to produce gels sufficiently strong to withstand slicing and handling.

Stopper the flask and apply vacuum to degas the hot starch solution (*fig. 4*). A rapid effervescent boiling will occur within the starch solution as gases are removed, but will quickly subside. Slowly swirl the flask while degassing to maintain an even consistency of the starch. Continue degassing until large bubbles boil through the solution. About 4 seconds after the large bubbles appear, release the vacuum and immediately pour the starch into the molds. The starch solution will be clear and will pour freely. The process of degassing should last only 15 to 20 seconds; the starch will congeal inside the flask if degassing is prolonged.

Rapidly pour the starch into the molds, filling each mold with one continuous pour, as the starch cools quickly. Start pouring midway between the upper left corner and the center of the mold. When the starch reaches the edge of the mold and mounds slightly above the top of the plastic bars, continue to pour, moving to the right, then down, then left. Continue pouring until the mold fills and starch bulges about 1 mm above the top of the forms. Pour the second gel in the same manner. With practice, you can produce two gels with equal quantities of starch, and thus equal thickness, from one starch preparation.

The starch mixture should be free of opaque streaks and small opaque pellets. These opaque areas are usually due to incomplete mixing and cooking when the boiling buffer is added. If you see inclusions, discard the contents of the flask and start over.

After pouring, gently shake or lightly tap each mold to distribute the starch evenly. Burst any bubbles on the gel surface with a warm needle. Cool the gels at room temperature until they turn opaque (about 10 to 15 minutes), then cover them with plastic wrap. If gels are prepared the day before they are used, store them at room temperature.

Gel Loading

Refrigerate prepared gels for 1 hour before inserting wicks. Never freeze gels. Use a scalpel (no. 11 blades are useful) to cut and trim the gels. Cut between the gel and all four sides of the gel mold. Remove any excess starch from the top of the bars. With the scalpel held vertically, cut along a straight-edge held in line with the origin marks on the right and left sides of the mold (*fig. 2*).

Remove the rubber bands holding the mold bars and slide the smaller cut portion of the gel toward the edge of the glass, using light pressure from both hands on the surface of the gel. The gel slice should be moved until the opening at the origin is about 1 cm. Place a wick spacing guide on the upper gel slice just at the origin (*fig. 5*). Repeat the process to trim, open, and place wick spacers on those gels required for the number of wicks prepared.

Use tweezers to remove the cold wicks from the wells of the grinding block, working with one well at a time. Lightly blot the wicks on a clean section of absorbent tissue. Place the wicks, one per gel system, on the fresh-cut gel surface of the larger gel portion. The bottom edge of each wick should touch the glass of the gel mold. The order of wicks along the gel should correspond to the sample order on the record sheet. Each gel accommodates 36 wicks.

When all the wicks are in place, push the smaller gel portion back against the wicks on the larger gel portion. Replace the gel mold bar and rubber bands. Press lightly on the gel near the wicks to remove air gaps. Cover the gel with plastic wrap that extends about 5 cm beyond the ends of the mold.

Gel and Tray Setup

Place the loaded gel on the electrode tray (see *fig. 6* for details of tray construction). Position the origin of the gel toward the cathodal connection of the electrode tray. Forming a sharp line across the gel, fold the plastic wrap back to the fold lines (*fig. 2*) marked on the gel bars. This procedure exposes an 18-mm strip of gel surface.

Place sponges in contact with gel surface, in each electrode tray. The sponges are nylon reinforced cellulose kitchen sponges. Because new sponges increase the time required for an electrophoresis run, condition new sponges by rinsing and using them in anodal trays with previously conditioned sponges in cathodal trays. Do not interchange the sponges between systems. Store sponges in plastic bags in a refrigerator.

Position sponges to cover 1 cm of plastic and all the exposed gel surface, and extend down into the electrode tray. Saturate sponges with electrode tray buffer and press sponges against the gel to make thorough contact. Fold the plastic wrap back over the sponge and attach the plastic wrap to the glass on both sides with binder clips (see *fig. 7* for views of the tray and gel setup).

Pour 250 ml of refrigerated electrode buffer into each electrode tray. Place the tray and gel unit in a refrigerator equipped to circulate cold air. The refrigerator should have the capacity to maintain the temperature at 4° C throughout the run.

ELECTROPHORESIS

Enzyme separation is achieved by applying direct current to the buffered gel. Ions from the buffer in the cathodal tray enter the gel. In the A and B gel systems (see *app. B*) the ions cause a clearing and a slight depression of the gel at the location of the fastest migrating ions. This area is the front. We allow the front to migrate 8 cm beyond the origin before turning off the electric current. Gels of the C and D systems do not develop fronts; the runs are timed so as to give consistent migration distances between gel runs on different days.

Electrical Requirements

Caution: Power sources for electrophoresis produce direct current at voltages high enough to cause severe injury. The possibility of electric shock must be eliminated by constant awareness of the electrical hazard, clear communication between workers, and safe work procedures to minimize shock hazards. All electrical equipment should be examined on a regular basis to verify that wires and connections are in safe condition. Special care should be taken to protect visitors from electrical hazards. New employees should be thoroughly trained in safe procedures.

Electrical current can be supplied to a gel with a Heathkit-Shumberger high-voltage power source (models IP-17 and SP-2717) or similar power sources. The power sources produce 400 volts and 100 milliamps at maximum settings. These models, once set, hold constant voltage. Adjust the amperage manually to the desired output until the voltage rises to 320 volts. Power adjustment is not required after the voltage reaches 320.

Each gel is attached to a power source; the current on each gel is monitored and adjusted separately. Monitoring each gel allows detection of problems such as poor sponge contact or separation of the gels at the origin; these conditions may lead to irregularities in enzyme migration.

To begin the run, connect wires from the power sources to the electrode terminals of the buffer trays in the refrigerator: the cathode (color-coded black) connects to the electrode on the origin side of the gel, the anode (color-coded red) connects to the opposite electrode. Apply current at amperages specified for the individual gel buffer systems as follows:

A buffer system 75 mA
B buffer system 70 mA
C buffer system 60 mA
D buffer system 60 mA

Periodically check the amperage and voltage gauges on the power sources and adjust the amperages to maintain the recommended values. Amperages tend to decrease during the run. Adjustments that return amperages to the recommended levels cause an increase in voltage.

Gain experience with the normal range of voltages for different buffer systems, gel thicknesses, and laboratory conditions. Abnormal voltages may signal problems such as poor contact between the electrode sponges and the gel or the use of the wrong solution as tray buffer.

Dewicking and Running Gels

After the current has been on for 15 minutes, turn off the power, disconnect a gel unit, remove it from the refrigerator, remove the clips holding the plastic wrap over the cathodal sponge, and fold back the plastic wrap and the sponge to expose the origin. Use slight pressure with the fingers of one hand to separate the gel slices at the origin. Lift the wicks out of the gel with tweezers. When all wicks are removed from a gel, rejoin the gel slices and verify that there is good contact between the surfaces. Eliminate bubbles between the gel and the glass plate. Reassemble the gel unit with the plastic wrap and the cathodal sponge in their original positions. Return the unit to the refrigerator and reconnect the electrical wires.

Place refrigerated waterbags on the dewicked gels. Waterbags are 20.3 × 30.5 cm heat sealable pouches of plastic 4.5 mils thick (Kapak/Scotchpak, stock no. 504). Replace waterbags on the gels with a second set of cold bags if there is any tendency for the gels to warm.

Reapply the electrical current at the recommended amperages for each gel system. Adjust the amperages throughout the run until voltages reach 320. Thereafter, further adjustments are unnecessary (amperages will continue to decrease). A sudden drop in amperage signals poor current flow and may be caused by poor contact between the electrode sponge and the gel, or separation of the cut gel surfaces at the origin. Correct poor sponge contact by resetting the sponge. Gel separation at the origin may be due to excessive tension on the covering plastic wrap or unusual heating and cooling conditions within the gel. Correct gel separations by pressing the surfaces back together and resetting the plastic wrap and sponges.

When the fronts on gels of the A and B buffer systems reach 8 cm beyond the origin, disconnect the current. The C and D system gels do not develop visible fronts and we have standardized the length of time for the C and D gel runs at 4.5 hours.

SLICING AND STAINING

Many stain solutions are perishable and should be prepared as close as possible to the time the gels are ready. Some chemicals used in stains are hazardous; several are carcinogenic. Handle all chemicals with extreme care and an awareness of OSHA guidelines for laboratory safety (U.S. Dep. Labor 1976). Follow the label precautions on all chemicals.

Slicing the Gel

Remove a gel setup from the refrigerator, unclip the plastic wrap, and fold the electrode sponges into the electrode trays. Remove the plastic wrap and the gel mold forms. Enzymes will be in the anodal section of the gel between the origin and the 8-cm front. The gel beyond the anodal side of the 8-cm front will not contain enzymes and can be trimmed away and discarded. The cathodal section should be sliced and stained to locate all bands. Cut one notch in the upper left hand corner to identify gel 1 and two notches to identify gel 2.

Attach plastic strips (200 × 25 × 1.0 mm) to the glass on either side of the gel slab using large spring-loaded clips (*fig. 8*). Wrap monofilament nylon sewing thread around the index fingers on both hands and use thumbnails to stretch the line taut. Adjust the length of the thread so that thumbnails ride on top of the plastic strips as the cut is made. Start with the sewing thread on the far side of the gel and pull the thread toward you, cutting one slice through the gel. Add a plastic strip at both sides of the gel and cut the next slice. Use a new section of sewing thread for each cut. Continue adding spacer strips to slice the entire slab. Do not separate slices at this time; return the sliced gel slab to the refrigerator. Trim and slice the second gel of the same buffer system.

Mixing the Stains

Consult *appendix C* for stain recipes. Stain buffer solutions and some stain components can be prepared in quantity for use over a period of time. The stain solutions (with some exceptions) are made up in 75-ml volumes for one-time use. Stain trays are glass baking dishes 20.5 cm square (2 qt Pyrex) that accommodate two gel slices, one from each of the two gels of a buffer system. Prewarm the stain solutions and staining trays to 37° C to maximize stain activity when the gel slices are placed into the solutions.

For each enzyme to be identified, write the abbreviation for it and the date of the run on a 5-cm strip of masking tape, and attach it to a 250-ml Erlenmeyer flask. Measure out and add the stain buffer to the flask, then add and mix the stain components in the same order they are given in the recipe (*app. C*). Each batch of stain is enough for a pair of gels.

Set out warm trays and place a flask of stain in each tray. Transfer the masking tape from the flask onto a stain tray and pour the stain solution into the tray. Prepare all the stain trays for one gel system.

Remove the sliced gels from the refrigerator; peel off and discard the top slice of the cut gel slab. Use fingertips to peel off the second slice and place it in the first stain tray (*fig. 7*). Proceed to put one slice from the first gel into each stain solution. Repeat with slices from the second gel. Agitate each tray to cover the gel slices with the stain solution. Cover each tray with plastic wrap and follow the incubation recommendations for specific stains. Warming ovens will maintain stains at 37° C and shield light-sensitive stains. If ovens are not available, shield light-sensitive stains with a cover of aluminum foil. Examine the gels frequently to follow the development of bands. When the bands on both gels in a stain tray are well resolved, draw off the stain solution and add just enough tap water to cover the gels. The resolution of bands is the clearest at this stage and data should be collected while the gels are in water.

Storing the Gels

To store the gels for 6 to 12 months, replace the water in a tray with a fixing solution consisting of a 5:5:1 mixture of methanol:water:glacial acetic acid. If the gels are not examined immediately after staining, skip the tap water step and replace the stain solution with fixing solution. The fixing solution toughens and shrinks the gels and the gels become opaque. Dark bands are distinct after fixing but faint bands may have to be viewed over a light table. *Caution: Keep stain trays with fixing solution covered with plastic wrap. Do not inhale the fumes from the fixing solution.* Methanol is a poison that is only slowly degraded by the body. Repeated exposure, sometimes over a warm light table, may lead to early signs of poisoning: headache, loss of energy, and fatigue. If possible, work with the fixing solution only in a vented hood.

Gels should remain in the fixing solution for a minimum of 2 hours. We place the gels in fixing solution overnight, then blot and wrap the fixed gels in plastic on the following day. Wrapped gels will remain readable for long periods of time if they are protected from desiccation by additional wraps of plastic and stored in a refrigerator.

SAFETY AND PROCEDURAL CAUTIONS

Safety

Gel Pouring

When combining the starch slurry and boiling buffer in the vacuum flask, wear gloves and safety glasses, and point the vacuum flask away from face and body to avoid the possible kickback of steam and hot starch.

Electrophoresis

Never touch electrodes or the tray solutions while current is supplied to the gels; a severe electric shock is possible.

Staining the Gels

Many of the compounds used for staining are hazardous to health. Wear protective clothing, particularly gloves and a dust mask, when handling. Avoid contaminating other items with these compounds. Follow prescribed safety measures. Mix the stains in a vented hood. Use similar care in examining stained gels treated with fixing solution.

Procedural Cautions

Seed Dissection

Work rapidly and keep the sample tissue as cool as possible to maintain enzymatic activity.

Make sure that accurate seed identity is maintained on the record sheet, in the seed tray, and in the gel.

Gel Pouring

Degas the hot starch solution no more than 20 seconds to avoid congealing of the starch while pouring.

Do not allow the gels to freeze during cooling.

Loading the Gels

Blot each wick to remove excess moisture.

Make sure the bottom edge of the wick touches the glass plate.

Eliminate bubbles between the gel and the glass at the origin, after loading and after dewicking.

Electrophoresis

Keep the gels as cool as possible, without freezing; refrigerate and place chilled water bags on the gels after the dewicking step.

Make sure that the wires to the electrode trays are not reversed; determine that the polarity is correct.

Hold amperage constant at the prescribed level until a gel system reaches 320 volts, then hold the system at 320 volts and allow the amperage to decrease for the rest of the run.

Slicing the Gel

Keep the monofilament thread taut between the thumbs.

Be sure to put the same number of plastic spacers on each side of the gel.

Notch the gels for identification.

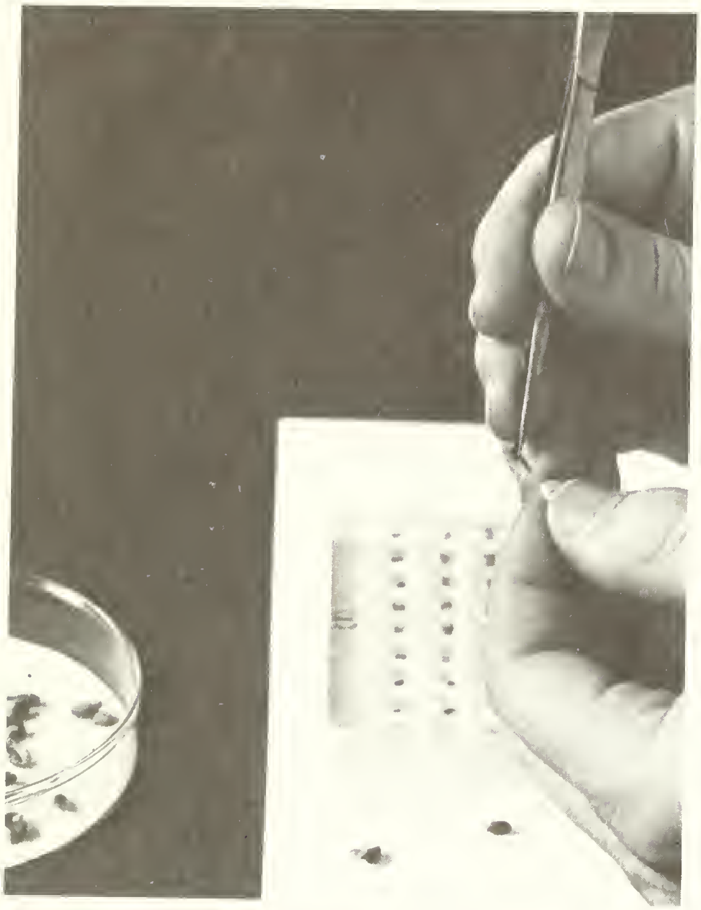
Staining the Gels

Warm the staining solutions to 37° C.

Because compounds are light-sensitive and perishable, cover trays with aluminum foil and handle chemicals as directed to preserve their activity.

TROUBLESHOOTING

Problem	Probable cause	Solution
Lumps or white specks appear in hot gel solution	Buffer solution may not have boiled rapidly or the starch may not have been well mixed with cold buffer to form the slurry	Discard lumpy starch and start over. Allow buffer to come to a rolling boil and thoroughly mix starch slurry
Starch is too thick or lumpy when poured from vacuum flask	Starch may have been degassed too long and is too cool	Start over; degas for a shorter time and quickly pour starch into mold
Voltage is abnormally high on a gel	Separation at origin or poor sponge contact with gel	After disconnecting power, open plastic wrap to inspect origin. Press sponges to improve gel contact
Front on gel is irregular:	Waterbag unevenly placed	
Straight but higher on one side than on the other	Worn electrode on anodal side. (Cathodal electrode is long-lasting)	Replace anodal electrode
	Gel is thicker on one side than on the other	Level mold before pouring gel for next run
	Gel separates in region of origin	Push gel surfaces together at origin and place a glass or plastic rod between gel and bar on cathodal end
Wavy	Uneven cooling of gel, separation at origin or poor sponge contact with gel	Check air flow in refrigerator or change waterbags more often. Push gel surfaces together at origin and place a glass or plastic rod between gel and bar on cathodal end
Gel front migrates slower in one gel than other gel of same system	New sponge may be on cathodal side of electrode tray	Place old sponge in well of cathode tray and new sponge in well of anode tray
	Electrode may be corroded	Replace with new electrode
	Unequal gel thickness	Decrease amperage on gel with faster migration so that electrophoresis proceeds to same point in same time
Stain does not work	Possible error in mixing stains or buffers	Check recipe. Some missed items can be added late and stain may still work
	Possible deterioration of buffers	Make new buffers. Prepare stocks of buffers in quantities that will last for about 1 month
	Possible deterioration of chemicals	Purchase fresh supplies. Date each bottle and use older supplies first. Follow storage instructions on bottles



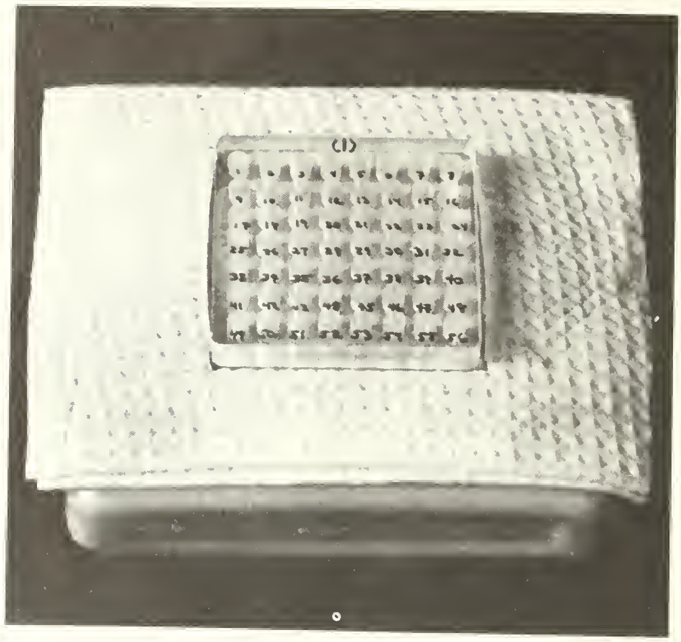
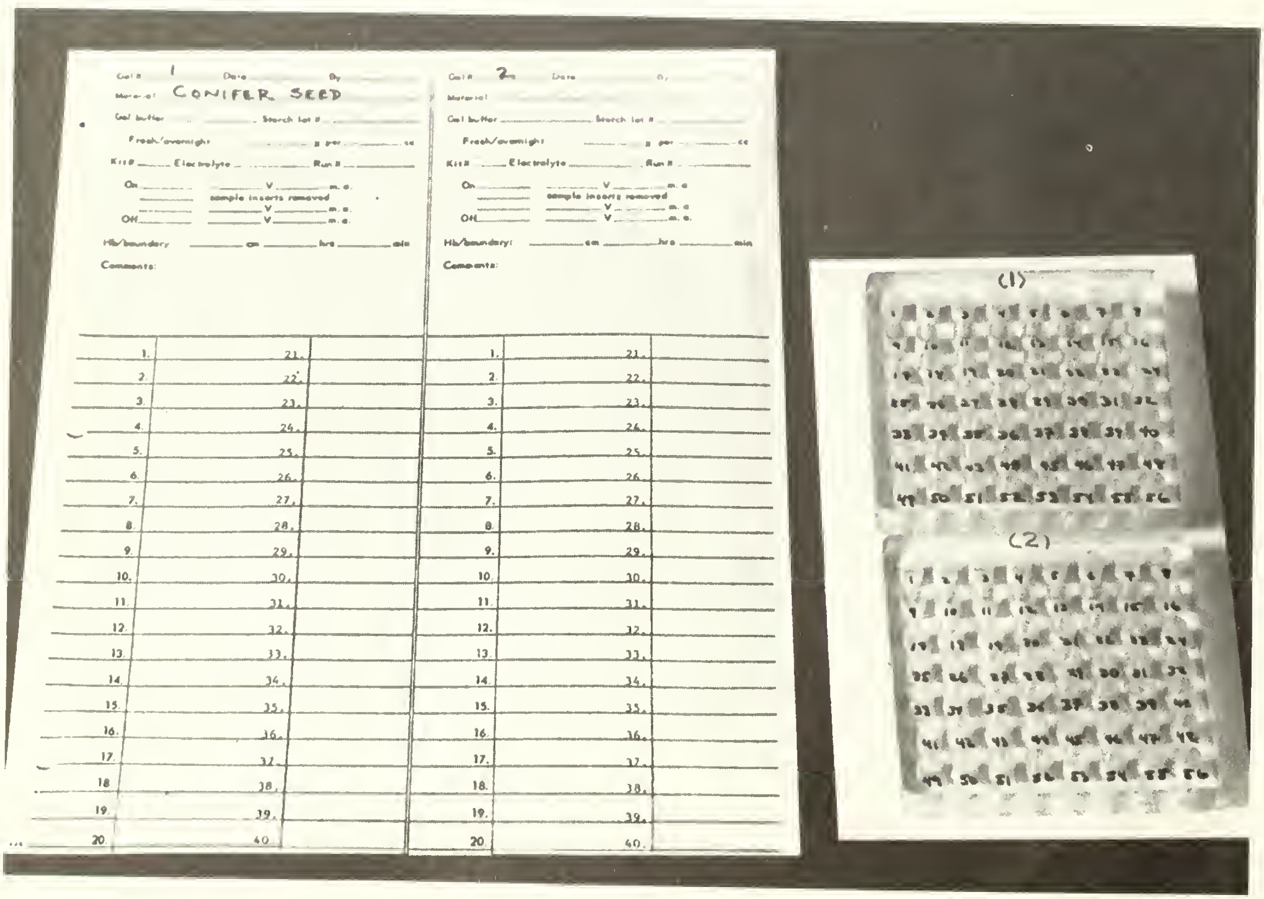


Figure 1—Sample preparation materials. *Left:* germinated seed in the petri dish used for germination, and a dissected seed with gametophyte and embryo. *Above:* grinding block, 8.5 × 8.5 × 1.3 cm clear plastic with 0.7-cm holes (¼ inch) drilled 1.0 cm deep (flat bottom holes were drilled with a bit squared off on a grinding wheel), placed on a frozen pad of Blue Ice for cooling (grinding block and pad were frozen together before samples were loaded into the holes). *Below:* data sheet with the identity of the samples coded to the numbered holes in the grinding blocks.



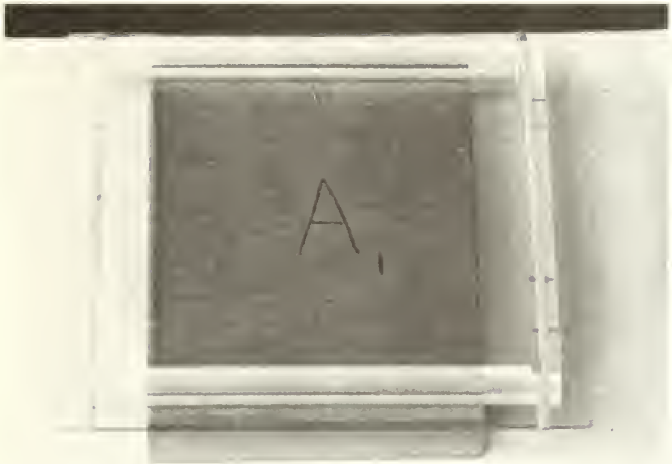


Figure 2—Gel mold consisting of plastic bars secured with rubber bands to single strength window glass.

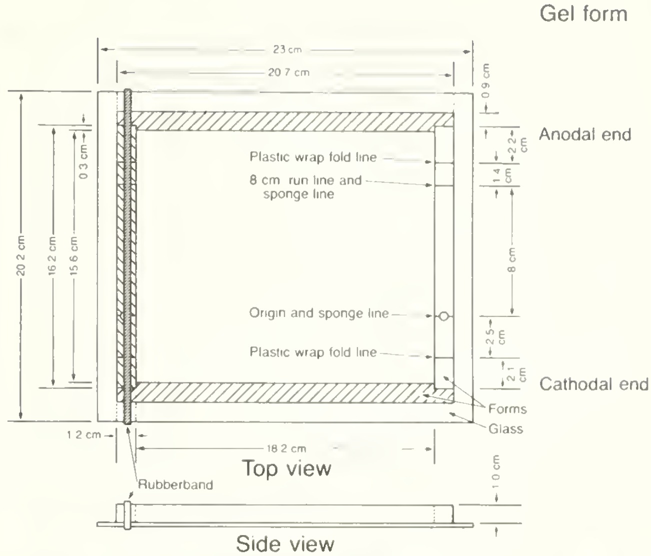
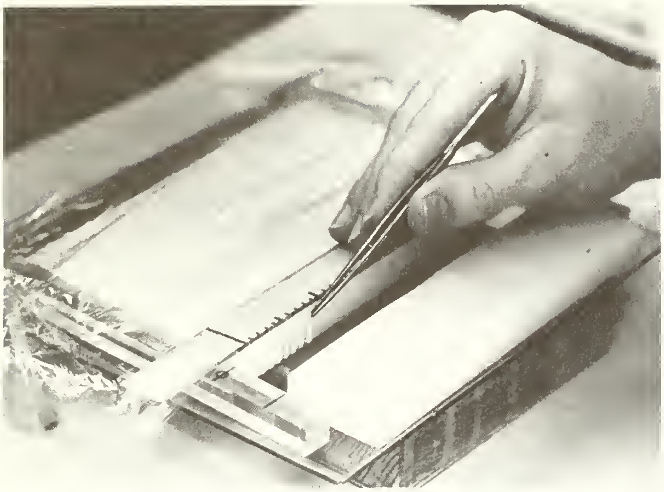


Figure 3—Pouring boiling buffer into starch suspension.

Figure 4—Degassing hot starch using vacuum line attached to a cork in the top of the vacuum flask while blocking side port of the flask with a finger.



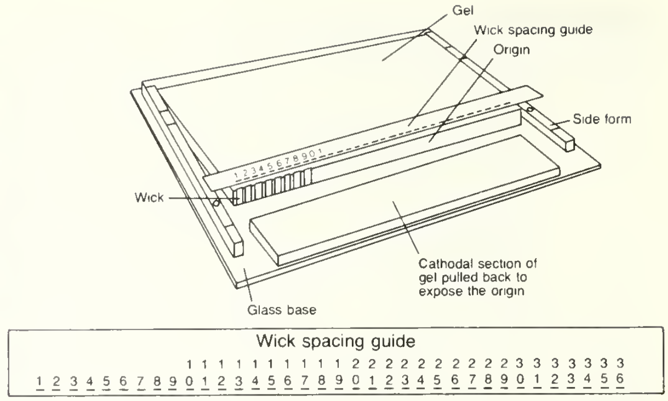


Figure 5—Cut gel surface open at the origin. Wicks containing the absorbed liquid fraction of samples are placed on the vertical surface in order corresponding to their listing on the data sheet.

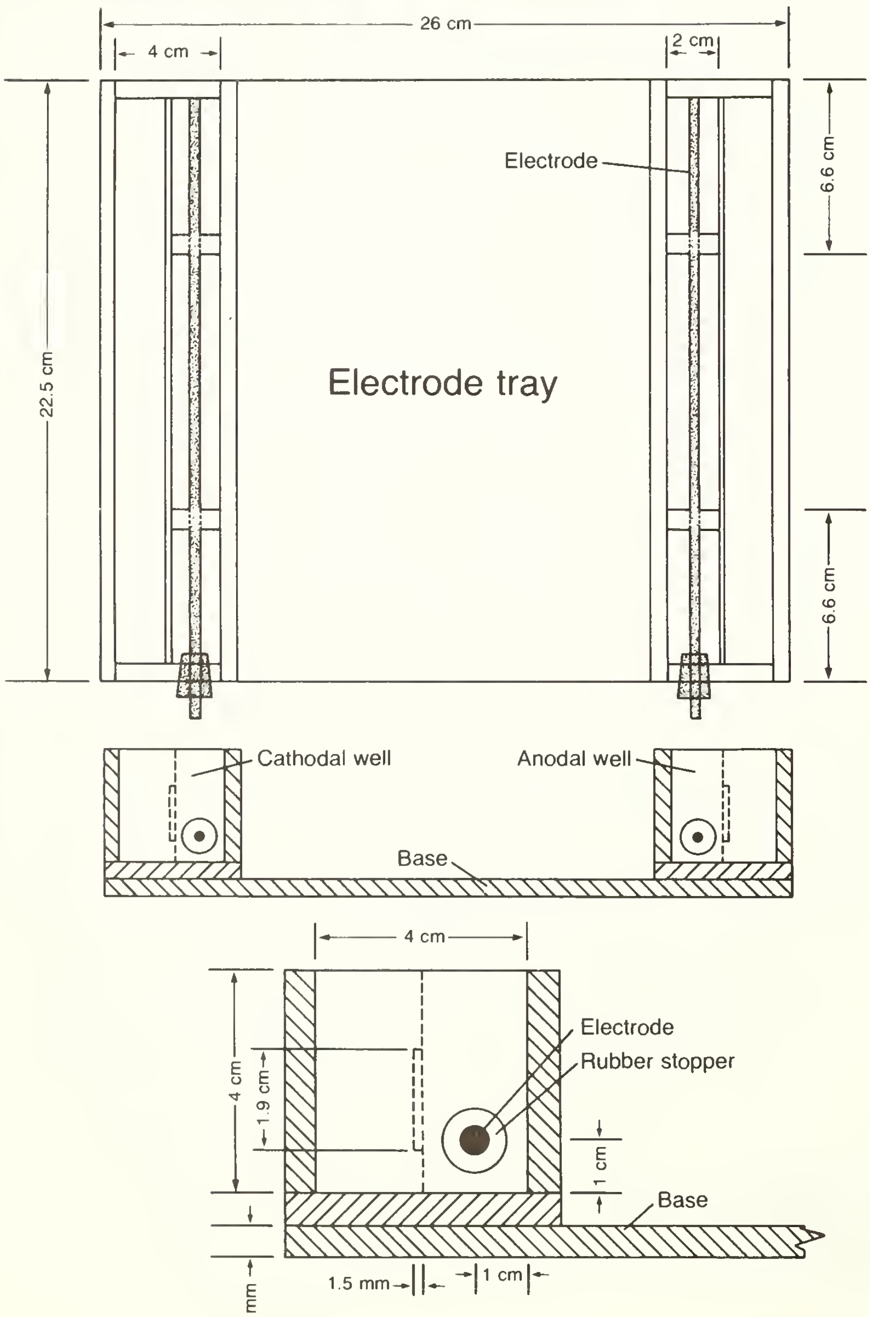
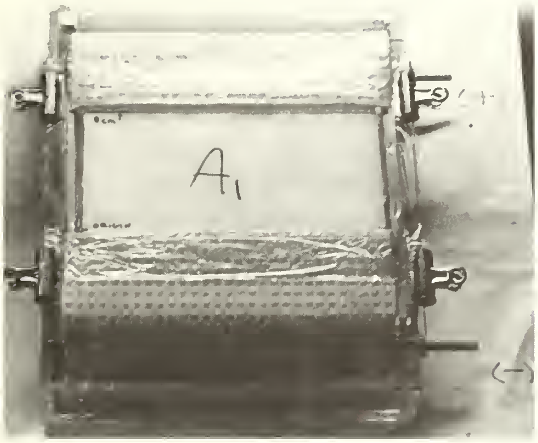


Figure 6—Exact dimensions of electrode tray. The $^3/_{16}$-inch pure carbon electrodes are secured into the tray with no. 00 rubber stoppers. The tray is constructed of $^1/_4$-inch lucite.

Figure 7—Side and top views of an electrode tray with gel and wicks, sponges, and plastic wrap in place.



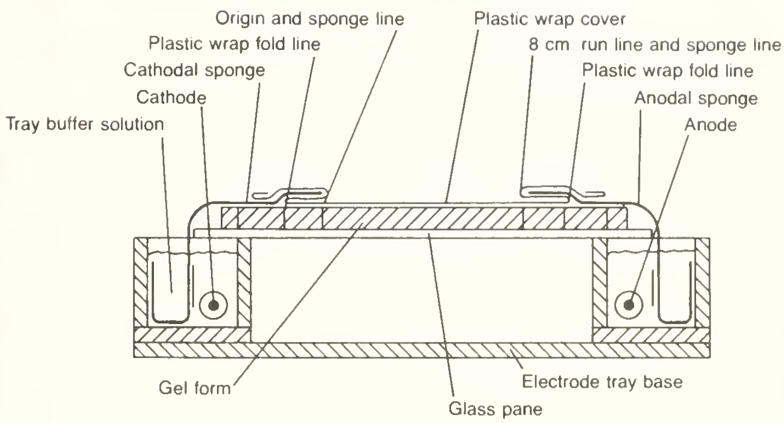


Figure 8—Gel is prepared for slicing by using plastic spacers attached to the glass on either side of the gel slab with spring loaded clips. *Above:* taut monofilament nylon sewing thread cuts horizontal slices through the gel slab. *Right:* gel slice is placed in an appropriate stain solution.

APPENDIX

A. Extraction Buffer

Use pH 7.5, 0.2 M phosphate (*app. C*, Stain buffer formulations) as the extraction buffer. Certain compounds added to the extraction buffer can improve poorly resolved sets of enzyme bands, and in the initial study of a new species, various such compounds should be tested. Our general rule is to keep the buffer as simple as possible by including only additives that improve resolution.

The addition of a small quantity (20 mg/100 ml buffer) of substrate to the extraction buffer may improve the resolution of specific enzymes. Several substrates can be added to the same extraction buffer (L-glutamic acid for GDH, D-glucose-6-phosphate for G6PD, α-D-glucose 1-phosphate for PGM, and others). From our experience, adding substrates to the extraction buffer is better than adding them to the gel or the cathodal electrode buffer as suggested in some literature. The substrate in the extraction buffer probably protects the active site of the enzyme while it is in the mixture of cell components. After a short period of electrophoresis, an enzyme is likely to be isolated from compounds that degrade it.

The resolution of some enzymes is greatly improved by the addition of bovine albumin (40 mg/100 ml) to the extraction buffer. The albumin binds phenolics and free fatty acids (Anderson 1968).

Seed resins and phenols can decrease resolution. The addition of a small quantity of 2-mercaptoethanol (1 drop/100 ml extraction buffer) helps to bind and reduce the effect of resins and phenols. Mercaptoethanol improves resolution in true firs, incense-cedar, and redwood, but we do not add mercaptoethanol to the extraction buffer for pines, cypresses, and Douglas-fir.

Complex extraction buffers are available for difficult tissues (Kelley and Adams 1977, Mitton and others 1979, Soltis and others 1980); but most conifer seed analyses do not require these complex buffers.

B. Gel and Tray Buffer Formulations

System	Gel Buffer	Tray Buffer
A[1]	**Tris citrate (pH 8.3)**	**Lithium borate (pH 8.3)**
Formulation	Trizma base .... 62.0 g Citric acid .... 14.6 g Distilled water .... 10.0 liters	Lithium hydroxide .... 12.0 g Boric acid .... 118.9 g Distilled water .... 10.0 liters
	Dissolve the chemicals and check the pH. Store at room temperature	Dissolve the chemicals and check the pH. Store at room temperature
Procedure	To use, add 75 ml of the lithium borate tray buffer to 675 ml of the tris citrate gel buffer to make the required 750 ml	Use as is
B[2]	**Tris citrate (pH 8.8)**	**Sodium borate (pH 8.0)**
Formulation	Trizma base .... 121.1 g Distilled water .... 10.0 liters	Sodium hydroxide .... 20.0 g Boric acid .... 185.5 g Distilled water .... 10.0 liters
	Dissolve the trizma base and titrate to pH 8.8 with 0.2 M citric acid solution. Store at room temperature	Dissolve the chemicals and titrate to pH 8.0 with 4N NaOH. Store at room temperature
Procedure	Use as is	Use as is
C[3]	**Tris citrate (pH 6.2)**	**Same as gel buffer**
Formulation	Trizma base .... 162.0 g Citric acid .... 108.9 g Distilled water .... 3.0 liters	Same as gel buffer
	Dissolve chemicals and titrate to pH 6.2 with 4N NaOH. Refrigerate	
Procedure	To use, mix 16 ml of the buffer with 734 ml of distilled water	Mix 250 ml of the buffer with 750 ml distilled water
D[4]	**Morpholine citrate (pH 6.1)**	**Same as gel buffer**
Formulation	Citric acid .... 15.4 g Distilled water .... 2.0 liters	Same as gel buffer
	Dissolve citric acid and titrate to pH 6.1 with N-(3-aminopropyl)morpholine (20 ml). Refrigerate	
Procedure	To use, mix 37.5 ml of buffer with 712.5 ml of distilled water	Use full strength

[1]Scandalious 1969
[2]Fowler and Morris 1977
[3]Nichols and Ruddle 1973
[4]Clayton and Tretiak 1972, Yeh and O'Malley 1980

C. Stains

Enzyme stains used on gel slices from specific gel systems are listed in *table 1*. Stock solutions for chemicals required in several stain recipes are listed in *table 2*. Stain buffer solutions are listed in *table 3*. Recipes for preparing stains are described in *table 4*. The stains listed in *table 4* are used in the analysis of conifer seeds. Additional stains can be found elsewhere in the literature (Harris and Hopkinson 1976, O'Malley and others 1980).

Prepare stock solutions for stains in quantities that will be used up in 4 weeks. Several of the components of these solutions are light-sensitive and perishable. Store them refrigerated (do not freeze) in dark containers; foil-wrap light-colored containers. Add these components to the stain solutions just before adding the gel slices.

Table 2—*Stock solutions for stain components*

Abbreviation	Name	Standard concentration
G6PDH	Glucose-6-phosphate dehydrogenase[1]	5 units/ml buffer
NAD	β-Nicotinamide adenine dinucleotide	10 mg/ml water
NADP	β-NAD phosphate	10 mg/ml water
NBT	Nitro blue tetrazolium	10 mg/ml water
PMS	Phenazine methosulfate	5 mg/ml water

[1]G6PDH is subject to sulfate ion inhibition. This enzyme is supplied in a concentrated solution, which should be diluted using 1 percent bovine albumin in 0.05 M phosphate buffer (pH 7.5). The albumin binds sulfate ions to enhance the activity of the enzyme.

Prepare stain buffers in quantities sufficient to last up to 2 months by anticipating laboratory schedules. These buffers can be stored at room temperature.

Table 1—*Stains by gel buffer system*

Gel system	Stain: Abbreviation	Stain: Name	EC reference
A	ADH	Alcohol dehydrogenase	1.1.1.1
	AAP	Alanine aminopeptidase	3.4.11.1
	EST	Alpha esterase	3.1.1.1
	EST	Beta esterase	3.1.1.1
	FLEST	Fluorescent esterase	3.1.1.1
	LAP	Leucine aminopeptidase	3.4.11.1
	MNR	Menadione reductase	
	PEP	Peptidase	3.4.13.1
	PER	Peroxidase	1.11.1.7
	PGM	Phosphoglucomutase	2.7.5.1
	PGI	Phosphoglucose isomerase[1]	5.3.1.9
B	ACP	Acid phosphatase	3.1.3.2
	CAT	Catalase	1.11.1.6
	G6PD	Glucose-6-phosphate dehydrogenase	1.1.1.49
	GDH	Glutamate dehydrogenase	1.4.1.3
	GOT	Glutamate-oxaloacetate transaminase[2]	2.6.1.1
	SOD	Superoxide dismutase[3]	1.15.1.1
C, D[4]	ACON	Aconitase	4.2.1.3
	ALD	Aldolase	4.1.2.13
	IDH[5]	Isocitric dehydrogenase	1.1.1.42
	MDH	Malic dehyrogenase	1.1.1.37
	MNR	Menadione reductase	
	PGD	Phosphogluconate dehydrogenase[6]	1.1.1.44
	SKDH	Shikimate dehydrogenase	

[1]Also called glucose phosphate isomerase (GPI) in the literature.

[2]Also called aspartate aminotransferase (AAT) in the literature.

[3]Also called tetrazolium oxidase (TO) in the literature.

[4]All of the stains listed for the C system resolve well with the D buffer system, but both systems are necessary to detect variants within different loci.

[5]Also abbreviated ICD in the literature.

[6]Also called 6-phosphogluconic dehydrogenase (6PGD) in the literature.

Table 3—*Stain buffer formulations*

Buffer	pH	Formulation
ACP acetate buffer	4.0	Sodium acetate, trihydrate ..... 2.43 g
		Acetic acid, glacial .... 4.7 ml
		1.0 M magnesium chloride ..... 5.0 ml
		Distilled water................ 1.0 liter
Aminopeptidase buffer	4.5	Trizma base .... 12.1 g
		Maleic anhydride .... 9.8 g
		Sodium hydroxide .... 1.6 g
		Distilled water................ 1.0 liter
Catalase buffer	6.5	Sodium phosphate, monobasic .... 18.5 g
		Sodium phosphate, dibasic .... 17.9 g
		Distilled water................ 1.0 liter
Esterase buffer	6.4	Sodium phosphate, monobasic .... 13.9 g
		Sodium phosphate, dibasic ..... 5.3 g
		Distilled water................ 1.0 liter
Peroxidase buffer	5.6	Arsenic acid, sodium salt....... 5.74 g
		Acetic acid, glacial .... 1.2 ml
		Distilled water................ 1.0 liter
0.2 M phosphate buffer	7.5	Sodium phosphate, monobasic .... 3.84 g
		Sodium phosphate, dibasic .... 23.86 g
		Distilled water................ 1.0 liter
1.0 M tris hydrochloride[1]	8.0	Trizma base .... 74.0 g
		Trizma hydrochloride......... 61.4 g
		Distilled water................ 1.0 liter
1.0 M tris hydrochloride[1]	7.0	Trizma base .... 16.0 g
		Trizma hydrochloride........ 137.4 g
		Distilled water................ 1.0 liter

[1]Dilute these solutions to the concentrations specified in the stain charts.

Table 4—*Stain recipes*

Enzyme	Gel buffer	Stain buffer	Stain components	Procedure
ACON Aconitase[1]	C,D	75 ml 0.2 M tris HCl pH 8.0	*Cis*-aconitic acid .... 150 mg NADP .... 1 ml NBT .... 1 ml 1% $MgCl_2$ solution .... 1 ml PMS .... 0.5 ml Isocitrate dehydrogenase .... 20 units (0.3 ml)	Add stain components to warm (37° C) stain buffer; incubate gels at 37° C in the dark
ACP Acid phosphatase[2]	B	80 ml ACP acetate buffer	α-naphthyl acid phosphate .... 100 mg Fast Garnet GBC Salt[2] .... 100 mg	Allow stain components to mix well in stain buffer. Develop at room temperature. Include cathodal slice of gel in the stain.
ADH Alcohol dehydrogenase[2]	A	75 ml 0.05 M tris HCl pH 8.0	NAD .... 1 ml NBT .... 1 ml PMS .... 0.5 ml 95% ethyl alcohol .... 1 ml	Add components to warm buffer and incubate gels in the dark
AAP Alanine aminopeptidase[4]	A	75 ml Aminopeptidase buffer	L-alanine β-naphthylamide[3] .... 30 mg dissolved in dimethylsulfoxide .... 2 ml Fast Black K Salt .... 20 mg	Add components to warm buffer and incubate gels in the dark
ALD Aldolase[1]	C,D	75 ml 0.05 M tris HCl pH 8.0	D-fructose-1,6-diphosphate .... 250 mg Arsenic acid, sodium salt .... 75 mg NAD .... 1 ml NBT .... 1 ml PMS .... 0.5 ml Glyceraldehyde-3-phosphate dehydrogenase .... 300 units (0.25 ml)	Add components to warm buffer and incubate gels
CAT Catalase[2]	B	100 ml Catalase buffer	2% potassium iodide solution .... 100 ml 0.03% H_2O_2 solution, (3% H_2O_2, 1 ml/100 ml distilled water) .... 100 ml	Refrigerate gels in catalase buffer for 30 min. Drain off buffer and soak in 2% KI for 2 min. Drain off KI and wash twice with tap water. Add H_2O_2 solution and score when resolved
EST Alpha esterase[2]	A	75 ml Esterase buffer	Fast Blue RR Salt .... 80 mg 1% α-naphthyl acetate solution (dissolve 1 g in 50 ml acetone, add 50 ml distilled water, store refrigerated) .... 1 ml	Add components to warm buffer. Add the naphthyl acetate solution late in mixing. Incubate the gels. Include the cathodal slice of gel
EST Beta esterase	A	75 ml Esterase buffer	Fast Garnet GBC Salt[3] .... 100 mg 1% 2-naphthyl acetate solution (dissolve 1 g in 50 ml acetone, add 50 ml distilled water, store refrigerated) .... 1 ml	Add components to warm buffer; add naphthyl acetate to solution just before adding gels. Incubate gels
FLEST Fluorescent esterase[5]	A	10 ml Peroxidase buffer	4-methylumbelliferyl acetate solution (1 mg dissolved in 3 ml acetone) .... 3 ml	Add solution to buffer and paint gels. Score bands on gels within 5 minutes under longwave UV light
GDH/SOD Glutamate dehydrogenase, superoxide dismutase[6]	B	75 ml 0.10 M tris HCl pH 8.0	L-glutamic acid .... 2 g NAD .... 1 ml NBT .... 1 ml PMS .... 0.5 ml	Add components to warm buffer. Incubate in the dark. (SOD bands are white against the blue background.)
GOT Glutamate-oxaloacetate transaminase[7]	B	25 ml 0.2 M phosphate buffer pH 7.5	0.5% pyridoxal 5-phosphate solution (0.5 g/100 ml of distilled water) .... 0.8 ml 3.0% bovine albumin solution (3 g/100 ml of distilled water) .... 1.6 ml 0.2 M L-aspartic acid (adjusted to pH 7.5 with 2N KOH) .... 6.8 ml	Combine first four components with buffer. When ready for staining add the Fast Blue BB solution to component solution. Add gels and develop at room temperature. Include a cathodal slice of gel

Enzyme	Gel buffer	Stain buffer	Stain components	Procedure
			α-ketoglutarate solution .... 2.0 ml Fast Blue BB Salt .... 120 mg dissolved in distilled water .... 8 ml	
G6PD Glucose-6-phosphate dehydrogenase[8]	B	75 ml 0.05 M tris HCl pH 7.0	D-glucose-6-phosphate .... 20 mg 3.0% bovine albumin solution .... 1 ml NADP .... 1 ml NBT .... 1 ml 1% $MgCl_2$ .... 1 ml PMS .... 0.5 ml	Add components to the warm buffer and incubate gels in the dark
IDH Isocitrate dehydrogenase[9]	C,D	75 ml 0.05 M tris HCl pH 8.0	DL isocitric acid .... 60 mg NADP .... 1 ml 0.25 M $MnCl_2$ .... 1 ml NBT .... 1 ml PMS .... 0.5 ml	Add components to warm buffer and incubate gels in the dark
LAP Leucine aminopeptidase[2]	A,D	75 ml Aminopeptidase buffer	0.4% L-leucine β-napthylamide solution (400 mg/100 ml distilled water) .... 5 ml Black K Salt .... 20 mg	Add components to warm buffer and incubate gels
MDH Malic dehydrogenase[9]	C,D	75 ml 0.05 M tris HCl pH 8.0	Malic acid solution .... 5 ml (134.1 g DL-malic acid, 80 g NaOH, 1.0 liter H_2O, adjust to pH 7.0 with about 18 ml of 4 N NaOH) NAD .... 1 ml NBT .... 1 ml PMS .... 0.5 ml	Add components to warm buffer and incubate gels in the dark
MNR Menadione reductase	A,C,D	75 ml 0.05 M tris HCl pH 7.0	NADH .... 25 mg Menadione .... 20 mg NBT .... 1 ml	Add components to warm buffer and incubate gels in the dark
PEP Peptidase[9]	A	75 ml 0.2 M tris HCl pH 8.0	Glycyl-L-leucine .... 10 mg L-leucyl-L-tyrosine .... 10 mg L-valyl-L-leucine .... 10 mg Peroxidase, crude .... 10 mg Snake venom .... 10 mg 50 mg of 3-amino-9-ethyl carbazole in 5 ml of N,N-dimethylformamide .... 5 ml	Combine first five components with buffer and mix well. When ready to stain, add amino-ethyl-carbazole solution and incubate gels
PER Peroxidase[8]	A	75 ml Peroxidase buffer	0.1 M $CaCl_2$ solution .... 2 ml 3-amino-9-ethyl carbazole .... 50 mg dissolved in N,N-dimethylformamide .... 5 ml 3% H_2O_2 .... 1 ml	Add components to buffer just before staining. Add gels and develop at room temperature. Use anodal and cathodal slices. Note: origin of gel could be moved 1 cm toward anode at beginning of the run for this system
6PGD 6-phosphogluconate dehydrogenase[10]	C,D	75 ml 0.05 M tris HCl pH 8.0	6-phosphogluconic acid .... 20 mg NADP .... 1 ml NBT .... 1 ml PMS .... 0.5 ml	Add components to warm stain buffer, add gels and incubate in the dark
PGI Phosphoglucose isomerase[10]	A	75 ml 0.05 M tris HCl pH 8.0	D-fructose-6-phosphate .... 25 mg 1% $MgCl_2$ solution .... 1 ml NADP .... 1 ml NBT .... 1 ml PMS .... 0.5 ml G6PDH .... 20 units	Add all components to warm buffer. Add gels and incubate in the dark
PGM Phosphoglucomutase[10]	A	75 ml 0.05 M tris HCl pH 8.0	α-D-glucose 1,6-diphosphate solution (10 mg/100 ml distilled water) .... 1 ml α-D-glucose 1-phosphate .... 140 mg	Add all components to warm buffer. Add gels and incubate in the dark

Enzyme	Gel buffer	Stain buffer	Stain components	Procedure
			1% $MgCl_2$ solution .... 1 ml NADP.................................. 1 ml NBT.................................... 1 ml PMS .... 0.5 ml G6PDH.............................. 20 units	
SKDH Shikimate dehydrogenase[8]	C,D	75 ml 0.05 M tris HCl pH 8.0	Shikimic acid .... 75 to 50 mg NADP.................................. 1 ml NBT.................................... 1 ml PMS .... 0.5 ml	Add all components to warm buffer and incubate in the dark

[1]Yeh and O'Malley 1980
[2]Scandalious 1969
[3]Carcinogenic, handle with care
[4]Ott and Scandalious 1978
[5]Mitton and others 1979
[6]Shaw and Koehn 1968
[7]Brewbaker and others 1968
[8]Shaw and Prasad 1970
[9]Nichols and Ruddle 1973
[10]Brewer 1970

D. Chemicals Needed for Processes Described[1]

Catalog number[2]	Chemical
	Acetic acid, glacial[3]
A7251	*Cis*-aconitic acid
A2628	L-alanine β-napthylamide[3]
A4503	Albumin, bovine, fraction V powder
A5754	3-amino-9-ethylcarbazole
12,390-9[4]	N-(3-aminopropyl)morpholine[3]
A6756	Arsenic acid, sodium salt[3]
A9256	L-aspartic acid, free acid
B0252	Boric acid
C0759	Citric acid, free acid, anhydrous
D4254	N,N-dimethylformamide[3]
D5879	Dimethyl sulfoxide
	Ethanol, 95%
F7253	Fast Black K Salt
F3378	Fast Blue BB Salt[3]
F0500	Fast Blue RR Salt[3]
F0875	Fast Garnet GBC Salt[3]
752-1	D-fructose 1,6-diphosphate, trisodium salt
F3627	D-fructose-6-phosphate, sodium salt, grade I
G5875	α-D-glucose 1,6-diphosphate, tetra(cyclohexylammonium) salt
G7000	α-D glucose 1-phosphate, disodium salt: tetrahydrate
G7879	D-glucose-6-phosphate, monosodium salt
G8878	Glucose-6-phosphate dehydrogenase, Type XI
G1626	L-glutamic acid, monosodium salt
G5126	Glyceraldehyde-3-phosphate dehydrogenase
G2002	Glycyl-L-leucine
	Hydrogen peroxide (3%)
I1252	DL-isocitric acid, trisodium salt
I2002	Isocitric dehydrogenase, Type IV
410-2	α-ketoglutarate solution, 0.1 M, pH 7.5 in 0.1 M phosphate buffer
L0376	L-leucine β-naphthylamide, hydrochloride[3]
L0501	L-leucyl-L-tyrosine
L4256	Lithium hydroxide, monohydrate[3]
M0250	Magnesium chloride, hexahydrate
M0625	Maleic anhydride[3]
M0875	DL-malic acid
M5626	Menadione
M6250	2-mercaptoethanol
	Methanol, 95%[3]
M0883	4-methylumbelliferyl acetate
N8505	α-naphthyl acetate[3]
N6875	2-naphthyl acetate[3]
N7000	α-naphthyl acid phosphate, monosodium salt[3]
N7004	β-nicotinamide adenine dinucleotide (NAD)
N8129	β-nicotinamide adenine dinucleotide, reduced form (NADH), disodium salt
N0505	β-nicotinamide adenine dinucleotide phosphate (NADP), sodium salt
N6876	Nitro blue tetrazolium (NBT)[3]
P8250	Peroxidase, type II
P9625	Phenazine methosulfate (PMS)[3]
P7877	6-phosphogluconic acid, trisodium salt
P1767	Potassium hydroxide[3]
P8256	Potassium iodide
P9255	Pyridoxal 5-phosphate
S5375	(-)shikimic acid
S8625	Sodium acetate, trihydrate
S5881	Sodium hydroxide, anhydrous pellets[3]
S0751	Sodium phosphate, monobasic
S0876	Sodium phosphate, dibasic
S4501[5]	Starch, hydrolyzed for electrophoresis
T1503	Trizma base
T3253	Trizma hydrochloride
V1625	L-valyl-L-leucine
V7000[3]	Venom, snake (*Crotalus atrox*)

[1]Many chemicals are available in different forms, with different salts and hydration levels. Sigma and Aldrich Chemical Company catalog numbers and chemical names are supplied to avoid confusion for all but the most common chemicals—glacial acetic acid, ethanol, hydrogen peroxide, and methanol.

[2]Sigma Chemical Co., P.O. Box 14508, St. Louis, Mo. 63178.

[3]Hazardous chemical, handle with care.

[4]Aldrich Chemical Co., 940 West Saint Paul Avenue, Milwaukee, Wis. 53233.

[5]Additional brands of starch are Fisher, Connaught, and Electro-starch.

REFERENCES

Anderson, J. W. **Extraction of enzymes and subcellular organelles from plant tissues.** Phytochemistry 7:1973-1988; 1968.

Brewbaker, James L.; Upadhya, Mahesh D.; Makinen, Yrjo; MacDonald, Timothy. **Isoenzyme polymorphism in flowering plants III: gel electrophoretic methods and applications.** Physiologia Plantarum 21:930-940; 1968.

Brewer, G. J. **An introduction to isozyme techniques.** New York: Academic Press; 1970.

Clayton, J. W.; Tretiak, D. N. **Amine-citrate buffers for pH control in starch gel electrophoresis.** J. Fish. Res. Board Can. 29:1169-1172; 1972.

Conkle, M. Thompson. **Isozyme specificity during germination and early growth of knobcone pine.** Forest Sci. 17:494-498; 1971.

Conkle, M. Thompson. **Analyzing genetic diversity in conifers ... isozyme resolution by starch gel electrophoresis.** Res. Note PSW-264. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972. 5 p.

Feret, P. P.; Bergmann, F. **Gel electrophoresis of proteins and enzymes.** In: Modern methods in forest genetics, Miksche, J., ed. New York: Springer-Verlag; 1976; 49-77.

Fowler, D. P.; Morris, R. W. **Genetic diversity in red pine: evidence for low genetic heterozygosity.** Can. J. Forest Res. 7:343-347; 1977.

Harris, Harry; Hopkinson, D. A. **Handbook of enzyme electrophoresis in human genetics** [with supplements]. Amsterdam: North-Holland Publishing Co.; New York: Oxford American Elsevier Publishing Co.; 1976.

Kelley, Walter A.; Adams, Robert P. **Preparation of extracts from juniper leaves for electrophoresis.** Phytochemistry 16:513-516; 1977.

Mitton, J. B.; Linhart, Y. B.; Sturgeon, K. B.; Hamrick, J. L. **Allozyme polymorphisms detected in mature needle tissue of ponderosa pine.** J. Hered. 70:86-89; 1979.

Nichols, Elizabeth A.; Ruddle, Frank H. **A review of enzyme polymorphism, linkage and electrophoretic conditions for mouse and somatic cell hybrids in starch gels.** J. Histochem. and Cytochem. 21:1066-1081; 1973.

O'Malley, David; Wheeler, Nicholas C ; Guries, Raymond P. **A manual for starch gel electrophoresis.** Staff Paper Series 11. Madison, WI: Department of Forestry, College of Agricultural and Life Sciences, University of Wisconsin; 1980. 16 p.

Ott, Lila; Scandalious, John G. **Genetic control and linkage relationships among aminopeptidases in maize.** Genetics 89:137- 146; 1978.

Scandalious, John G. **Genetic control of multiple molecular forms of enzymes in plants: a review.** Biochem. Genet. 3:37-79; 1969.

Shaw, Charles R.; Koen, Ann L. **Starch gel zone electrophoresis of enzymes.** In: Smith, I., ed. Chromatographic and electrophoretic techniques. Volume II. Bath, England: Pitman Press; 1968: 325-364.

Shaw, Charles R.; Prasad, Rupi. **Starch gel electrophoresis of enzymes—a compilation of recipes.** Biochem. Genet. 4:297-320; 1970.

Soltis, Douglas E.; Haufler, Christopher H.; Gastony, Gerald J. **Detecting enzyme variation in the fern genus *Bommeria*: an analysis of methodology.** Systematic Botany 5(1):30-38; 1980.

U.S. Department of Agriculture, Forest Service. **Seeds of woody plants in the United States.** Agric. Handb. 450. Washington, DC: U.S. Department of Agriculture; 1974. 883 p.

U.S. Department of Labor, Occupational Safety and Health Administration. **General industrial safety and health standards.** Washington, DC; 1976. 649 p.

Yeh, F. Ch.-H.; O'Malley, D. **Enzyme variations in natural populations of Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, from British Columbia. 1. Genetic variation patterns in coastal populations.** Silvae Genet. 29:83-92; 1980.

The Forest Service, U.S. Department of Agriculture, is responsible for Federal leadership in forestry. It carries out this role through four main activities:

- Protection and management of resources on 191 million acres of National Forest System lands.
- Cooperation with State and local governments, forest industries, and private landowners to help protect and manage non-Federal forest and associated range and watershed lands.
- Participation with other agencies in human resource and community assistance programs to improve living conditions in rural areas.
- Research on all aspects of forestry, rangeland management, and forest resources utilization.

The Pacific Southwest Forest and Range Experiment Station

- Represents the research branch of the Forest Service in California, Hawaii, and the western Pacific.

Conkle, M. Thompson; Hodgskiss, Paul D.; Nunnally, Lucy B.; Hunter, Serena C. **Starch gel electrophoresis of conifer seeds: a laboratory manual.** Gen. Tech. Rep. PSW-64. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 18 p.

This manual describes fast, low-cost biochemical procedures for separating enzymes representing numerous genes of forest trees. During electrophoresis the mixture of enzymes from a megagametophyte or embryo of a germinated seed separates in a gel. Specific stains applied to gel slices locate each enzyme. These procedures expand on those developed for crops research. They provide a means for forest geneticists to get urgently needed information on the amount and geographic distribution of genetic variation in conifers for evaluating species relationships, for protecting rare natural populations, and for deciding on breeding programs for commercial species. Electrophoresis of conifers is an alternative to long-term, high-cost field trials.

Retrieval Terms: technique, gametophytes, embryos, allozymes, electrophoresis

United States
Department of
Agriculture

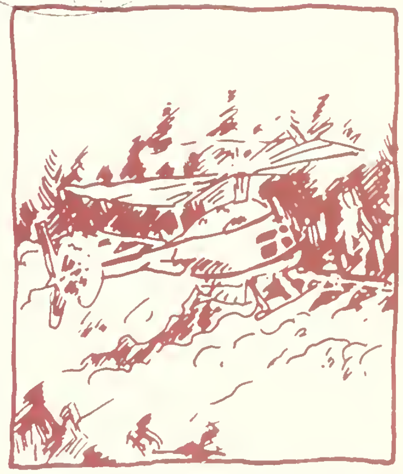
Forest Service

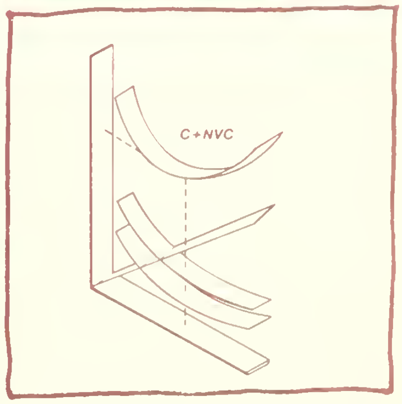
**Pacific Southwest
Forest and Range
Experiment Station**

General Technical
Report PSW-65

FEES: design of a *F*ire *E*conomics *E*valuation *S*ystem

Thomas J. Mills Frederick W. Bratten





The Authors:

are with the Station's research unit studying fire management planning and economics, headquartered at the Forest Fire Laboratory, Riverside, California. **THOMAS J. MILLS**, a forest economist, is in charge of the unit. He earned degrees at Michigan State University (B.S. in forestry, 1968; and M.S., 1969, and Ph.D., 1972, in forest economics). **FREDERICK W. BRATTEN**, an operations research analyst, received degrees in physics at the Case Institute of Technology (B.S., 1950) and the University of California, Berkeley (M.S., 1952).

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

December 1982

FEES: design of a *F*ire *E*conomics *E*valuation *S*ystem

Thomas J. Mills Frederick W. Bratten

CONTENTS

Introduction 1
Fire Management Program Decisionmaking 2
Information Requirements 2
Analysis Resolution 3
Earlier Studies 3
Overview of FEES 5
Input Supplied by User 5
Fire Management Program Options 5
Fire Management Situation 7
Time Horizon 7
Output Produced by FEES 8
Economic Efficiency 8
Resource Output Changes 9
Risk Assessment 10
Inferences About Program Effects 11
Output Display 11
Design of the FEES Model 13
Inferred Parameter Cells 14
Fuel Treatment Module 15
Fire Behavior Module 16
Initial Attack Module 16
Large Fire Suppression Module 17
Cost Module 17
Fire Effects Module 18
Resource Value Module 20
Fire Occurrence Module 20
Probability Calculations 20
Sensitivity Analysis and Model Validation 22
Application of FEES 23
References 24

IN BRIEF...

Mills, Thomas J.; Bratten, Frederick W. **FEES: design of a *F*ire *E*conomics *E*valuation *S*ystem.** Gen. Tech. Rep. PSW-65. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 26 p.

Retrieval Terms: economic efficiency, risk, fire suppression, probability mode, fire effects

Currently available procedures for analyzing fire management program options are significant improvements over the analysis capability which existed a decade ago, and they provide important information for fire program planning. Major expansion and refinement of the existing capability is necessary, however, to cope with the persistent questions about public program efficiency.

In particular, a subregional-resolution analysis system is needed which can estimate the economic efficiency, fire-induced change in resource outputs, and risk consequences of a broad array of fire management program options. That subregional analysis would act as a screening step for subsequent high-resolution analyses which are more site- and time-specific. The high-resolution, and generally higher cost, analyses should be restricted to that narrow range of fire program options which show promise of high performance. As a minimum, the fire program options evaluated in the subregional analysis system should include alternatives with fuel treatment, initial attack, and large fire suppression program components. Each program option should be further defined by dollar program level, fire management mix or program emphasis, and large fire suppression strategy.

The *F*ire *E*conomics *E*valuation *S*ystem (FEES), the conceptual design of which is described in this report, can provide that subregional-resolution analysis of a broad range of fire program options. This simulation model is designed to evaluate situation-specific fire management situations or "kinds of areas" that have no site-specific delineation except that of regional fire climate zone. There is no reason to repeatedly apply a site-specific model to different areas if the characteristics of the area which influence fire program performance are essentially the same. The fire program option evaluated in FEES embodies all of the fire management inputs applied to the fire management situation rather than just those contributed by a single agency. The question of who should pay for the fire program cannot be logically answered until a total fire program option has been selected. FEES can be used by any public agency with wildland fire management responsibilities.

Development of an operational system that fulfills this conceptual design should proceed with a prototype version of the system applied to one area of the country, the Northern Rocky Mountain and Intermountain fire climate zone, for example. Once the prototype model has been subjected to extensive sensitivity analysis and validation tests, it should be applied to another study area, such as the Pacific Northwest fire climate zone. Different factors are important to fire program performance in different parts of the country. For example, timber losses are relatively more important in the Pacific Northwest, sharing of fire management inputs and multiple fires are relatively more important in southern California, and the many influences of complex terrain are relatively more important in the Northern Rocky Mountains. Even the first prototype version of FEES must recognize these differences so that subsequent expansion of model capability is easy to accomplish.

Once FEES is completed, it is proposed that the system be operated at a central location to produce a FEES guidebook of model output which can then be used directly by local fire program planners. Centralized operation of FEES would greatly reduce the training costs over the alternative of direct application of the FEES computer software by the fire program planner, and centralized operation would greatly increase the consistency of model results, thus enhancing the ability to make funding allocations on the basis of FEES results. Centralized processing is not synonymous with centralized decisionmaking. The relative weights among the decision criteria must still be assigned by a local decisionmaker who has an understanding of the ramifications of a fire program selection on the other management programs.

No simulation model is a substitute for a decisionmaker, and FEES is no exception. A decisionmaker must still weigh and assimilate a large number of relevant factors, many of which cannot be measured in common units or even be measured quantitatively at all, and must place the fire program within the context of other management programs and institutional constraints. FEES simply quantifies some of the factors which are relevant to fire management program planning and traces the interaction of relationships too complex and numerous for a person to easily follow. FEES is designed to show some of the costs of imposing institutional constraints. While many of those constraints are valid, their costs must always be considered.

FEES contains many of the parameters important in fire management program planning but others are left out; fire effects which cannot be measured in dollars, for example. It is essential that a decisionmaker, who is knowledgeable about the setting within which FEES results will be applied, fully understand these limitations of scope.

Wildfire is such an awesome and frightening natural phenomenon that funding for wildland fire management programs was relatively easy to obtain in the past. This was particularly true immediately after a severe fire season, when funding levels often rose quickly, only to erode away before the next severe fire season occurred. They were seldom scrutinized as closely as those of other land management programs.

This view of fire programs has progressively changed in the last decade, however, in response to the sheer size of fire program budgets, to greater appreciation of fire's natural role in the environment, and to recognition that fire management activities should be evaluated on the basis of their impact on resource outputs, just like any other land management activity. A symptom of the change was a request in 1975 by the U.S. Office of Management and Budget that the Forest Service, U.S. Department of Agriculture, estimate the real cost of its fire management program and identify the "best" fire management practices (U.S. Dep. Agric., Forest Serv. 1977). The best practices were to be identified through an evaluation of appropriate costs and returns.

Another symptom of change was the concern expressed by the U.S. Senate Appropriations Committee during review of the fiscal year 1979 budget request for the fire management program on National Forest lands. The Committee observed that "presuppression costs have risen dramatically in recent years, but the Committee is unable to discern any marked benefits stemming from these expenditures" (U.S. Senate 1978). The Committee requested that the Forest Service "conduct a cost-benefit analysis of both presuppression and suppression activities" as a basis of future budget requests. In simple terms, what benefits are being generated that justify the ever larger fire program funding levels?

Revisions in the land management planning process on National Forests, and their implications for fire management analyses, are other symptoms of the change. Regulations that implement the National Forest Management Act of 1976 require fully integrated analysis of all land management planning activities, formulation and evaluation of a range of feasible management alternatives, and selection of one alternative on the basis of explicit criteria (U.S. Dep. Agric., Forest Serv. 1979a, 1979b, 1982c). The fire program can no longer be evaluated in isolation from other land management programs.

The fire program on the National Forests is not the only fire program being scrutinized more closely. Funding for the Forest Service's Cooperative Forest Fire Program, which coordinates activities among the fire programs in the States, was reduced from $30.5 million in 1978 to $19.9 million by 1981 and is under continually closer scrutiny. Fire management programs are also being more closely studied by legislatures in many States—California and Oregon, for example.

In response to this changing attitude, the Forest Service made a major policy change in 1978 by requiring that the fire management program be cost-effective and become a part of integrated land management (Nelson 1979). The policy language was further refined in 1981 to state that economic efficiency and probability of success are important criteria for selecting among fire suppression actions (U.S. Dep. Agric., Forest Serv. 1981).

Economic efficiency case studies of the fire program options have been completed in progressively greater rigor (Oregon State Dep. of Forestry 1972; Schweitzer and others 1982; U.S. Dep. Agric., Forest Serv., 1980, 1982a; Winkworth and others 1981). Similarly, improved analysis procedures have been developed to implement policy changes (Calif. Dep. of Forestry 1979; U.S. Dep. Agric., Forest Serv. 1982a). Recent analysis procedures are great improvements over our past capability, and they provide valuable information for some fire program decisions. But important refinements in the fire program planning and evaluation capability are necessary.

Fire programs should not be viewed solely as a support function in the land management planning analysis even though protection of life and property is a goal of the program. Fire management activities influence resource outputs just as other land management activities do, and should be evaluated in the same manner, in terms of program cost increments compared to the changes they bring about in resource outputs. Fire suppression increases timber output above the unmanaged output level just as tree planting does. The fire program options should, therefore, be considered at the same time as other means of accomplishing land management objectives. The fire program *contributes* to the accomplishment of the land management objectives, it does not simply *support* other activities.

This paper identifies the information required for long-term fire program planning decisions and discusses its implications for design of a system to evaluate fire program options. On this basis, and recognizing recent advances in fire program analysis methodology, it describes the design of a particular *F*ire *E*conomics *E*valuation *S*ystem (FEES) capable of providing the required information. An improved operational system can be developed from this design. Fire program managers and economic analysts should also find the design useful in their attempts to interpret output from currently available fire management analysis models.

FIRE MANAGEMENT PROGRAM DECISIONMAKING

Information Requirements

Ideally, at least three types of analytical information should be developed for each fire management program option evaluated: dollar estimates of economic efficiency, quantitative estimates of effects on resource outputs, and assessments of the risk associated with these values. This information is especially relevant in the screening of fire program options early in the planning process.

Concerns about *economic efficiency* are apparent in the questions raised by the Office of Management and Budget and the Senate Appropriations Committee. These are the same cost-benefit questions that have long faced Federal water projects, questions addressed in the description of procedures for economic analysis by the Water Resources Council (1979). Economic efficiency is also a planning criterion in the National Forest Management Act regulations.

The minimization of the sum of fire program costs and the dollar value of net resource output changes which result from fire is a correct economic efficiency criterion (*fig. 1*). It leads to the same program selection as more commonly used economic efficiency criteria, such as present net worth

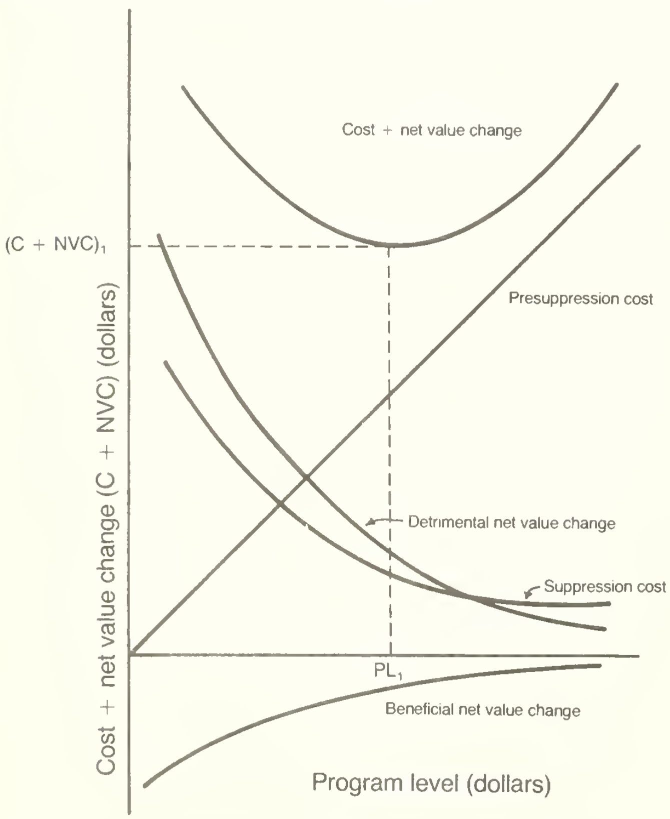


Figure 1—The cost plus net value change as an economic efficiency criterion has four components: presuppression and suppression costs, beneficial and detrimental net value changes.

maximization. The criterion of minimizing cost plus net value change (C + NVC) is more convenient than others to apply to fire control programs because the primary objective of the control activity is to reduce the losses from fire. The C + NVC criterion recognizes that resource output gains, as well as losses, sometimes result from fire. Other than that distinction, it is an only slightly modified version of the criterion of least-cost-plus-loss, first applied to fire programs by Headley in 1916 (Baumgartner and Simard 1982, Gorte and Gorte 1979). Simard (1976) refined the C + NVC concept for fire management analyses by using conventional economic theory principles of marginality, and Herrick (1981) applied the same procedure to an analysis of insect control programs. The difficulty has not been the lack of an appropriate economic efficiency criterion, but rather the lack of a model from which the cost and net value change relationships could be derived.

Some fire program inputs and resource output consequences cannot be readily measured in a common denominator of dollars. Fire effects on cultural sites, rare and endangered species, and air quality are examples. These effects should not be forced into an economic efficiency analysis. As a result, C + NVC is not a holistic measure of economic efficiency and is not a sole decision criterion. Instead, C + NVC must be considered in combination with other effects which cannot be readily measured in dollars.

The second relevant decision criterion is the *change in resource output* levels over time. Although all changes in those resources that can be measured in dollar units are included in the net value change computation, the timing and magnitude of the output changes are often treated as decision criteria themselves. The repeated attention that the Office of Management and Budget and Congress gives to National Forest timber harvest levels and the perennial debate over nondeclining even flow of timber harvests are examples of the importance placed on quantitative resource output effects themselves.

The *risk level* inherent in the fire program option is a third important decision criterion. By risk, we mean the variability in fire program performance which can result from the application of a single program. The severity of the fire season often changes dramatically from year to year, reflecting variations in fire weather and fire occurrence. The pervasive stochastic character of the fire system has generally been recognized in program evaluation procedures through adjustments of the analytical process itself rather than by treating risk preference as a separable decision criterion. The 1972 fire planning process that was applied to National Forests, for example, evaluated fire program performance against effects of fires burning in weather conditions typified by the 90th percentile burning index in the fourth worst fire year of the previous 10 years (U.S. Dep. Agric., Forest Serv. 1972). If only one point on the distribution of possible fire conditions can be measured, there may be some logic in measuring a severe condition, because the greatest suppression costs and damages occur then.

A more complete risk representation is possible, however, with the calculation of probability distributions about the other two decision criteria—economic efficiency and resource output changes. Those probability distributions display the range of possible consequences of a fire program option because of the inherent variability of the fire system. The probability distribution and the expected value (the probability-weighted average that can be calculated from the distribution) permits the decisionmaker to apply specific weights to efficiency, resource outputs, and risk consequences of each fire program option. The importance of risk should be assigned by the decisionmaker, not by the analyst through some adjustments or selective use of empirical model input. Since some public program decisions are not risk-neutral, the expected value outcome should be accompanied by a display of potential variability about the expected value.

Analysis Resolution

The range of time and space resolutions appropriate to fire management analysis is wide. The information needed for highly time- and site-specific attack decisions on individual fires, for example, must be more detailed than that needed to determine the most efficient size and composition of the long-term fire program in a geographic region. This requirement influences system design. It is probably much more efficient to construct an interrelated set of two or three fire management analysis models, each one tailor-built to answer the questions relevant at the different levels of analysis resolution, than to build one larger model capable of addressing all possible levels (Mills 1982). High-resolution models demand large amounts of data, so they should be preceded by low-resolution models that screen potential fire program options down to that subset which warrants further investigation in greater detail. Very detailed, site-specific analysis should only be applied to the small subset of program options that can contribute most to management objectives.

Given the wide range of potential fire program options, two outcomes are possible if a preliminary low-resolution model is not used. The high resolution model, with its associated higher cost, could be applied to all potential fire program options. This would lead to high analysis costs. Alternatively, the high-resolution model could be applied to a small subset of the potential fire program options, leading to suboptimization. The cost of an errant decision through suboptimization could be greater than the higher analysis cost of the first possibility.

Where should the low-resolution analysis start? Probably the best place is at the point where a wide array of fire programs are being evaluated for subregional areas, areas of 1 to 3 million acres in size. Areas of this size are large enough to require a mostly self-contained fire management program, yet they still retain a large amount of resources and topography homogeneity. It is difficult to model the heterogeneity of larger areas, but the modeling trade off for these smaller areas is that some fire program inputs, such as hand crews and air tankers, are shared with other areas. This subregional analysis is not only a useful first step in evaluating programs for a given planning unit, the results can also be used in the development of national- or state-level fire program aggregates.

The size of the area to which the fire management program is applied influences optimum model form, a point sometimes overlooked in the rush to site-specific land and resource management planning. For example, a fire management program option composed of prevention specialists, fire detection personnel, initial attack crews, and fuel treatment specialists is not designed to manage fire on a 1000-acre parcel, but rather an area composed of a substantial number of such parcels.

The most crucial information required for a low-resolution evaluation of fire management programs is a description of the area, specifying characteristics that influence the performance of the fire management program options, such as resource management emphasis and vegetation. How the fire program performs on a certain kind of area is more important in the low-resolution analysis than "where" that area resides within the overall fire management area.

Once a fire management program option has been selected, the "where" and "when" to use individual fire program inputs is a central focus of operational planning. Site-specificity is very important at that planning stage. Before that stage, site-specificity within the fire management area is excess baggage in a modeling sense, and very expensive baggage to carry.

Earlier Studies

Several fire management analyses at approximately the same level of resolution addressed here have been completed. None of the studies meet the scope requirements outlined above, but all provide valuable insights into the most efficient design of FEES.

A number of historical series studies of fire management programs compare program funding levels to program performance indicators, such as acres burned. Fedkiw (1965) compared fire program expenditure levels from 1945 to 1964 to acres burned across the entire nation. Years were separated into two classes: those with more than 90,000 acres burned and those with less. Marginal cost curves which showed the added fire program cost per acre of reduced burning were calculated from the data. Winkworth and others (1981) compared the increases in fire program funding in North Carolina to reductions in the timber value lost to fire. The 4 years analyzed were all severe fire seasons that were adjusted into closer comparability using the average burning index for the year. Benefit-cost ratios were calculated from the cost and net value changes. The Oregon State Department of Forestry (1972) conducted a similar study based on a comparison of fire program funding levels to changes in the net value of resource outputs caused by fire. The C + NVC or cost-plus-loss criterion was used in that analysis.

These historical studies have a strong appeal because they stand on true empirical data which, with all of its reporting weaknesses, have certain advantages over simulation model results. They have two important weaknesses. First, a large number of important parameters, such as fire weather and fire occurrence levels, cannot be controlled because they vary within a year and between years. Fire program funding is not the only variable. Even with the adjustments for burning index or the stratification of areas by acres burned, too many important parameters are still uncontrolled. The difference in acres burned cannot be attributed to changes in fire program funding alone.

Second, the historical analysis is restricted to fire program funding levels and program compositions which have actually occurred in the past. This is a limited subset of the potential program options that should be evaluated, yet there is little basis in the historical models to extrapolate the results to other fire program options or to other fire years. The historical approach may provide a rough approximation of the efficiency of past expenditures, but it is insufficient for the broad-scope screening of future fire program options.

There have been studies of separate components of the fire management program, such as fuel treatment or initial attack, but few attempts to incorporate all major fire program components into the same model. Without that integration, trade-offs cannot be evaluated. Trade-off analysis is a major function of the screening process in a broad resolution fire economics evaluation system.

Fuel treatment program options were studied by Hirsch and others (1979) in the Southwest and by Barrager and others (1982) in the Pacific Northwest. Both of these studies used a decision-tree approach. Nodes on the tree reflected the probabilities that various fire behavior conditions would occur and that certain fire sizes would result. Wood (1978) studied fuel treatment programs in the northern Rocky Mountains. The effectiveness of fuelbreaks has been evaluated by Davis (1965) and Omi and others (1981).

The FOCUS model was designed to evaluate alternative initial attack programs (Bratten and others 1981). Although it was constructed for a more site-specific or location-specific application than is best for the low-resolution, subregional analysis, certain of the design characteristics of FOCUS are relevant to lower-resolution models. Modifications of FOCUS which reduce its site specificity can be made by replacing the transportation network and historical fire data with direct travel time estimates to sample or representative fire locations (Lehto and See 1981). This reduces the cost of FOCUS implementation, but retains the rigor of its fire containment simulation. The study of initial attack fire programs on six National Forests by Schweitzer and others (1982) used FOCUS to assess initial attack options. Procedures for fire effects and resource value considerations were added to derive the net value change for each program option. The stochastic nature of the fire system was recognized by evaluation of three historical fire years which varied in fire season severity.

The study of the fire program on 41 National Forests (U.S. Dep. Agric., Forest Serv. 1980) is the most complete subregional analysis of fire management program options to date. The analysis model used in the 41-forest analysis was refined and is now contained in a draft fire planning handbook for use on all National Forests (U.S. Dep. Agric., Forest Serv. 1982a). The resolution of the handbook model is higher resolution, especially more site-specific, than the subregional-resolution being considered here. The fire effects and resource valuation procedures in the handbook are similar to those used by Schweitzer and others (1982), but the initial attack evaluation process is quite different. Fire program performance in the handbook model is evaluated against "representative" fire locations rather than each historical fire location. Most of the major behavioral relationships, such as fire effects and fire behavior, are assumed to be homogeneous over the area assigned to the representative location, which has been as large as 18,000 acres in some applications. The handbook model was also applied to several state protection areas throughout the country (U.S. Dep. Agric., Forest Serv. 1982b).

Although the fire planning handbook is well suited to answer some program planning questions at fairly high-resolution levels, it is primarily designed to evaluate the initial attack component of the fire program using an expected value analysis. Fuel treatment alternatives are not fully included in the analysis model nor are escaped-fire suppression alternatives. The latter omission is particularly important because the differences in cost among suppression alternatives can be high enough to outweigh changes in the presuppression program cost. Failure to evaluate suppression alternatives can lead to selection of a larger-than-optimum presuppression program.

These past fire planning efforts contribute greatly to the design of a fire economics evaluation system for subregional analyses. No existing model, however, provides the information needed at the targeted analysis resolution. The capability of calculating risk consequences, in particular, is missing. Risk is not adequately displayed in expected value analyses or in the analysis of selected historical years that have varying fire season severity but unknown probability of occurrence in the future. Yet, the concern over low-frequency severe events greatly influences fire program decisionmaking. The capability to evaluate trade-offs between major fire program components, especially fuel treatments, initial attack, and escaped fire suppression, is also largely missing from currently available models. Another weakness in current models is reliance on an overly generous homogeneity assumption in the description of the fire program areas. This in turn ignores important variability in fire behavior, suppression effectiveness, and fire effects, all of which are critical in the selection of a fire management program option.

These conclusions do not imply that past studies and exisiting models are not useful for the purpose toward which they were directed. They do not, however, fulfill all of the needs of a subregional fire management analysis that can screen a wide array of fire program options to identify a subset that warrants high-resolution analysis.

OVERVIEW OF FEES

The proposed Fire Economics Evaluation System (FEES), once it becomes operational, will meet most of the fire management analysis information needs at the subregional level of resolution. The subregional resolutions correspond to the fire management analysis Level I as described by the Fire in Land Management Planning Task Force (U.S. Dep. Agric., Forest Serv. 1979a) and Mills (1982), the broadest resolution analysis relevant to an individual land and resource planning unit. A brief overview of the system is provided here to place the detailed description that follows in better perspective.

FEES is a simulation model, an appropriate format because empirical data are not available to evaluate all of the fire management programs that should be investigated. The limited empirical data that are available are used to construct the basic behavioral relationships within the model. Those underlying behavioral relationships are then interrelated in different combinations to simulate the performance of a fire management program option that may never have been applied to a particular fire management situation.

The eventual user of FEES will be a program analyst or fire program planner who will provide two types of input (*fig. 2*). One input is a general description of the *fire management situation*; that is, the characteristics of the subregional area that influence fire program performance. The other is a general description of the *fire management program options* being evaluated for that area.

The output from FEES for each fire program option evaluated meets all the major information needs described earlier. Two FEES outputs are the expected value C + NVC and expected value physical change in resource outputs by resource category. The third output is the probability distributions about each of the two expected value outputs. The probability distributions permit an assessment of risk.

To produce these outputs, the user inputs are translated within the FEES model into (1) descriptions of strata within the fire management situation, and (2) a list of the pool of fire management inputs. The more detailed strata are needed to drive the behavioral relationships found within the simulation components or modules internal to FEES. The model simulation then progresses through these modules for each fire management situation stratum, from estimating fire behavior through the assignment of per-unit resource values. The outcomes are then weighted for each stratum by the probability of fire occurrences in

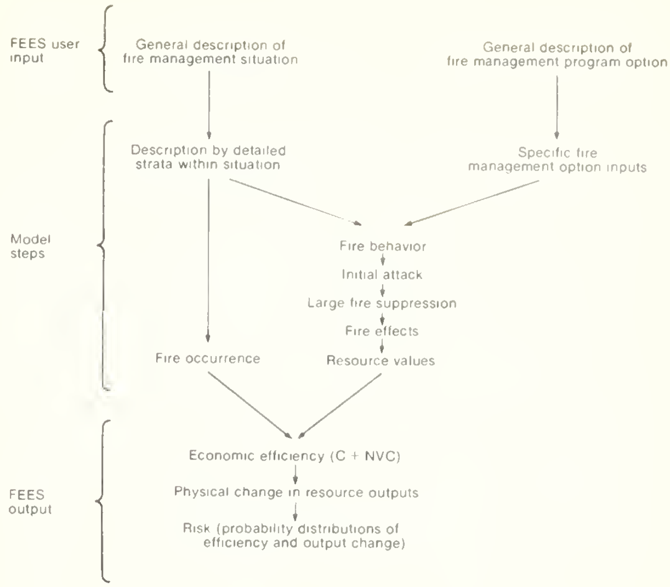


Figure 2—The Fire Economics Evaluation System diagrammed to simplified form shows model input, primary processing steps, and output for one subregional area.

that stratum and summed together to yield the results for the fire management situation as a whole.

The inputs supplied by the user to FEES are described in more detail in the next section, which is followed by a discussion of the actual output FEES will yield. The input and output are discussed together, before the actual structure of the simulation model is described, because in large part they determine the functions the model must perform.

INPUT SUPPLIED BY USER

As indicated earlier, the two major user-supplied inputs to FEES are descriptions of the fire management program option being evaluated and the fire management situation to which the program is being applied. These user-supplied inputs are different than those supplied by the model builder. The model builder provides all behavioral relations within the model, such as the fire growth and fire containment algorithms, and all data relevant to that fire management situation, such as per unit resource values and fire occurrence frequencies.

Fire Management Program Options

FEES includes the capability to evaluate alternatives of three major components of the fire program—fuel treatment for hazard reduction, initial attack, and large fire suppression. Together, these account for the vast majority of fire program funding, approximately 80 percent on National Forest land in fiscal year 1979 and similarly high proportions in other Federal and State wildfire organizations. Two of the three selected program components, fuel treatment and initial attack, are part of the planned or presuppression funding, and the other component, large fire suppression, is usually funded on an emergency basis.

The fire prevention and fire detection program components are not evaluated in FEES because it is difficult to estimate their influence on overall program performance. Both components are funded at relatively low levels. In using empirical data on fire occurrence frequencies and fire size at time of detection, the past performance of the two components is assumed to be constant.

If desired, prevention and detection could be evaluated with a break-even analysis. For example, the maximum increase in prevention funding that would be justified by a 10 percent reduction in fire ignitions could be determined. This break-even information would permit a fire program specialist to judge whether the fire ignition reduction could be accomplished for less than that break-even increase in funding.

Only fuel treatments undertaken for hazard reduction are included in FEES. Fuel or vegetation management treatments applied primarily for other objectives, such as wildlife habitat improvement and site preparation, should be evaluated with those respective programs rather than with the fire program. This is a boundary condition in the design of FEES rather than a land management planning constraint. The results of all programs should be combined and analyzed again in an integrated land management planning model like FORPLAN (Johnson and others 1980).

Each fire program option is described by three parameters—presuppression program funding level, presuppression program mix or composition, and large fire suppression strategy. Presuppression *program level* is the total dollar amount available to build the program and is expressed as true economic costs rather than budgetary dollars. Accounting systems were established for accountability rather than for tracking true economic costs yet economic costs are required in the estimation of economic efficiency. The costs of all fire management inputs are annualized, even the durable inputs that are purchased with a single year's appropriations. If the cost of durable inputs were not annualized, the fire program selection would be biased toward inputs with a useful life of 1 year or less. The program level should encompass all presuppression inputs available for the entire area rather than only the inputs supplied by any one agency. The relevant point at the subregional resolution level of FEES is identification of the optimum total fire program, however optimum is defined.

The presuppression *fire management mix* describes the composition or emphasis of the program constructed with the program level. For example, one program mix may emphasize initial attack with ground crews while another may be more heavily weighted toward broadcast fuel treatments. Each of these fire management programs has a different and unique production function, or influence on program outcome, so each must be evaluated separately. One approach which might be followed to implement the fire management program mix notion is to describe mix as the proportion of total dollars allocated to each type of fire management input, such as smokejumpers and engines (Hunter 1981a).

In the past, fire program analyses have not included a rigorous evaluation of fire program mix as such. As a result, fire program descriptions have tended to be too general or too detailed. There has been an apparent assumption that the most efficient program mix was obvious and that finding the most efficient program level was the only problem. Since it is our contention that the most efficient mix is no more obvious than the program level, it is an important dimension of the FEES design.

Consistent with FEES' subregional resolution, the fire management inputs available for initial attack are described by a few categories in FEES (Gonzalez-Caban 1981). For example, all engines are described by three size classes and hand crews are generally described either as Category I or Category II-IV. The fire program inputs in each category are described by the average cost and production rates for the class. A finer distinction among inputs is not justified at this level of resolution.

A note on terminology—the entities which construct fireline or accomplish fuel treatments are termed "inputs" here rather than "resources" even though the latter is the term more commonly applied by fire program personnel. The term "inputs" is used to distinguish them from natural resources, such as timber and livestock grazing.

The total pool of program inputs available for large fire suppression is essentially limitless. Within the constraints of delivery time, fire suppression inputs can, and are, literally drawn from all over the country and from inputs commonly used for other land management activities, such as timber inventory or brush disposal. The relevant question then is not how many suppression inputs should be made available, but rather how many should actually be requested and how should they be used in large fire suppression? In short, what is the most efficient *suppression strategy*?

Both the presuppression management mix and large fire suppression strategy can and should be treated as variables for a given fire management situation. For any one overall mix and strategy evaluated, however, it may be necessary to apply them differentially by strata within the fire management situations. These differences in fire management input use can be reflected through internalized rules for dispatching personnel and equipment to fires.

Fire management inputs should only be used for large fire suppression if they lead to a more than offsetting reduction in the fire-induced net value change in resource outputs, provided economic efficiency is the objective. If suppression input use is not evaluated on this basis, an overly aggressive suppression strategy will lead to unsupportably high suppression costs for all large fires. If suppression strategy is overly aggressive, the presuppression program funding could be elevated above the optimum level simply to avoid high suppression costs. In the last analysis, the cost of all fire program inputs must be compared with the changes induced in the net value of resource outputs, not simply the reduction in other program costs.

Since presuppression fire management mix and suppression strategy have a major influence on the program's underlying production function, and therefore the C + NVC relationships, they are included in FEES. Each program option is defined by a specific combination of these three parameters supplied by the user. Those combinations must be varied systematically to trace out the full set of relevant options.

Fire Management Situation

The fire management situation evaluated in FEES is not a real area in the site-specific or location-specific sense. It is not an actual piece of land. Rather, it is a hypothetical area which is representative of a group of real areas. The fire management situation is a "kind of area." It captures the essence of the real areas in the parameters which describe the fire management situation. Only those characteristics which influence fire program performance are embodied as parameters to distinguish one fire management situation from another. They are very much "situation-specific" then, even if they are not site-specific.

This type of abstraction permits us to accomplish the low-cost screening of fire program options without sacrificing knowledge of planning area characteristics which influence fire program performance. The data required in the fire management situation model building may be taken from samplings of the real areas but this approach avoids the wholesale duplication of data collection and analysis of real areas even though they are in essence the same, i.e., they show similar performance patterns. Ownership delineations are ignored in the fire management situation just as agency delineations are ignored in the fire management program option. Basic questions about program performance must be addressed at this first low-resolution analysis. The incidence of benefits and costs should be addressed later.

The situation-specific nature of a fire management situation is really no different from the development and use of timber yield tables. The most important independent variables in yield tables, such as site index, species, and age, are identified in a data set drawn from some sample area and the yields corresponding to each combination of those variables are estimated. Those yield results are then extrapolated to any area which is similar in the describing parameters of site index, species, and age.

The seven parameters that describe a fire management situation are fire climate zone, acreage, resource management emphasis, topography class, vegetation class, person-caused fire occurrence level, and lightning-caused fire occurrence level (Bratten 1981b). Fire climate zones are contiguous geographic areas which have similar synoptic weather types associated with critical fire weather (Schroeder and others 1964). There are 14 climate zones in the United States, varying in size from the smallest in southern California to the largest in the Southeast, which includes seven States and portions of several others. The climate zone is the only fire management situation parameter that indicates geographic location. It also is an important index of weather conditions. The other parameters are situation-specific only.

The fire management situations are all assumed to describe hypothetical areas of 1 million acres but once FEES is operational, it will include an algorithm to adjust results for larger and smaller areas. Economies related to scale, as well as the indivisability of some of the high-cost fire management inputs, will require some form of nonlinear scale adjustments.

Resource management emphasis is framed broadly, for example, to distinguish a commercial timber management objective from a wildlife habitat and dispersed recreation objective. The resource management emphasis class is the vehicle by which the land and resource management objectives are addressed within FEES. The management emphasis, in combination with the vegetation class, is linked to decision rules within FEES, such as timber rotation ages, livestock grazing levels, and action taken in response to sedimentation problems. The without fire time stream of resource outputs is a much more direct articulation of resource management objectives than a transformation of that output objective into an acreage burn standard.

There is a long history of resource management on both public and private lands. Private management actions can be observed even if the objectives behind those management actions are difficult to determine. Observed management actions permit the selection of a resource management emphasis class in FEES.

Topography and vegetation can be described by any one of a number of available classification schemes. The fire occurrence level provides a partial measure of fire program workload. This design produces a FEES which evaluates fire program options for individual fire management situations. Most National Forests or State protection areas are probably composed of several fire management situations. The correct way to join the situations and their respective optimum fire programs is beyond the scope of this design, but it is largely a question of how to model the sharing of fire management inputs between areas.

Time Horizon

Two time horizons are relevant in FEES one for fire program planning, another for the time over which fire effects are measured. The program planning horizon is 10 years. This 10-year horizon is addressed in FEES by repeating the 1 year fire program performance for 10 years. Because weather and fire occurrences are treated as probability distributions, the simulation of the first year's fires is actually a simulation of all possible combinations of fires that could occur in 1 year. The results from that first-year analysis are valid for the planning area as long as the characteristics of the program option and fire management situation remain unchanged. Those characteristics are assumed unchanged for 10 years in FEES. If, on the other hand, the underlying makeup of the fire management situation changes, the optimum fire management program changes in turn, and a separate analysis must be made. It is easier, and probably adequate for most purposes, to apply FEES to the changed situation when it occurs rather than construct a dynamic model that simulates the changes over time.

The time horizon for the fire effects calculation is long enough to encompass all of the net change in resource outputs that results from the fires that occur in the single simulated year. This period is only a few years for range output effects, since postfire grazing levels quickly approach the prefire level after a fire of moderate intensity. The time horizon of timber effects is probably the longest. The change in timber output from the loss of an immature timber stand does not occur until the time when the burned stand would have been harvested, some 60 to 100 years in the future for some species, sites, and ownerships.

OUTPUT PRODUCED BY FEES

FEES produces output on three separate decision criteria: economic efficiency, change in resource output due to fire, and risk. This output is displayed in such a way that program planners using FEES can also draw inferences about the incidence of program costs and benefits. The output includes data that can be used in consistency checks between the FEES analysis at the subregional resolution and subsequent higher resolution analysis, using more site-specific models. Each of these classes of output is developed for each program option applied to each fire management situation.

Economic Efficiency

FEES provides C + NVC estimates for each program option evaluated. Recall that C + NVC is the sum of presuppression costs, suppression costs, and the net fire-induced change in the value of resource outputs. The minimization of C + NVC is a correct economic efficiency criterion and leads to the same program selection as present net worth maximization. The application of C + NVC differs, however, from that used for economic efficiency criteria. Accordingly, the data required for the C + NVC calculation and interpretation of the C + NVC values also differ.

Typically, benefit-cost ratio or present net worth calculations for a total resource management program compare the costs and benefits of the *program* to the costs and benefits of having no management program at all. This "with" versus "without" program calculation is not feasible for fire management, because it is not possible to estimate how large and damaging fires would become if no fire management program existed.

Instead, with the C + NVC criterion, the resource outputs with the fires are compared to those without the fires. The net value change is calculated by subtracting the present value of the estimated time stream of resource outputs without the fires from the present value of the resource outputs assuming fire occurrence corresponding to a particular program option:

$$\text{net value change} = \sum_{i=1}^{n} (Q_{1i} - Q_{2i})\, V_i$$

where

Q_1 = resource output without fires
Q_2 = resource output with fires
V = per unit value
i = resource category

The net value change, therefore, corresponds to the net "loss" in the value of resource outputs. The "without fire" time stream of output provides a common benchmark for comparison. There is no implication that the without-fire benchmark is any more desirable than any other, nor that exclusion of all fires is even feasible. The net value change is a margin between two time streams of resource output, but it is not a margin which results from adding an increment of program input.

The cost component of C + NVC, on the other hand, is the total economic cost of the particular program option being evaluated and not the incremental cost between the program level and the cost of a program which would exclude all fires. Therefore, the C + NVC criterion is not a marginal efficiency criterion in a strict sense since a single C + NVC calculation does not estimate the efficiency of a marginal change in the program.

One implication of this C + NVC nature is that a single C + NVC calculation provides no efficiency information (Mills 1979). The C + NVC of successive program options must be compared; the program option with the lowest C + NVC is the most efficient. The increase in the present net worth associated with the incremental change in the fire management program equals the difference in the C + NVC's. Thus, a true marginal efficiency measurement can be derived by comparing separate C + NVC calculations even though efficiency conclusions cannot be drawn from individual C + NVC estimates.

Defining a program option as a composite of program level, fire management mix, and suppression strategy implies that instead of a single C + NVC curve, as shown in *fig. 1*, there is a whole family of C + NVC curves. If suppression strategy is held constant and program level and fire management mix are varied, a family of curves result, such as the hypothetical set shown in *fig. 3*. The objective of the efficiency analysis is to trace the loci of minimum points shown by the dashed line. The production function of the fire program for each fire management mix eventually encounters diminishing returns as the program level is increased and another fire management mix becomes more efficient. If the suppression strategy is varied too, each of the C + NVC curves for separate fire management mixes in *fig. 3* further expands into a family, one curve for each suppression strategy and fire management mix combination.

The foregone present net worth of a fire program budget constraint can be derived from these curves. If the fire program level is constrained at PL_2 (*fig. 3*), the foregone present net worth of a program planning horizon application of the fire program option is $(C + NVC)_2 - (C + NVC)_1$. Similarly, if PL_3 and fire management mix 3 are selected to achieve environmental benefits to which dollars are not assigned, the implied minimum value of the environmental outputs is $(C + NVC)_3 - (C + NVC)_1$.

The three descriptors of the fire management program (program level, fire management mix, and suppression strategy) are incorporated in the FEES design because of the hypothesis that, under certain conditions, each influences economic efficiency. There is limited empirical evidence to date to test this hypothesis because there are only a few studies in which the fire management mix was varied at all and none in which the suppression strategy was systematically varied as well. The fire management analysis on 41 National Forests (U.S. Dep. Agric., Forest Serv. 1980b) contained program level variations but relatively small fire management mix changes. No consideration was given to alternative large fire suppression strategies.

Holding suppression strategy constant for the sake of illustration, four possible C + NVC relationships can be hypothesized. First, both program level and fire management mix may influence the shape of the C + NVC family and, therefore, the fire program efficiency (*fig. 3, 4A*). Second, program level may be important while program mix is not (*fig. 4B*). Third, program mix may be important while program level is not (*fig. 4C*). Finally, there may be situations where neither has a major influence on economic efficiency (*fig. 4D*). The limited evidence available from the 41-Forest analysis lends support for all four hypotheses for different areas of the country. If the hypothesized conditions depicted in *fig. 4B and 4C* are substantiated for a given area through the FEES analysis, the subsequent site-specific analysis conducted with a high-resolution model can center even more closely on the important variables. If the conditions in *fig. 4D* are substantiated, a more detailed site-specific analysis is not needed unless changes in resource outputs or risk are differentially affected by the program level or mix. Since we cannot determine, at this time, which condition will fit a particular fire management situation, FEES is designed to evaluate variations in all three program descriptors.

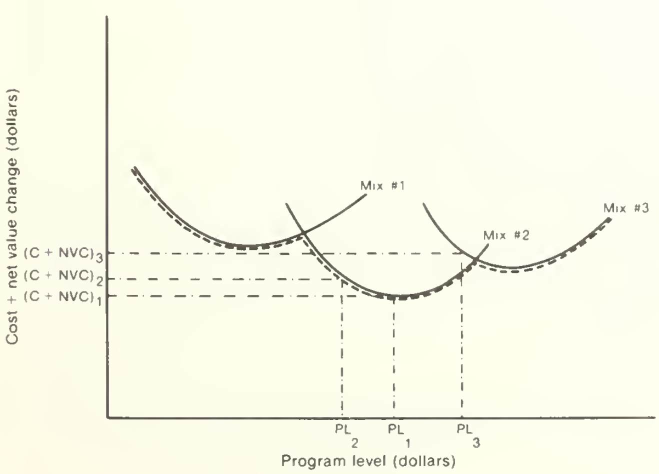


Figure 3—A family of cost plus net value change curves might result from various fire management mixes.

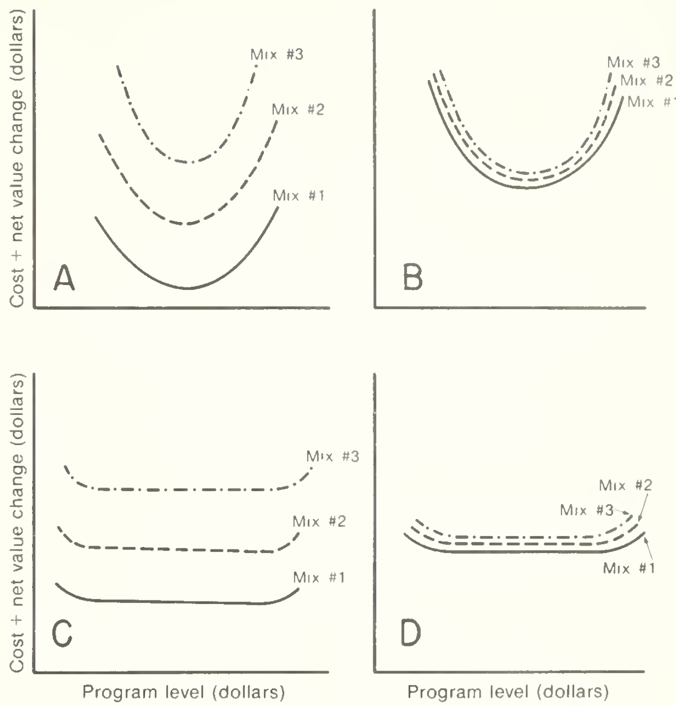


Figure 4—Curves for cost-plus-net value change are shown for four hypothetical conditions: *A*, both program level and fire management mix influence economic efficiency; *B*, program level influences economic efficiency but fire management mix has a minor impact; *C*, fire management mix influences economic efficiency but program level has a minor impact; and *D*, neither fire management mix nor program level have a major impact on economic efficiency.

Resource Output Changes

FEES provides estimates of fire-induced changes in resource outputs over time for each program option tested. The net change is the resource output "without" the fires minus the output that will occur "with" the fires simulated to occur with that program option. For example, if the net change (net loss) in timber output with program option A is

10 million board feet and with program option B is 7 million board feet, the marginal increase in timber output achieved in moving from fire program A to B is 3 million board feet.

FEES provides net output change estimates for timber, range, water, wildlife and fish, recreation, and improvements—all of the outputs to which dollar values are assigned in the net value change calculation. The C + NVC calculation is actually built from an even finer resource stratification since fire effects and resource values vary considerably within these broad resource categories. The time stream of the net change in output is needed for discounting in the net value change calculation, so the time stream of output change is reported separately.

Risk Assessment

The risk embodied in any program option is displayed through the probability distributions about the expected values of C + NVC and resource output changes. The sources of the variability are mostly fire weather, fire occurrence levels, and the location of fire occurrences (Bratten 1981a). Additional variability originates in estimates of fire size at time of detection (Salazar 1981), elapsed time between detection and first arrival of initial attack (Hunter 1981a), and large fire suppression effectiveness (Hunter 1981b).

Risk exists if an outcome is variable, but the outcomes vary with a known probability distribution (Knight 1965). Uncertainty exists if the variable outcome cannot be described with a probability distribution. An example of risk is fire occurrence, which varies significantly from year to year, but the probability can be fairly well predicted from historical fire occurrence frequencies. The probability distributions for the major fire system variables can be similarly defined empirically. This is an example of a risk situation. The distributions of other important variables, however, such as large fire suppression effectiveness, are much more difficult to derive. They interject an element of true uncertainty. Although probability distributions about the FEES model outputs are treated if they are known, an unmeasurable amount of uncertainty remains.

Program options which minimize the expected C + NVC lead to the greatest long-run efficiency. Decisions based on expected values are valid if the estimated net value change accurately reflects the disbenefit associated with infrequent but very severe fires and if all of the probability data accurately reflects the likelihood of those severe fires.

If, however, the survival of society itself were at stake, the appropriate per unit value for the net change in resource outputs approaches infinity rather than the per unit resource value which is used in FEES. Under that situation, a risk-averse selection is justified on the implied assumption that there is measurement error in the FEES per unit resource values. A risk-averse selection is also justified if the fire-induced loss is large in relation to the total size of the society, that is, if there is a cash flow problem. If the probability of the severe event is thought to be underestimated, the decisionmaker may also make what appears to be a risk-averse decision. In reality, the decisionmaker is acting under conditions of uncertainty rather than risk. Expected-value decisions are also not proper if the group that the decisionmaker represents is not risk-neutral. Furthermore it is doubtful that wildfire has a truly "catastrophic" nature which would threaten society (Blattenberger and others 1982).

Whatever the risk preference may be, the extent of risk embodied in a fire program must be explicit. The degree of risk preference should not be embedded in the analytical procedures themselves, such as through model builder adjustments of discount rates, or some subset of the total variability in an important parameter, such as the 90th percentile weather. The probability output of the FEES model permits the decisionmaker to measure explicit trade-offs among the economic efficiency, resource output change, and risk consequences of each fire program option so as to treat risk as a separate decision criterion.

There are several ways to display the risk dimension. One way is to describe the expected value C + NVC curve for a particular fire management mix and also the curves that trace the 90th percentile probability band or envelope about the expected value (*fig. 5*). Our hypothesis is that the C + NVC probability distribution narrows about the expected value as the program level increases. Greater initial attack and large-fire suppression capability is available at higher program levels to more completely control severe fires when they occur.

Another way to display risk is to calculate the difference in C + NVC between the expected value and the top end of the 90th percentile probability band, D_1 in *fig. 5* at PL_1. That difference could be shown as a percentage of the expected value C + NVC for that program level, $(C + NVC)_1$ in *fig. 5*. The "risk percentage" R for PL_1 in *fig. 5* is then:

$$R_1 = \left[\frac{D_1}{(C + NVC)_1}\right] 100 \text{ percent}$$

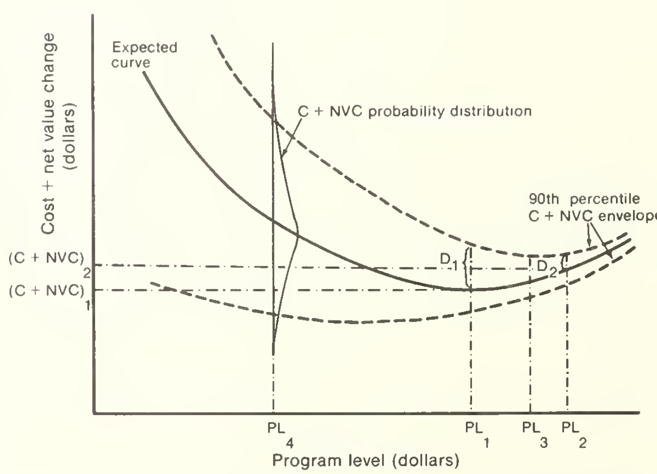


Figure 5—Trade-off between economic efficiency and risk is diagrammed at four program levels.

A risk-averse decisionmaker may choose PL_2 instead of PL_1. This could result from a conscious decision that the reduction in risk from R_1 to R_2 is more valuable than the foregone efficiency, $(C + NVC)_2$ minus $(C + NVC)_1$. This simple difference between the two C + NVC's is the risk premium, the reduction in efficiency that the decisionmaker must pay to achieve a lower risk level.

A more complete way to display the risk is to select points from the cumulative distribution of C + NVC (*fig. 6*). A hypothetical cumulative C + NVC distribution is shown in *fig. 6*, with an expected value of $(C + NVC)_{ev}$. Three additional C + NVC values can be calculated in relationship to the expected value—one 50 percent as large, $(C + NVC)_1$, one 150 percent as large, $(C + NVC)_2$, and one 200 percent as large, $(C + NVC)_3$ as the expected value. The corresponding values from the vertical axis show the probability that a C + NVC of that size or smaller would result from the application of the fire program option which was evaluated—P_1, P_2, and P_3 in *fig. 6*. Another way to display risk is to compare the mean and variance of any program outcome with the parameter preference utility function of mean-variance trade-off (Blattenberger and others 1982).

The FEES probability output can be used to identify the most efficient program option in a high- or low-severity fire year. As Schweitzer and others (1982) found in their analysis of six National forests, the most efficient fire program level in a high-severity year is sometimes larger than in a low-severity year. In our hypothetical example in *fig. 5*, the most efficient program for the high-severity end of the 90th percentile band is PL_3, that is, the program level with the least C + NVC. The most efficient at the low end of the probability band is PL_4. If reliable estimates of the current year's severity could be made, this information could be used to adjust the presuppression programs during a fire season.

The probability information may also help distinguish between the occurrence of a low frequency but severe fire

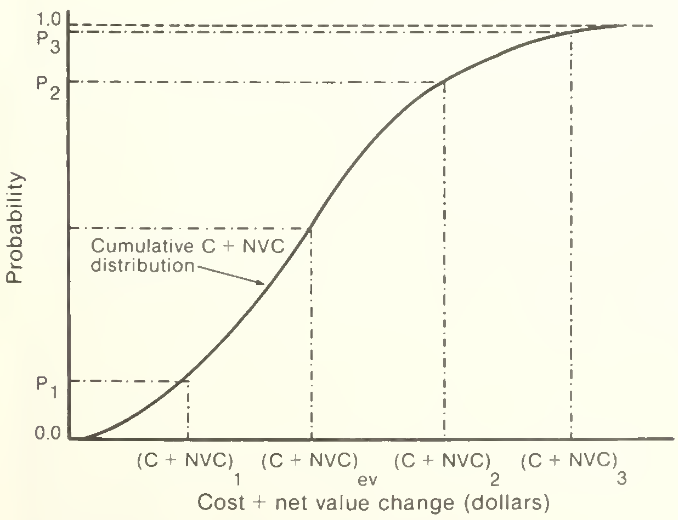


Figure 6—Risk can be displayed by selected points on the cumulative probability distribution of cost plus net value change.

season from a poor program decision, that is, to distinguish bad outcomes from bad decisions. High fire losses do not necessarily mean that someone made a program mistake any more than a severe earthquake does. Some severe fire conditions are beyond our technological capability of control and our ability to predict.

Inferences About Program Effects

It is possible to infer from the FEES output certain information that is not produced directly or in detail. The incidence of fire program effects—the number and kind of people who are affected—can be inferred from the C + NVC components, which indicate how much each group pays for or benefits from the program. The new value change component also shows the incidence of the program on user groups, such as the timber industry and recreationists. The fire program planner could also estimate the program-induced employment and income change by applying appropriate multipliers to the estimates of resource output changes.

Some of the FEES output also permits a fire program planner to draw inferences about environmental effects that are not valued in dollars. One intermediate model output, the probability distribution of fires by fire size and fire intensity classes for each fire program option, indicates whether such effects are likely. Long-term effects on soil productivity, for example, may be positively correlated with fire size and fire intensity in certain soils and slopes, and air quality deterioriation may be related to the same parameters. Inferences about the extent of these effects are possible even though the FEES output does not include complete data.

Output Display

A full display of the major decision parameters provided by FEES would be large and difficult for the fire program planner or decisionmaker to assimilate. A full display would contain C + NVC and resource output change estimates, both as probability distributions and over time, and the probabilistic fire size and intensity for each program option evaluated.

One solution to this overabundance of information is to display only a subset of the decision criteria. The abbreviated FEES output contains the expected values for all components of C + NVC; the expected change in resource output by resource category; the 90th percentile risk percent; and selected points on the cumulative probability distribution of C + NVC (*table 1*). The probability distributions for the resource output changes and the time dimension can be shown separately (*tables 2, 3*) along with the results on fire size and fire intensity (*table 4*).

A second solution to the output display problem is to include full output sets in a simple linear programming or goal programming optimization module, where the output parameters could be assimilated into one objective function. The optimization module would help the decisionmaker understand the implications of the relative weights

Table 1—*Economic efficiency, risk, and changes in resource output per million acres from applying selected fire management program options for 10 years in:*

Fire management situation ____________________

Fire management program option			Cost-plus-net value change									Change in resource outputs[4]								
Program level (Dollars/ million acres)	Fire management mix	Suppression strategy	Expected[1] value				Cumulative probability for expected value fractions[2]				Risk[3]									
			A	B	C	Total	≤0.50	≤1.00	≤1.50	≤2.00		D	E	F	G	H	I	J	K	L
			Thousand dollars								*Pct*									
PL_1	FMM_1	SS_1																		
.	.	.																		
.	.	.																		
.	.	.																		
PL_n	FMM_n	SS_n																		

[1]A = Presuppression cost
B = Suppression cost
C = Net value change

[2]Probability that cost-plus-net value change less than or equal to the various proportions of the expected value of cost-plus-net value change will actually occur.

[3]Difference between 90th percentile cost-plus-net value change and the expected value of cost-plus-net value change as percent of expected value of cost-plus-net value change.

[4]Net change in output without fire minus output with fire; therefore, positive net changes are "losses" and negatives are "gains." Outputs are:
D = Timber (thousand cubic feet)
E = Range (thousand animal unit months)
F = Water (thousand acre feet)
G = Recreation (thousand visitor days)
H = Wildlife (thousand visitor days)
I = Fisheries-sport (thousand visitor days)
J = Fisheries-commercial (thousand pounds)
K = Improvements-public (number of structures)
L = Improvements-private (number of structures)

Table 2—*Probabilities of net changes in resource outputs and net value change in resource output per million acres for a 10-year program*[1]

Fire management situation = ____________________
Program level/ million acres = ____________________
Fire management mix = ____________________

Probability	Timber[2]		Range		Water		Recreation		Wildlife		Fisheries		Improvements Public		Improvements Private	
(proportion)	(MCF)	($)	(MAUM)	($)	(MAF)	($)	(MRVD)	($)	(MRVD)	($)	(MRVD)	($)	(Units)	($)	(Units)	($)
0.25																
0.50																
0.75																
0.90																
Expected value																

[1]Net resource output is calculated from (output without fire) − (output with fire) so a positive net change is a "loss." A net output change less than or equal to the number shown in the body of the table will occur with the specified probability.

[2]See *table 1*, footnote 4, for definition of units.

Table 3—*Expected net changes in resource outputs over time per million acres for a 10-year program*[1]

Fire management situation = ______________________
Program level/million acres = ______________________
Fire management mix = ______________________

Time periods	Timber[2]	Range	Water	Recreation	Wildlife	Fisheries	Improvements	
							Public[5]	Private[6]
(year)	(MCF)	(MAUM)	(MAF)	(MRVD)	(MRVD)	(MRVD)	(Units)	
1-5[3]								
6-10								
11-20								
21-30								
31-40								
41-50								
51-100								
101-150								
151-200								
Total[4]								

[1]Change in net resource output is calculated from (output without fire) − (output with fire) so a positive net change is a "loss."
[2]See *table 1*, footnote 4 for definition of units.
[3]Average net change during the time period.
[4]Total net change over the 200-year period as a result of applying the specified fire management program for 10 years.
[5]"X" percent of the losses resulted from fire. "1−X" percent of the loss was from resulting flooding or sedimentation.
[6]"Y" percent of the losses resulted from fire. "1−Y" percent of the loss was from resulting flooding or sedimentation.

among the decision parameters and the implications of program selection constraints. Steuer and Schuler (1978), for example, describe a multiple-objective linear programming model for forest management which was designed to assist the decisionmaker in selecting a program. Schuler and others (1977) also describe some of the characteristics of goal programming and the type of problems it can most efficiently address. For example, the C + NVC of a program option could carry a relative weight of 1.0 in the objective function and the change in recreation output of 2.0. The risk could be handled as an element in the objective function or treated as a constraint to the solution. This is the same mental process the decisionmaker will follow in evaluating FEES model output anyway. An optimizing routine would simply assist in the program option comparison.

Table 4—*Average annual probabilities of fire size and fireline intensity and expected values for number of fires and acreage burned*

Fire management situation = ______________________
Program level/million acres = ______________________
Fire management mix = ______________________

Fire size (acres)	Fire line intensity (BTU/ft)[1] 0-99			100-499			500-999			1000+		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
0.25												
0.25 − .9												
1.0 − 9.9												
10.0 − 99.9												
100.0 − 999.9												
1000.0 +												

[1]X = Probability of that fire size and fire intensity occurring
Y = Expected value (EV) of number of fires/million acres/year
Z = Expected value (EV) of acreage burned/million acres/year

DESIGN OF THE FEES MODEL

The FEES model simulation starts with the user-specified fire program option and a fire management situation. The program option is transformed within FEES into a list of fire management inputs for the fuel treatment and initial attack components of the presuppression program. The fire management situation is similarly subdivided within FEES into homogeneous strata, defined here as "inferred parameter cells." The inferred parameter cells are described by the parameters, such as slope and cover type, which are needed to determine fire program performance. The simulated progress of fires within each homogeneous cell is traced from the time of fire detection through each one of an interrelated set of behavioral modules until suppression costs and net value change are estimated. FEES contains separate modules for fuel treatment, fire behavior, initial attack effectiveness, large fire suppression effectiveness, fire effects, resource values, and cost calculations. Probabilistic results for each inferred parameter cell are then weighted by the fire occurrence probability in that cell. Similar results from all the cells are summed across the fire management situation, providing the model output for one program option.

One execution of the model for a given fire program option produces one C + NVC point on the family of curves and one line of FEES output for the abbreviated display in *table 1*. Systematic changes of the program option and repeated executions of the FEES simulation trace the full family of C + NVC curves and the full display of model output for one fire management situation.

FEES is designed in a modular fashion. The modules are quasi-independent sets of computations (*fig. 7*). The modules all interact with an underlying probability model that passes inputs and outputs between the various modules, condensing output where appropriate. This model structure permits the model builder to refine behavioral relationships in one module (initial attack effectiveness, for example) without forcing major modeling changes in other modules or in the underlying probability model. Each module receives specified input from the probability model. Using that input, each module performs the necessary calculations to yield the output information required for the next step in the model simulation. The transformation from input to output within each module is largely unencumbered by the rest of the model structure.

Inferred Parameter Cells

The parameters used to describe the fire management situation are kept to a minimum (seven) to simplify the fire program planners' interaction with the FEES model. Areas of 1 million acres are not homogeneous in all the variables that influence fire program performance, however, even if they are fairly homogeneous in the fire management situation parameters. Additional parameters are needed within the FEES model to reflect the heterogeneity within the fire management situations and to drive the behavioral relationships in the modules.

FEES accomodates this heterogeneity internally by stratifying the fire management situation into "kinds of fire sites," termed inferred parameter cells because their composition is inferred from characteristics of the fire management situation. Examples of the parameters that distinguish between inferred parameter cells include slope, aspect, elevation, time of year, time of day, cover type, and cover type age class. Fuel characteristics are inferred from cover type and cover type age class. The net change in timber output and the stumpage price, for example, are much more easily calculated from the cover type inferred parameter than from the more aggregative vegetation class parameter of the fire management situation.

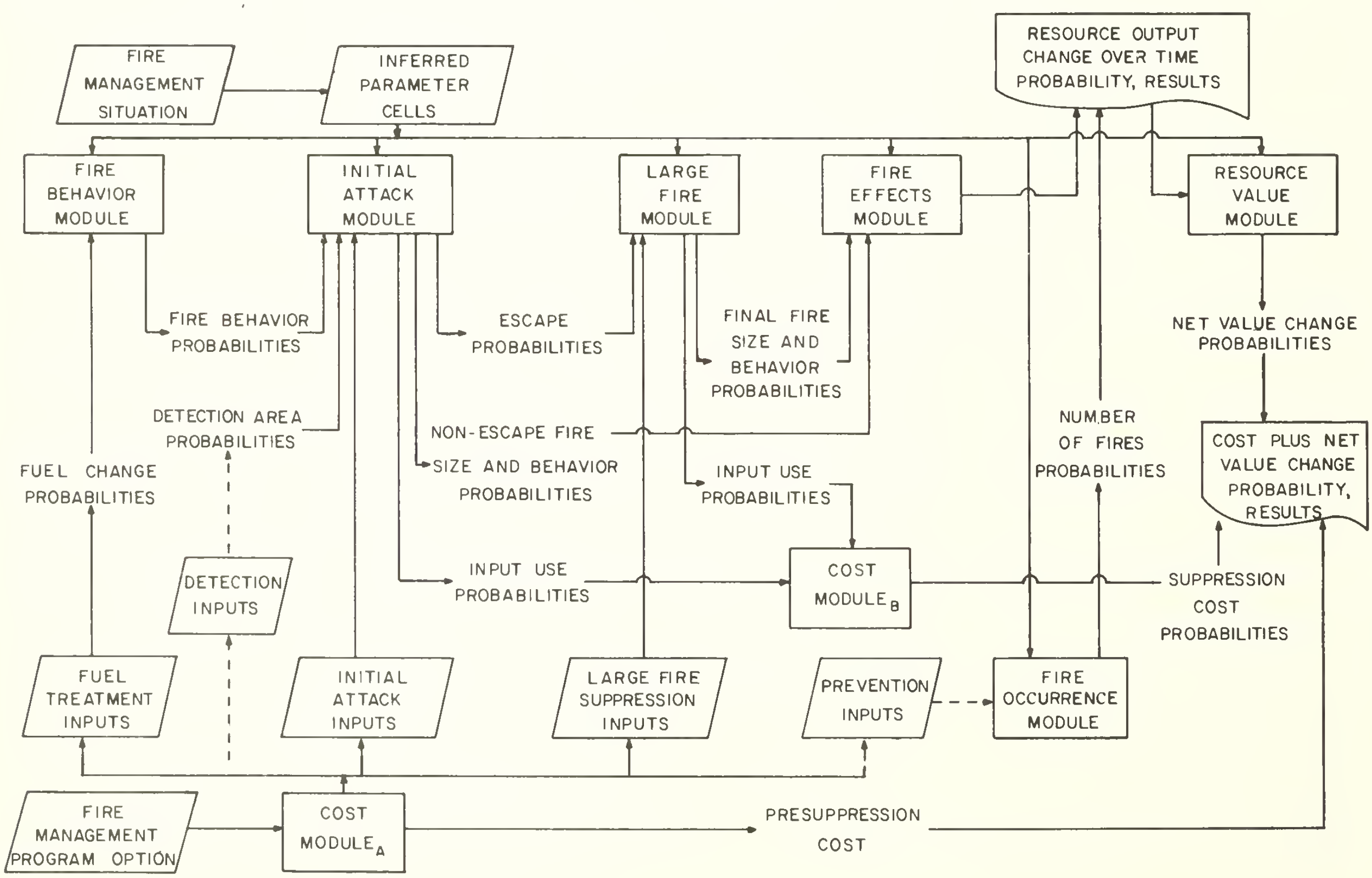


Figure 7—Detailed schematic of FEES shows the modules of this simulation model and their interactions.

An important modeling trade-off is related to the size of the fire management situation. Small fire management situations are more homogeneous. The number of inferred parameters, and classes for each parameter, needed to fully describe the areas for modeling purposes are in turn small. On the other hand, the proportion of the fire management inputs that are shared between fire management situations increases as the fire management situation shrinks. Modeling the probability that shared fire management inputs are available when needed may be as difficult as retaining more heterogeneity in the area description. The optimum modeling size of the fire management situation is related to the true amount of heterogeneity in the area, the amount of fire management input sharing, and difficulty in modeling both of these factors.

The relative frequencies of fires in the various inferred parameter cells within a fire management situation are derived from historical fire occurrence data. The fire occurrences for each cell can be drawn from individual fire reports for actual areas that represent the fire management situation in the fire climate zone. Those same fire occurrence probabilities can be applied to all other areas which have the same fire management situation parameter values. The fire occurrence probabilities for inferred parameters that are not recorded on the fire reports must be inferred from other sources, for example, from acres of certain cover types that are managed for timber production.

The inferred parameter cells, just like the fire management situation itself, are not location- or site-specific but instead are situation-specific. They are hypothetical fire locations just as fire management situations are hypothetical segments of a fire program planning unit. They condense the essence of real fire locations into abstract "kinds of fire locations." They describe homogeneous areas within which "kinds" of fires are simulated from time of detection through containment and on to an assessment of fire effects and resource values. In an actual planning unit, examples of an inferred parameter cell may occur at several locations. This causes no modeling problems, as long as all segments are serviced by the same fire program inputs.

The correct criterion for determining which parameters are needed to distinguish between inferred parameter cells, and therefore kinds of fires, is whether that parameter influences performance of the fire management program. Slope, for example, affects fire behavior, the rate of fireline construction, the cost of silvicultural treatments, timber stumpage prices, peak water discharge, and sediment yield. Similarily, cover type influences fuel model, fireline construction rates, timber yields, stumpage prices, grazing yields and a host of other factors which enter into the C + NVC calculation. Which inferred parameter cell descriptors are finally included in FEES and how many classes are used to represent each parameter is eventually a question of sensitivity of program performance to their exclusion. The logic used above for slope and cover type was used to set the preliminary design of FEES.

The question of site specificity is relevant in this context too. Geographic location is only one parameter that describes a kind of fire. If the behavior of a fire, effectiveness of fire suppression, and fire effects can be determined by the characteristics of the fire site, site specificity provides no additional information for long-term planning. For example, initial attack arrival time is an important input item in the simulation of initial attack effectiveness but it can be drawn empirically from fire report data rather than map locations of fires and initial attack bases.

The output from the respective modules are accumulated and combined at appropriate points through underlying probability computations within the main FEES model. The FEES model produces similar information for each cell. Once joined together by fire occurrence probabilities, that common output provides the output for the whole fire management situation.

Fuel Treatment Module

The amount of fuel treatment activity, by practice or treatment class, is specified in the fire management input list. The fuel treatments are identified by three parameters: pretreatment fuel model, post-treatment fuel model, and method of treatment (Salazar 1981). The Northern Forest Fire Laboratory fuel models (Albini 1976), or groupings of the fuel models if sensitivity analysis demonstrates that the resulting fire behavior does not differ significantly among individual fuel models, are used in FEES. The fuel treatment-induced change in the fuel model "shifts" the treated area from one inferred parameter cell to another based on the change in fuel model. This shift registers within the model through a change in the fire occurrence probability associated with the affected inferred parameter cells. The method of treatment classes are needed for treatment cost estimation.

Only broadcast or broad area fuel treatments, such as the removal of logging slash through mechanical or prescribed burning methods, are included in FEES. Fuelbreak analysis requires juxtapositional information not easily included in a nonsite-specific model. Only fuels management activities directed primarily at hazard reduction are evaluated, although almost any vegetation manipulation has an impact on fire behavior. The total treatment cost should be allocated among the various objectives of the treatment, even though any such allocation rule is arbitrary. Only that portion charged to fire hazard reduction is included in FEES.

Fuel treatments, especially when the method is prescribed burning, do not always produce the targeted post-treatment fuel loadings. In recognition of this variability in fuel treatment performance, the probability of achieving various post-treatment fuel models by means of a given treatment method are included in FEES. A less rigorous modeling approach would be to list only the expected post-treatment fuel model rather than the distribution of actual fuel model outcomes.

Fuel treatments are the only fire management activities that have a major impact on the inferred parameter cell composition of the fire management situation. Many long-term fuel treatment programs can be evaluated within the 10-year program time horizon, but not by repeating the 1-year results for 10 consecutive years. Under certain simplifying assumptions about the nature of the C + NVC change from the initial fire management situation to the situation which exists when all fuel treatments are completed, the efficiency of a multiyear fuel treatment program can be constructed from a sequence of 1-year analyses of different fire management situations.

Fire Behavior Module

The fire behavior module estimates the probabilities of values for the set of fire behavior parameters that are required in the initial attack and fire effects modules (Salazar 1981). The fire behavior parameters required for the initial attack module are forward rate of spread, length-to-width ratio, and fireline intensity. The fire effects module needs scorch height.

The fire behavior values are estimated from inferred parameter cell descriptors and weather variables. The mathematical fire behavior model is adopted from Rothermel (1972) and Albini (1976). Important inferred parameters for fire behavior prediction are slope, aspect, time of day, time of year, and fuel model. Important weather parameters are windspeed and fuel moisture. Since the weather variables are described as probability distributions, the estimated fire behavior parameter values are similarly probability distributions rather than arithmetic means for each inferred parameter cell. This weather variation leads to different "kinds of fires" within each cell.

Fire behavior is simulated from the time of detection until such time as the fire behavior model assumptions of homogeneous fuel, weather, and topography are violated. The fire is assumed to be burning in a steady state at time of detection. The distribution of fire sizes at time of detection are empirically derived from individual fire report forms from the 1960's and then adjusted using data on changes in fire detector classes to reflect subsequent changes in fire detection programs. Use of these historical detection size distributions implicitly assumes the fire detection program is fixed at its historical level and its performance is reflected in the fire size distributions.

When the homogeneity assumptions of the fire behavior model are violated, the fire is identified as "escaped." The fire size at which escape occurs will vary with fuel model and fire climate zone. For example, the contiguous areas of grass fuels are generally larger than areas of slash fuels so the "escape" size is correspondingly larger. The appropriate fire size and burning time homogeneity thresholds can be derived empirically from field studies of the size of homogeneous fuels and terrain, and from homogeneous weather parameters, respectively.

Initial Attack Module

The majority of all fires are contained when they are small, but the few fires which escape initial attack account for almost all of the suppression costs and net value change in resource outputs. The primary objective of the initial attack module then is to estimate the number of escaped fires rather than to model initial attack for its own sake. The initial attack module, as well as the initial attack program, is based on the hypothesis that the percentage of escapes is a function of the size and composition of the initial attack organization. If it were not, the highly dispersed initial attack organization should be disbanded in favor of a more centralized, but highly mobile, large fire suppression organization.

Our hypothesis is that fires can be separated into three subsets by forward rate of spread and fireline intensity. Fires with low spread and intensity can be contained by almost any initial attack organization (subset A) (*fig. 8*). This includes the majority of all fires. Conversely, a smaller set are of such high spread and intensity that they are beyond the technological capability of almost any initial attack organization (subset C). Whether the fires of intermediate spread and intensity (subset B) escape or not is a function of the performance of the initial attack organization.

The initial attack module is constructed to concentrate modeling effort on subset B (Hunter 1981a). Fires in subset A are assigned negligible fire sizes and those in subset C are passed directly onto the large fire suppression module. The proportion of all fires which fall into each subset and the relationship between the initial attack program and escape probability will probably vary by fire management situation.

Using fire behavior input, selected inferred parameter cell values, and the list of the fire management inputs, the initial attack module provides output useful in the fire effects, large fire suppression, and cost modules (Hunter 1981a). The module output is joint probability distribu-

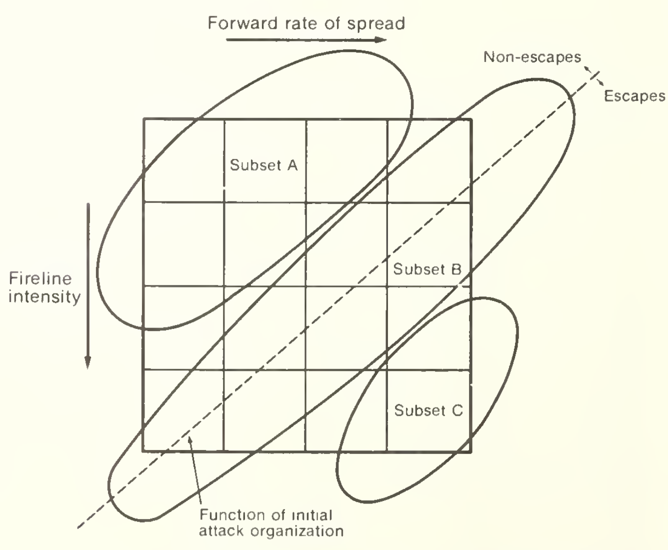


Figure 8—Hypothetical subsets of fire escape potential as a function of forward rate of spread and fireline intensity.

tions of fire size and fire behavior parameters, for the fire effects module; the probability of escape and the fire characteristics at the time of escape, for the large fire suppression module; and the probability of the time that each fire management input is used in initial attack, for the cost module.

The arrival time of attack forces is represented by cumulative distributions of arrival time by fire management input class and fire cause (Hunter 1981b). The arrival time distributions are derived from individual fire report forms (Mees 1981). These empirical arrival time distributions are consistent with the nonsite-specific design of the fire management situation, since information on the juxtaposition between fires and initial attack bases is not required in the derivation or use of the distributions. Historical arrival time distributions are representative of future distributions as long as the location of initial attack bases relative to fire locations does not change over time or with different program options. The arrival time distributions for individual fire management situations can be drawn from a sampling of geographic areas representative of the respective fire management situations.

Rules for dispatching initial attack inputs to fires are drawn from existing preplanned dispatch records and expert opinion. Fireline production rates for various fire management input classes can be adapted from past studies. Because of the wide variability in line production rate estimates (Haven and others 1981), the production rates may be represented as probability distributions rather than point estimates. The distributions can be subjectively derived from an amalgamation of past study results.

One of the more difficult design elements of the initial attack module is the sharing of initial attack inputs among fire management situations or even among competing multiple fires within a single fire management situation. Queuing analysis may provide a method of addressing this problem.

The initial attack module is constructed as a Monte Carlo simulation model. Initiating fire behavior parameters, arrival times, and line production rates are randomly drawn from their respective distributions. Fires which will obviously be small (subset A) or will obviously escape (subset C) are allocated at this point to avoid a detailed computerized simulation of fire containment. The initial attack containment is then simulated mathematically for the remaining fires (subset B) by using a simplified version of the FOCUS containment algorithm (Bratten and others 1981). Repeated draws from the distributions and subsequent containment simulations are made until a sufficient frequency distribution of module output is achieved.

Large Fire Suppression Module

Once a simulated fire burns out of the inferred parameter cell, the homogeneity assumptions of the fire behavior module are violated. The fire is identified as escaped and is evaluated in the large fire suppression module (Hunter 1981b). Mathematical models which simulate large fires require much data, especially on very heterogeneous fuels and topography, and empirical data from past large fires are too fragmentary to allow construction of an empirical module of large fire suppression effectiveness. Recent attempts using expert opinion gaming to evaluate large fire suppression effectiveness have led to questionable results (Joseph 1981), possibly because the escape fire scenario was described in such general terms that the experts actually perceived different situations and, therefore, provided different answers.

Hunter (1981c), by refining Schultz's (1964) approach, proposed to evaluate large fire suppression effectiveness by using a modified version of expert opinion gaming. The experts are only asked to estimate fire behavior and suppression effectiveness for relatively homogeneous time segments of an escaped fire, rather than for the entire fire. The time segments are described by initiating conditions, such as fire size and contained perimeter. Environmental conditions, such as weather, terrain, and fuel model, are also specified and assumed homogeneous throughout the time segment. Given data on the initiating conditions and available suppression forces, the experts provide probabilistic estimates of suppression force usage and end-of-period fire characteristics, such as fire size and contained perimeter.

This expert opinion gaming process, just like the initial attack module, must be exercised using hypothetical "kinds of fires" to remove the dependence on a location parameter. For example, the experts are asked to game burning event scenarios described by a set of representative photographs and maps.

The gaming results from the time segments are then joined together within the large fire module into complete fires from time of escape through containment time using transition probabilities. These are estimates of the probability that the environmental conditions of one time period will change into some other set of environmental conditions for the next time period, for example, the probability that windspeed will be 10 mi/h in period t+1 if it was 5 mi/h in period t. These probabilities can be drawn empirically from weather records and samples of the size of contiguous area of homogeneous fuel and topography areas.

The outputs of the large fire module are probabilistic estimates of fire size at time of containment and fire behavior throughout the fire, both of which are needed in the fire effects module. The module output also includes probabilistic estimates of suppression force usage which are needed in the cost module.

Cost Module

The cost module performs two functions (Gonzalez-Caban 1981). First, it transforms the fire management program option into the list of fire management inputs available for fuel treatment and initial attack activities. Second, it calculates the suppression costs incurred above the cost of inputs already funded through the initial attack portion of the program level.

Although the cost module includes estimates of the true economic cost of the fire management inputs, rather than the costs from a particular accounting system, not all accounting-like rules can be bypassed. This is especially true in the separation of suppression costs from the cost of actions already funded in the initial attack program. This suppression cost separation is important because one objective of FEES is to measure the trade-off between the initial attack and suppression components of the fire program.

Most public agencies fund their initial attack program from beginning-of-year appropriations, and their suppression actions from emergency, supplemental appropriations during the year. Until we can better predict the severity of the upcoming fire season or until the suppression appropriations are treated as a multiyear revolving account, the suppression activities should continue to be financed through supplemental appropriations rather than beginning-of-year appropriations. Since the various public agencies do have different rules for allocating costs among program components, however, a procedure is needed to transform FEES program level into corresponding budgetary estimates.

The major building block for the cost calculations is the per unit cost of each class of inputs. All costs are allocated to the fire program inputs that actually accomplish the fire management activity. For example, the per hour cost of a Category I hand crew is composed of cost components for salary, supplies, training, facilities, and overhead (McKetta 1981). Other inputs, such as smokejumpers, have additional special training cost. The overhead cost is composed of general administrative overhead (GA) and the cost of the fire program management staff. These overhead costs are equally allocated to each fireline personnel. An annualized cost of all facilities is calculated that reflects the true opportunity cost of the input. The annualized cost calculation includes the initial capital cost, useful life, salvage value, and discount rate. Large fire costs resulting from the onsite fire overhead team, mop up, and demobilization are also included as separate entries in the cost module.

Fire Effects Module

The fire effects module provides estimates of the fire-induced change in resource outputs over time from the fires which occur in each inferred parameter cell (Peterson 1981). Inputs to the module include values of the inferred parameters, such as vegetative cover, slope, and management objective, and the fire behavior characteristics, such as fire size, fireline intensity, residence time, and scorch height.

There are important scope restrictions in the FEES fire effects module that have only been alluded to so far. Only resource outputs which can be reasonably valued in dollars are included. Recreational use is included, for example, but fire effects on rare and endangered plant and animal species are not. The resource actually valued is the one affected by fire and used by humans. Wildlife impacts, for example, are registered as changes in the number of days of consumptive and nonconsumptive use of the wildlife resource, rather than as changes in acres of wildlife habitat or changes in wildlife populations. The wildlife populations or habitat are much more difficult to value than user days. Effects on the fire site and direct offsite effects are included, but secondary effects on local employment and income are not. Fire effects are estimated for various categories of timber, range, water, wildlife and fish, recreation, and improvements (*table 5*).

The fire effects calculation progresses through a four-step process. In the first, the resource output levels over time that would have occurred in the absence of the simulated fires are estimated. The direct physical and biological effects of the fire on each resource are estimated in the second step. For example, tree mortality and the stream flow changes are estimated.

In the third step, the resource output time stream that results from the direct fire effect is estimated, such as the future time stream of timber yields and recreation usage. Management objective or intended resource use plays an important part in determining the postfire resource output levels. This calculation requires establishment of assumptions about rehabilitation actions, such as reseeding grass, that influence the postfire costs and output levels. These assumptions are internally linked within FEES to resource management emphasis. The rehabilitation decision is separable from the fire program decision, and inefficient rehabilitation decisions can influence which fire program is most efficient. Nonetheless, the consequences of the rehabilitation treatment must be reflected in FEES, since they influence the resource output time stream.

In the fourth step, the resource outputs in the presence of fire (step 3) are subtracted from the output level in the absence of fire (step 1), yielding the net change in resource outputs over time for that fire. Since the entire probability distribution of fire behavior characteristics is available as input into the fire effects module, the probability distribution of net change in resource outputs is calculated within the module.

The four steps in fire effects calculation are illustrated in a hypothetical timber example (*fig. 9*). The without-fire

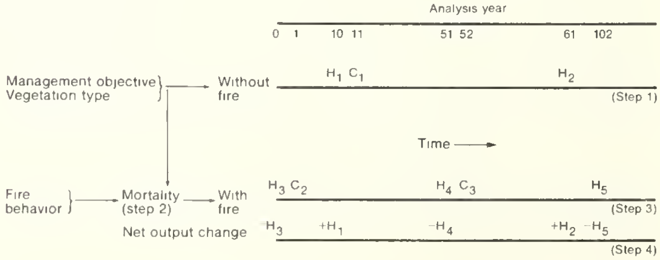


Figure 9—Illustrative net change in timber output shows the effect of fire on the magnitude and timing of costs and harvests.

Table 5—*Resource categories and units of measure used in the FEES fire effects calculations*[1]

Resource and resource elements	Effects	Physical units
Timber:		
Roundwood output[2]	Change in production	Thousand cubic feet
Range:		
Livestock grazing	Change in carrying capacity	Animal unit months
Recreation:		
Developed	Change in use	Recreation visitor-days
Dispersed	Change in use	Recreation visitor-days
Wilderness	Change in use	Recreation visitor-days
Wildlife:		
Hunting	Change in hunter use	Recreation visitor-days
Fishing—Commercial	Reduced take (catch)	Pounds
Fishing—Sport	Change in angler use	Recreation visitor-days
Water:		
Yield usable		
Domestic	Change in quantity	Acre-ft
Agricultural	Change in quantity	Acre-ft
Improvements:		
Public—buildings	Destroyed or damaged	Number of structures
Public—other improvements[3]	Destroyed or damaged	Number of structures
Private—buildings	Destroyed or damaged	Number of structures
Private—other improvements	Destroyed or damaged	Number of structures

[1]Includes only fire effects to which dollar values can be assigned; relative importance of the resources vary by area and characteristics of the simulated fire.

[2]The timber output category is further stratified by cover type. Source: Peterson (1981).

[3]Such as bridges, fences, or catchment basins.

time stream (step 1) would have started with a final harvest of the existing timber stand in 10 years (H_1). That would have been followed by a stand establishment cost (C_1) in analysis year 11 and a subsequent second rotation harvest (H_2) after a 50-year rotation in analysis year 61.

Through consideration of vegetative type, such as tree species and tree size, and fire behavior parameters, such as scorch height, tree mortality is estimated (step 2). Tree mortality, in combination with information about the management objective, such as stand stocking standards, is used to estimate the postfire salvage harvest (H_2). The salvage is followed by a stand establishment cost (C_2) in analysis year 2 and a future harvest (H_4) in analysis year 51. C_2 is the cost of the "rehabilitation" practice in this example. In keeping with the economic efficiency dimension of FEES, only rehabilitation practices that pass a minimum economic efficiency test are included in the FEES time stream. A second rotation starts in analysis year 52 with stand establishment (C_3) and ends in year 102 with final harvest (H_5).

The step 4 estimation at the bottom of *fig. 9* is the harvest time stream witohout the fire minus the stream with the fire. Entries in the with- and without-fire time streams need to be traced into the future until their corresponding discounted net value change is negligible. Even if harvests H_1, H_2, H_4, and H_5 are of equal volume and the stand establishment costs C_1 and C_3 are of equal magnitude, they will generally occur at different points in time. They must therefore all be included separately, because their discounted values will be different.

The "loss" in this fire effects calculation is the foregone future harvest (H_1) or rather difference in the timing of the harvest. The stand establishment cost which led to H_1 is irrelevant. That past cost is sunk and cannot be recouped, whether there is a fire or not.

Because only those resource output changes on the fire site and direct offsite effects are included, substitution of unburned timber at another location for the burned timber on the fire site is not accounted for, whether the substitution occurs this year or in the future. Alternatively FEES could have been designed to evaluate the fire site resources within the context of the entire planning unit and the administrative policies which regulate resource uses on the planning unit. If this alternative design were pursued, the substitution, otherwise termed "allowable cut effect" (Schweitzer and others 1972, 1973; Lundgren 1973), would lead to a much lower net value change in timber output and a reduced efficiency of the fire management program (Bell and others 1975). Van Wagner (1979) argued for this approach to estimating wildfire effects on timber output. Inclusion of the substitution assumption is pervasive in land management planning analyses on public lands, and it has been used in some individual investment analyses (for example, Sassaman and others 1972). It is a fact which affects the cash flow on public lands managed under an even flow policy where "excess" old-growth timber exists.

These substitutions were not included in FEES because we believe, following Teeguarden's (1973) arguments, that investment funds should be allocated in relationship to inherent productivity of the site affected by the management action rather than site productivity and the institutional setting within which the site lies. Excluding substitution yields a more unencumbered reflection of inherent productivity than does including institutionally induced substitution. The design of FEES is consistent on this point with the fire program analyses reported by Schweitzer and others (1982) and the U.S. Department of Agriculture, Forest Service (1980), but is inconsistent with the operation of land management planning models, such as FORPLAN (Johnson and others 1980).

Resource Value Module

The objective of the resource value module is to estimate net value change by applying per unit resource values to the net physical change in resource outputs and by discounting the resulting net value changes to the present. The present value is an estimate of the net value change from the simulated fires in that one inferred parameter cell.

The correct per unit resource value is the value of the resource actually affected by the fire, for example, stumpage rather than lumber. Where available, appropriate real value changes over time should be considered since the resource output should be valued at the time the output would actually occur. For example, Haynes and others (1980) estimate that real stumpage price changes will occur in the future. To be consistent with the fire program costs, the values should reflect true value to society, rather than any particular land owner.

Faced with these design criteria, we decided that the bases for resource valuation in FEES should be marginal willingness-to-pay (Althaus and Mills 1982). The margin, across which willingness-to-pay is measured, is the change in resource outputs caused by the fire. The marginal willingness-to-pay can be approximated by the prefire per unit value *if* the demand function is very elastic *or* the change in output caused by the fire is small.

Row and others (1981) suggested using a 4 percent real discount rate for long-term forestry investment analyses, but it is doubtful if the longstanding controversy over discount rates is over. Different rates might also be appropriate for different agencies. FEES is, therefore, designed to permit easy modification of the discount rate used in the present value calculation of the net value change and in the estimation of the annualized cost of fire management inputs that have a useful life of greater than 1 year.

The effect of discount rate changes on fire program efficiency may be opposite of its impact on timber growing activities (Blattenberger and others 1982). A reduction in the discount rate improves the economic efficiency of the timber growing activity, but it may decrease the efficiency of the fire program. Consistent with the fire effects calculation procedure, a fire delays future harvest rather than irrevocably removing it. The harvest delay is less important if the interest rate is low.

Per unit values are needed for all the harvest volumes as of the point in time when they occur (*fig. 9*). The net value change (NVC) for this example equals:

$$NVC = -(H_3)(V_3) + \frac{C_2}{(1.04)^1} + \frac{(H_1)(V_1)}{(1.04)^{10}} - \frac{C_1}{(1.04)^{11}} - \frac{(H_4)(V_4)}{(1.04)^{51}} + \frac{C_3}{(1.04)^{52}} + \frac{(H_2)(V_2)}{(1.04)^{61}} - \frac{(H_5)(V_5)}{(1.04)^{102}}$$

The net value change may be negative (beneficial effect) even if the fire leads to a physical loss in output; that is if H_1 is greater than H_3. This can occur if the salvage value (V_3) approaches the green timber value (V_1), if the mortality loss ($H_1 - H_3$) is small, and the without fire harvest occurs far in the future. These conditions are approximated whenever the without fire timber rotations are far longer than the financial maturity rotation.

Fire Occurrence Module

The modules discussed to this point simulate fires which occur in one inferred parameter cell. Estimates of the suppression cost, fire-induced changes in resource outputs, and the present value of the net value change are available at this point in the model. The variable fire weather, initial attack arrival times, fireline productivity rates, and large fire suppression effectiveness which entered the various modules influenced the model output for each inferred parameter cell. The output is in the form of probability distributions rather than point estimates or expected values alone.

The last stochastic input, the probability of fire occurrence, is incorporated in the fire occurrence module through a two-step calculation (Bratten 1981a). First, the probability distribution of annual fire occurrences for the whole fire management situation is derived empirically from summarized fire report statistics. The distribution of occurrences in the fire management situation is derived as a function of mean fire occurrence level. The mean occurrence level is one of the seven parameters that define the fire management situation. Second, given one fire in the fire management situation, the probability that it will occur in each of the inferred parameter cells is derived from individual fire reports. The resource change and net value change probabilities for each inferred parameter cell are multiplied by the corresponding fire occurrence probabilities in each cell and summed over the cells to get total probabilities for the fire-induced changes, given a fire in the fire management situation. The numbers of fires and their probabilities are then combined with the change probabilities to yield the FEES outputs for one line in the abbreviated output display (*table 1*).

Probability Calculations

The underlying probability model combines the probability distributions produced by the various modules at appropriate points in the simulation to provide inputs for subsequent modules. The probability computations are continued until the distributions for C + NVC and resource output effects are derived. *Fig. 10* shows the major proba-

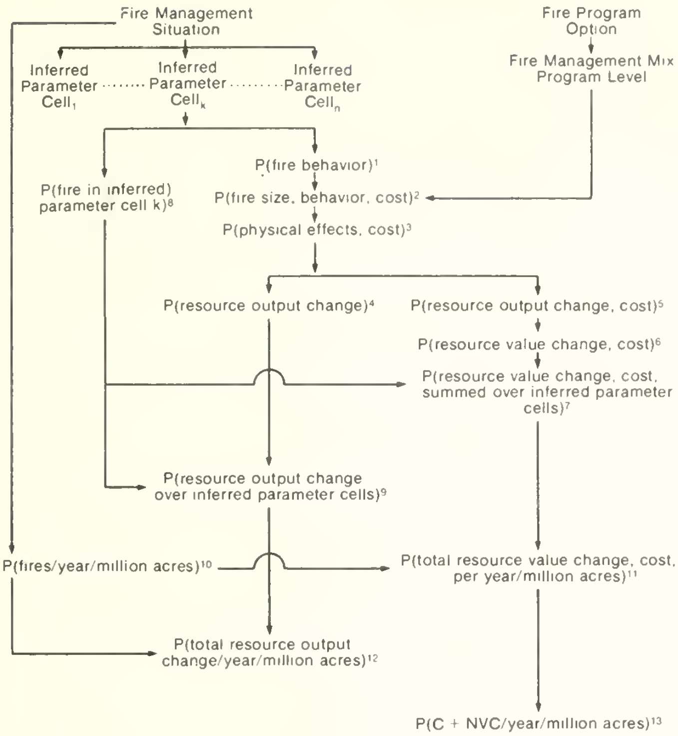


Figure 10—Sequence of combining probability distributions within the FEES model begins with the selection of fire management situation and program option.

bility functions used and the computational flow from the model inputs (Fire Management Situation, Fire Management Mix, and Program Level) to the outputs (Resource Changes and Cost plus Net Resource Value Changes). The functions and relationships shown in *fig. 10* are discussed briefly here, referring to the parenthetical numbers in the figure. A more complete development and discussion is given by Bratten (1981a).

The fire behavior probability function (1) is produced by the fire behavior module. The variables used to describe fire behavior are forward rate of spread and fire intensity which are needed in the modeling of fire spread and suppression force effectiveness. Fire behavior values, such as tree crown scorch height and fire residence time, are needed to model fire effects on forest resources. That is, P (fire behavior) gives the probabilities of sets of values for fire spread rate, intensity, scorch height, and other conditions, for a fire in a given inferred parameter cell of the fire management situation. An inferred parameter cell is a set of values for parameters for a fire location needed to calculate fire behavior and fire effects on land resources given the behavior and results of fire suppression action. Other probabilities are used within the fire behavior module. Weather and fuel probabilities for the inferred parameter cell and fire management situation, for example, are derived from various data sources and used within the module as inputs to a fire behavior model to generate the fire behavior probabilities (Salazar 1981).

The fire behavior variables and their joint probabilities are used as inputs to the initial attack and large fire suppression modules which produce probability function (2) (Hunter 1981c). Probabilities of final fire sizes and suppression costs are calculated by using an initial attack model and, for fires which escape initial attack, the large fire suppression model. Probabilities of fire behavior are then passed on from (1) in the initial attack model or generated in the large fire analysis procedure.

Fire size and fire behavior variables are used to calculate the physical effects of fires on forest resources in the fire effects module. Direct physical effects are measured with variables such as tree mortality, tons of grass burned, and acres of wildlife habitat destroyed. Since each set of values for fire size and behavior has an attached probability (2), the probabilities (3) for the resulting fire effects can be calculated. In some cases, probabilistic models may be used along with the inputs to generate function (3).

Costs have been carried forward from (2) to (3). However, the left-hand branch to (4) in *fig. 10* concerns only resource changes. Costs are not needed. A simple summation of function (3) on costs provides the simplification. Physical effects of fire are translated into changes in forest resource outputs over time. These changes are summed over time, and probabilities are appropriately combined to give probabilities of total resource changes from a fire. Resource changes include variables, such as volume of stumpage, animal unit months of grazing, and recreation visitor-days. These changes are total values calculated by summing all changes (positive and negative) in the time stream following a fire.

In function (5), costs are carried along because this branch of the calculations is concerned with the economic consequences of the fires. The resource changes described above for (4) are the same in (5). Resource changes are translated into dollar value changes, and probabilities are transformed to give function (6). Here, the time stream of value changes is appropriately discounted to give present net values.

All calculations described above (functions 1 to 6) are completed for the fire set in each inferred parameter cell. The range of outputs of the various modules encompasses the results which might occur (with appropriate probabilities) for any fire in a given inferred parameter cell. Up to this point, results for each cell have been analyzed without considering the liklihood that a fire might occur in such circumstances. Fire occurrence probability is introduced by function (8).

Functions (4) and (6) in *fig. 10* are conditional probabilities (c.f. Feller 1960). Expression (4) can be interpreted as "the joint probability of resource changes $x_1, x_2, \ldots$ for the various resources is . . . , given that a fire occurs with inferred parameter value set k." When this function is multiplied by function (8) for that cell, the result is the joint probability that a fire has occurred with parameter value k and that the resource changes are $x_1, x_2, \ldots$. These joint probabilities are then summed over the inferred parameter cells to give total probabilities (9) of resource change values, given a fire in the fire management situation.

The reasoning for function (7) is similar to that given above for function (9). The difference is that suppression costs are carried along in function (7).

We want to produce results from the FEES model which are standarized for time span and land area. That is, we want quantities of resource change or dollars per million acres for the 10-year planning horizon and the time span of fire effects. These standards are achieved by using numbers of fires per year per million acres in the fire management situation being analyzed. The form of probability function (10) is developed by analysis of historic fire occurrence data. The scale is set by some of the fire management situation parameters, namely, expected numbers of fires per year per million acres for the various fire types.

Functions (7) and (9) are defined, given a fire in the fire management situation. What if there are more than one fire, say N fires? Assumptions are made that the N fires are independent and that the fire consequences are additive. The independence assumption implies that each of the N fires can be assigned to one of the sets of resource change values of function (9), governed only by the probability values. An assignment of all N fires results in a distribution of the N fires over the sets of change values, say n_1 in set 1, n_2 in set 2, etc. The n_i's must add up to N. Mathematically, the probability of a set of n_i's is given by a multinomial probability distribution. The total resource changes for any set of n_i's are calculated, using the additive assumption, by multiplying the change values in set i by n_i and summing over i. Repeating this process for all, or a large sample, of the possible n_i sets and summing both of the resource changes and associated probabilities over the sample gives the desired results for N fires. Multiplying by the probability of N fires, function (10) in *fig. 10*, gives the final results (12) for this branch of the model. A strictly analogous process for resource value changes and costs, in place of resource changes, results in function (11) and the final result, function (12).

Sensitivity Analysis and Model Validation

This design of FEES describes a particular level of model sophistication, but it is very difficult to determine *a priori* the most appropriate level of model detail and input data accuracy, especially in a system with many complex interrelationships. The data requirements for FEES are extensive and diverse, ranging from probability distribution estimates of fire weather and fireline productivity to point estimates of tree mortality and recreation value. The cost of tabulating existing data, such as fire occurrences, is fairly low but it is much more costly to generate new data, such as fireline productivity estimates, to refine existing data. Similarly, the cost of constructing the model is sensitive to model detail, especially in the fire behavior, initial attack, and large fire suppression modules. Those costs of data collection and model construction should be balanced against the cost of an errant decision caused by inaccurate FEES output.

Final decisions on the most appropriate model detail and data accuracy will flow from a structured sensitivity analysis conducted with a prototype version of FEES. The sensitivity of the final model output, and fire program selection in turn, is the sensitivity that should influence these decisions. It may not be important for example, that fire behavior is sensitive to windspeed, if the final model output is not highly sensitive to fire behavior.

The detail built into some dimensions of this conceptual design of FEES is less than has been built into some fire planning models, FOCUS for example (Bratten and others 1981), and more than was built into others, for example, the fire planning handbook model constructed for use on National Forests (U.S. Dep. Agric., Forest Serv. 1982a). The level of detail built into the FEES design, at this point, is based on our judgment about how an operational version of the model will perform. We have tried to err on the side of greater detail because it is easier to reduce model detail than to determine from the performance of an aggregative model where more detail is needed. The modular design of FEES will permit selected changes in calculations without major disruptions elsewhere in the model.

Fortunately, there are reasons to believe that the model output is fairly insensitive to some errors. The accuracy of the per unit resource value is important, for example, only if the corresponding resource output is materially affected by fire and if the net change in output occurs soon enough after the fire that its value is not all dissipated through discounting to a present value (Althaus and Mills 1982). The net value change calculation itself tends to cancel out similar errors in the with and without fire time streams of resource output. Similarly, since the C + NVC is a marginal criteria of sorts, errors in one C + NVC are partially canceled when two C + NVC's are compared. Timber and capital investment improvements were generally the resources affected most in previous fire program analyses (Schweitzer and others 1982; U.S. Dep. Agric., Forest Serv. 1980, 1982b). Wildlife and water impacts were generally small and therefore, errors in their per unit value estimate would have little impact on model output or fire program selection.

Model validation is also important and validation must be distinguished from sensitivity. Validation is the determination of whether model output for a particular fire program option corresponds to what would happen in the real world. Complete analytical validation is particularly difficult to achieve with a model of a highly stochastic process. Even if a FEES fire program option was applied for a year, the only empirical data generated would be for that year's unique combination of weather, fire occurrences, fireline production rate, and large fire suppression effectiveness, that is, only one point on the joint probability distributions. By the time enough years had passed to validate the full probability distribution of model output, secular changes in population and technology will have changed the underlying structure of the system.

With model validation in mind, we designed FEES around empirical relationships whenever possible. Simulation is only used when empirical data are sparse or nonexistent and expert opinion is only proposed when a mathematical simulation is not practical. The fire occurrence, fire weather, most fireline productivity rates, most fire effects, fire program costs, and resource value relationships are empirically derived. The fire behavior, initial attack, and parts of the fire effects modules are largely simulation models even though some of the input data are empirical. Many of the relationships in the large fire suppression module are based on expert opinion.

Attention will be focused on validating the output of individual modules of FEES where the validation task is tractable. If the model pieces are valid, the whole should be valid as well. The empirical modules, such as fire occurrence and resource values, can be validated with standard statistical procedures. The mathematical fire behavior simulation model which underlies the fire behavior module has already been validated in selected circumstances (Salazar 1981). For example, Brown (1972) validated the rate of fire spread predictions in Douglas-fir and ponderosa pine logging slash fuels on sample plots with zero slope under conditions of low wind velocity and low fuel moisture. He concluded that the model-predicted rates were reasonably close to observed rates in the test fires.

The initial attack module can be validated by comparing the actual results of real fires with the model-predicted outcome on similar individual fires. The attack forces which were dispatched in the real fire can be duplicated in the initial attack module and the fire size results can be compared. The large fire suppression module can be similarly validated by comparing the historical record of actual large fires with the expert opinion results from a similar hypothetical large fire.

While short of a complete mathematical validation of the model, these steps, in addition to reasonableness checks by knowledgeable people, is probably all the validation that is possible. If enough empirical data were available to completely validate the model analytically, there would be enough data to design an empirical version of FEES rather than a model which relies on simulation and expert opinion modules.

APPLICATION OF FEES

The FEES design to this point could be applied in a number of ways and still meet its objective of providing a first screening of fire management program options at the subregional level of resolution. One alternative is to provide a computer software package to fire program planners. The program planner would then collect all the necessary model input data, such as resource values and fireline productivity rates, and operate the model. This is the alternative which was followed with FOCUS (Bratten and others 1981) and FORPLAN (Johnson and others 1980). This approach is justified if the program planner has unique data and the necessary expertise to operate the model. A disadvantage of this approach is the cost of preparing all the necessary user software material and the cost of training. Another possible outcome is inconsistent data collection or model operation among planning units. Inconsistencies in model use could influence the allocation of fire program funding among competing fire planning areas.

A preferable alternative is the collection of data and operation of FEES at a central location for a wide range of fire management situations and fire program options. The results of this centralized model operation would be printed as a *FEES Guidebook* containing pages of output similar to *table 1*. This alternative has lower training costs; the consistency of data and model operation would improve; and the local program planner could still make interpretations of the output for a particular area.

Once completed, the FEES system output would contain fire program information and analysis procedures to assist the program planner and decisionmaker select a fire program option. The system would contain (1) a key for sorting among the fire management situations to locate the one which most closely resembles a given portion of the planning unit; (2) separate sets of FEES model output for each fire management situation; (3) optimization procedures which would assist in the selection among competing program options using relative weights set by the local deci-

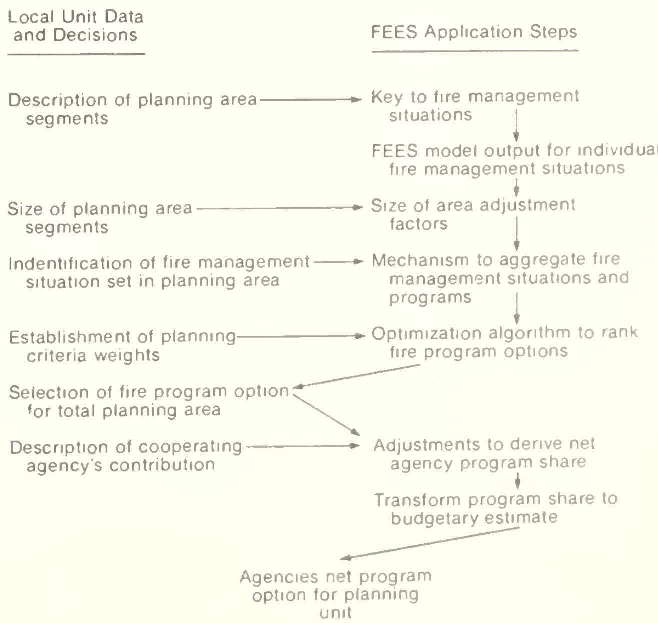


Figure 11—Steps in the application of FEES to identify the fire program for a planning unit of a particular agency.

sionmaker; (4) procedures for scaling results from the standard 1-million-acre fire management situation size to the acreage of the actual planning unit segments; and (5) instructions on how to combine the fire management situations into a cohesive fire program for the planning unit (*fig. 11*). The program level and fire management mix would then be adjusted by the net program contributions of cooperating agencies, and the economic program costs would be converted into budgetary figures relevant for the particular agency. These same steps would apply for any of the public agencies with fire management responsibilities.

Centralized data collection and operation of FEES should not be confused with centralized fire program decisionmaking any more than centralized development of timber yield tables means that timber management decisionmaking is centralized. The FEES output must still be interpreted at the local level and the relative weights among the various outputs must be assigned by someone familiar with the local ramifications of a particular fire program selection. FEES is not designed to be a total decisionmaking model. It simply provides some of the information which is relevant to fire program selection.

The institutional setting within which FEES is used is an important consideration in the interpretation of the output. Management constraints should be the *output* of natural resource program planning rather than an *input* to the planning process.

FEES will estimate economic efficiency, resource output change, and risk relatively unfettered by most institutional constraints. For example, the net change in timber output is estimated by considering only the timber on the fire site. Substitution of unburned timber at another location for burned timber on the fire site is not included in FEES design. Substitution, both temporal and spatial, is relevant only if the fire program analysis is fully submerged within the institutional setting of a planning unit. Similarly, a legislative mandate in some States to suppress all wildfires, irrespective of cost or potential net value change, is excluded from the FEES design. That constraint would artificially restrict the range of technologically feasible initial fire program options evaluated.

Some constraints are included in portions of the FEES design, however. Currently applied rehabilitation practices are included, for example, subject to an economic efficiency screening. Similarly, the timber rotations included in the timber net value change calculations are set by the predominant rotation age in the particular climate zone. That rotation age, if drawn from public lands, more closely approximates the age when mean annual timber increment is maximized than when financial maturity occurs and the rotation age is influenced by the timber even flow constraint.

There are several reasons why the minor management constraints were not excluded from the FEES design. First, the scope of the FEES model had to stop at some point. Including an economic efficiency evaluation of postfire rehabilitation options within FEES, for example, would have led to a model of unmanageable size. The constraints or management directions that were retained were the minor ones which will probably have a small impact on fire program efficiency if they are subjected to an approximate efficiency test.

The final fire program selection may well be other than the most economically efficient program as identified by FEES results. Whether the final fire management program selection is the result of institutional constraints or the consideration of additional fire system effects, at least the FEES output will display the foregone efficiency and risk consequences of those considerations and other effects.

REFERENCES

Albini, Frank A. **Computer-based models of wildland fire behavior: a user's manual.** Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. 1976; 68 p.

Althaus, Irene A.; Mills, Thomas J. **Resource values in analyzing fire management programs for economic efficiency.** Gen. Tech. Rep. PSW-57. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 9 p.

Barrager, Stephen M.; Cohan, David; Roussopoulos, Peter J. **The economic value of improved fuels and fire behavior information.** Res. Paper RM-239. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 32 p.

Baumgartner, David C.; Simard, Albert J. **Wildland fire management economics: a state of the art review and bibliography.** Gen. Tech. Rep. NC-72. St. Paul, MN: North Central Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 46 p.

Bell, Enoch; Fight, Roger; Randall, Robert. **ACE: the two-edge sword.** J. For. 73(10):642-643; 1975 October.

Blattenberger, Gail; Hyde, William F.; Mills, Thomas J. **Techniques and criteria for decisionmaking in risk situations related to fire management.** 1982. Unpublished draft supplied by authors.

Bratten, Frederick W. **Fire occurrence.** 1981a. Unpublished draft supplied by author.

Bratten, Frederick W. **Probability model for analyzing fire management alternatives: theory and structure.** 1981b. Unpublished draft supplied by author.

Bratten, Frederick W.; Davis, James B.; Flatman, George T.; Keith, Jerold W.; Rapp, Stanley R.; Storey, Theodore G. **FOCUS: a fire management planning system—final report.** Gen Tech. Rep. PSW-49. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1981. 34 p.

Brown, James K. **Field test of a rate-of-spread model in slash fuels.** Res. Paper INT-116. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972. 24 p.

California Department of Forestry. **Guide for preparing the CDF's fire protection plan for state responsibility areas (fire protection section).** Sacramento, CA, 1979; 166 p.

Davis, Lawrence S. **The economics of wildfire protection with emphasis on fuel break systems.** Berkeley, CA: Univ. of California; 1965. 236 p. Dissertation.

Fedkiw, John. **Some economic principles and viewpoints related to fire damage appraisal.** 1965. Unpublished draft supplied by author.

Feller, William. **An introduction to probability theory and its application.** Volume I, 2d ed. New York: John Wiley and Sons; 1960. 461 p.

Gonzalez-Caban, Armando. **Fire management program economic cost: initial attack and large fire suppression.** 1981. Unpublished draft supplied by author.

Gorte, Julie K.; Gorte, Ross W. **Application of economic techniques to fire management—a status review and evaluation.** Gen. Tech. Rep. INT-53. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 26 p.

Haven, Lisa; Hunter, T. Parkin; Storey, Theodore. **A compilation and extrapolation of existing fireline production rates.** 1981. Unpublished draft supplied by authors.

Haynes, Richard W.; Connaughton, Kent P.; Adams, Darius M. **Stumpage price projections for selected western species.** Res. Note PNW-367. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 14 p.

Headley, Roy. **Fire suppression district 5.** Washington, DC: U.S. Department of Agriculture, Forest Service; 1916. 58 p.

Herrick, Owen W. **Forest pest management economics—application to the gypsy moth.** Forest Sci. 27(1):128-138; 1981 March.

Hirsch, Stanley N.; Meyer, Gary F.; Radloff, David L. **Choosing an activity fuel treatment for southwest ponderosa pine.** Gen. Tech. Rep. RM-67. Fort Collins, CO; Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 15 p.

Hunter, T. Parkin. **Initial attack module, problem analysis.** 1981a. Unpublished draft supplied by author.

Hunter, T. Parkin. **Initial attack times and the influence of multiple fires.** Proceedings of the Intermountain Fire Council; 1981 October 20-22; Salt Lake City, UT; 1981b; 157-173.

Hunter, T. Parkin. **Large fire module, problem analysis.** 1981c. Unpublished draft supplied by author.

Johnson, Norman K.; Jones, Daniel B.; Kent, Brian M. **Forest planning model (FORPLAN) user's guide and operations manual (draft).** Washington, DC: U.S. Department of Agriculture, Forest Service; 1980. 258 p.

Joseph, Chris A. **The use of gaming in forest fire management planning.** Riverside, CA: Univ. of California; 1981. 106 p. Dissertation.

Knight, Frank H. **Risk, uncertainty, and profit.** New York: Harper & Row; 1965. 381 p.

Lehto, Frank; See, Thomas. Aviation and Fire Management Staff, U.S. Department of Agriculture, Forest Service, Washington, DC. [Personal communication]. February 1981.

Lundgren, Allen L. **The allowable cut effect: some further extensions.** J. For. 71(6):357, 360; 1973 June.

McKetta, Charles W. **Documentation of data collection for fire management cost model.** 1981. Unpublished draft supplied by author.

Mees, Romain M. **INIAT: a computer program to analyze initial action and first reinforcement times of fire suppression resources.** 1981. Unpublished draft supplied by author.

Mills, Thomas J. **Economic evaluation of alternative fire management programs.** Barney, Richard J., ed. Proceedings of the symposium on fire control in the 80's. 1979 October 30-November 1; Missoula, MT: Intermountain Fire Council; 1979; 75-89.

Mills, Thomas J. **A design for fire management program analysis within land management planning.** 1982. Unpublished draft supplied by author.

Nelson, Thomas C. **Fire management policy in the National Forests—a new era.** J. For. 77(11):723-725; 1979 November.

Omi, Philip N.; Murphy, James L.; Wensel, Lee C. **A linear programming model for wildland fuel management planning.** Forest Sci. 27(1):81-94; 1981 March.

Oregon State Department of Forestry. **The fire control program; a cost analysis of fire control activities** [Fire Control Division]. Eugene, OR, 1972; 32 p.

Peterson, David. **Fire effects module, problem analysis.** 1981. Unpublished draft supplied by author.

Rothermel, Richard C. **A mathematical model for predicting fire spread in wildland fuels.** Res. Paper INT-115. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972. 40 p.

Row, Clark; Kaiser, H. Fred; Sessions, John. **Discount rate for long-term Forest Service investments.** J. For. 79(6):367-369, 376; 1981.

Salazar, Lucy. **Fire behavior and fuel treatment modeling, problem analysis.** 1981. Unpublished draft supplied by author.

Sassaman, Robert W.; Barrett, James W.; Smith, Justin G. **Economics of thinning stagnated ponderosa pine sapling stands in the pine-grass area of central Washington.** Res. Paper PNW-144. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972. 17 p.

Schroeder, Mark J.; Glovinsky, Monte; Hendricks, Virgil F.; and others. **Synoptic weather types associated with critical fire weather.** Berkeley, CA; Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. 1964; 492 p.

Schultz, R. D. **Decisionmaking in a wildland fire game.** Berkeley, CA: Univ. of California; 1964. 184 p. Dissertation.

Schuler, Albert T.; Webster, H. H.; Meadows, J. C. **Goal programing in forest management.** J. For. 75(6):320-324; 1977 June.

Schweitzer, Dennis L.; Andersen, Ernest V.; Mills, Thomas J. **Economic efficiency of fire management programs at six National Forests.** Res. Paper PSW-157. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 29 p.

Schweitzer, Dennis L.; Sassaman, Robert W.; Schallau, Con H. **Allowable cut effect: some physical and economic implications.** J. For. 70(7):415-418; 1972 July.

Schweitzer, Dennis L.; Sassaman, Robert W.; Schallau, Con H. **The allowable cut effect: a reply.** J. For. 71(4):227; 1973 April.

Simard, A. J. **Wildland fire management: the economics of policy alternatives.** For. Tech. Rep. 15. Ottawa, Ontario, Canada: Forest Fire Research Institute, Canadian Forestry Service, Department of Environment; 1976. 52 p.

Steuer, Ralph E.; Schuler, Albert T. **An interactive multiple-objective linear programing approach to a problem in forest management.** Oper. Res. 26(2):254-269; 1978.

Teeguarden, Dennis E. **The allowable cut effect: a comment.** J. For. 71(4): 224-226; 1973.

U.S. Department of Agriculture, Forest Service. **National fire planning.** Washington, DC; U.S. Department of Agriculture, Forest Service; 1972. 121 p.

U.S. Department of Agriculture, Forest Service. **Evaluation of fire management activities on the National Forest.** Washington, DC; U.S. Department of Agriculture, Forest Service; 1977. 127 p.

U.S. Department of Agriculture, Forest Service. **Fire considerations in forest planning.** [Fire in Land Management Planning Task Force]. Washington, DC. 1979a; 50 p.

U.S. Department of Agriculture, Forest Service. **National Forest System land and resource management planning.** Federal Register 44(181): 53928-53999; 1979b.

U.S. Department of Agriculture, Forest Service. **National Forest System fire management budget analysis, 1980.** [Aviation and Fire Management Staff]. Washington, DC. 1980; 29 p.

U.S. Department of Agriculture, Forest Service. **Forest Service manual, Title 5100 fire management, section 5130.3 fire suppression policy.** Washington, DC; U.S. Department of Agriculture, Forest Service; 1981.

U.S. Department of Agriculture, Forest Service. **Fire management analysis and planning handbook.** Forest Service Handbook 5109.19. Washington, DC; U.S. Department of Agriculture, Forest Service; 1982a.

U.S. Department of Agriculture, Forest Service. **Fire protection on non-Federal wildlands.** [Cooperative Fire Protection Staff]. Washington, DC. 1982b; 62 p.

U.S. Department of Agriculture, Forest Service. **Guidelines for economic and social analysis of programs, resource plans, and projects; final policy.** Federal Register 47(80):17940-17954; 1982c.

U.S. Senate. **Report on Department of Interior and related agency appropriations bill.** Rep. 95–1063. Washington, DC; 1978.

Van Wagner, C. E. **The economic impact of individual fires on the whole forest.** The For. Chron. 55(2):47–50; 1979 April.

Water Resources Council. **Procedures for evaluation of national economic development (NED) benefits and costs in water resources planning (level C); final rule.** Federal Register 44(242):72892-72976; 1979.

Winkworth, Ralph; Shepard, John; Holley, Lester. **Benefit-cost study of progress in forest fire protection in North Carolina.** 1981. Unpublished draft supplied by authors.

Wood, Donald B. **Fuel management opportunities on the Lolo National Forest: an economic analysis.** Res. Note INT–272. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1978. 9 p.

The Forest Service, U.S. Department of Agriculture, is responsible for Federal leadership in forestry. It carries out this role through four main activities:

- Protection and management of resources on 191 million acres of National Forest System lands.
- Cooperation with State and local governments, forest industries, and private landowners to help protect and manage non-Federal forest and associated range and watershed lands.
- Participation with other agencies in human resource and community assistance programs to improve living conditions in rural areas.
- Research on all aspects of forestry, rangeland management, and forest resources utilization.

The Pacific Southwest Forest and Range Experiment Station

- Represents the research branch of the Forest Service in California, Hawaii, and the western Pacific.

Mills, Thomas J.; Bratten, Frederick W. **FEES: design of a *F*ire *E*conomics *E*valuation *S*ystem.** Gen. Tech. Rep. PSW-65. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 26 p.

The Fire Economics Evaluation System (FEES)—a simulation model—is being designed for long-term planning application by all public agencies with wildland fire management responsibilities. A fully operational version of FEES will be capable of estimating the economic efficiency, fire-induced changes in resource outputs, and risk characteristics of a range of fire management program options. Risk is described by the probability distributions of economic efficiency and resource output changes that result from annual variation in factors such as fire occurrences and fire weather. Particular attention is given to the fuel treatments, initial attack, and large fire suppression portions of the fire management program. FEES evaluates the performance of fire management program options as they are applied to particular fire management "situations," described by parameters which influence program performance, such as vegetation, topography, resource management objective, and fire occurrence levels. Location is addressed only through the regional fire climate zone. The situation-specific design, as opposed to location- or site-specific design, was chosen to avoid duplication of data collection and analysis costs. Duplication costs occur when site-specific planning models are applied independently to planning areas even though the characteristics of the area which influence fire program performance are essentially the same.

Retrieval Terms: economic efficiency, risk, fire suppression, probability model, fire effects

United States
Department of
Agriculture

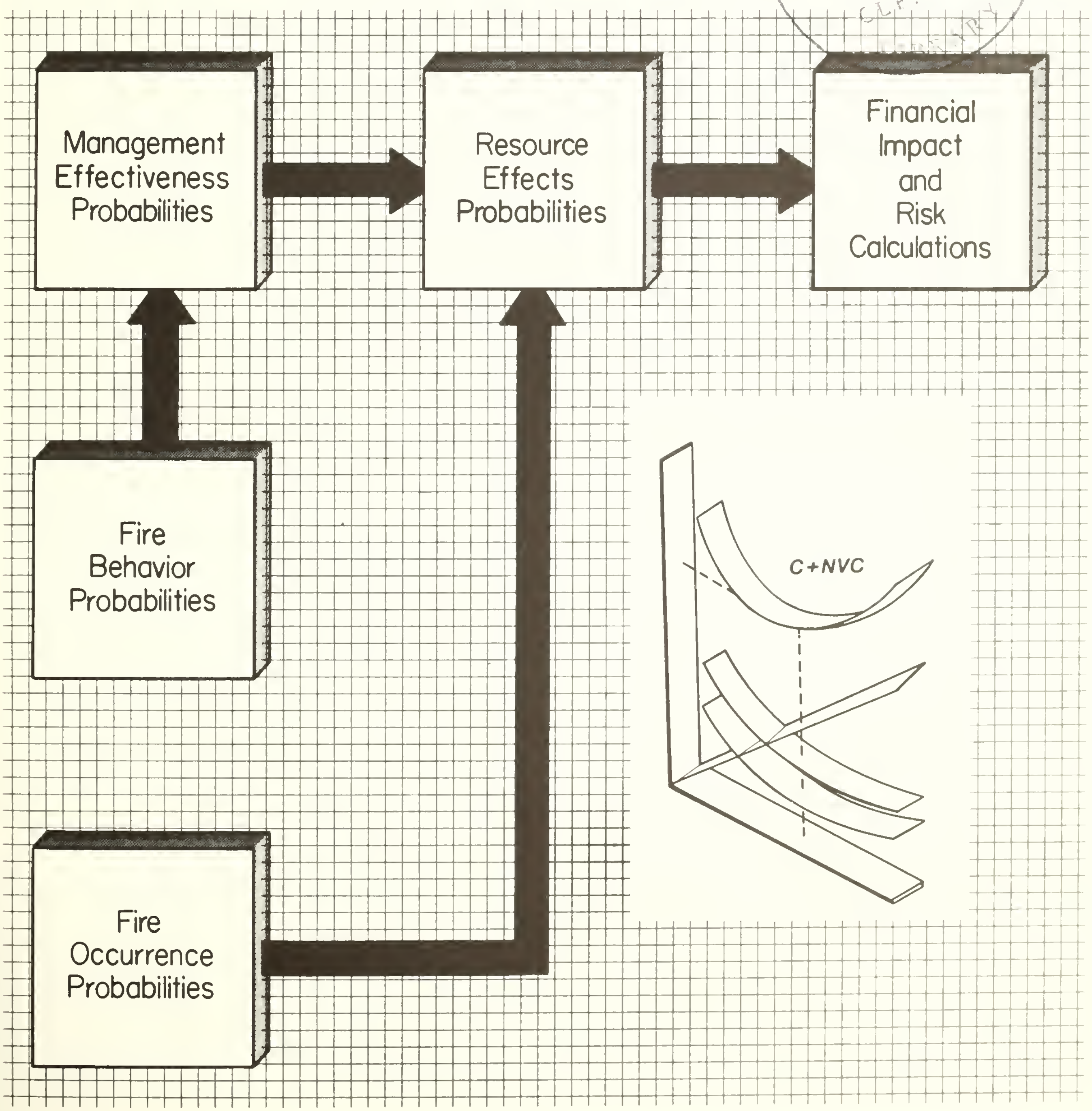
Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

General Technical
Report PSW-66

Probability Model for Analyzing Fire Management Alternatives: theory and structure

Frederick W. Bratten



The Author:

FREDERICK W. BRATTEN, an operations research analyst, is assigned to the Station's research unit studying problems in fire management planning and economics, with headquarters at the Forest Fire Laboratory, Riverside, Calif. He received degrees in physics at the Case Institute of Technology (B.S., 1950) and the University of California, Berkeley (M.S., 1952).

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

December 1982

Probability Model for Analyzing Fire Management Alternatives: theory and structure

Frederick W. Bratten

CONTENTS

Introduction 1
Design of the Model 1
Fire Management Situations 1
Inferred Parameter Cells 1
Fire Management Program Options 2
Outputs 2
Model Structure 2
The Probability Model 4
Fire Behavior 4
Fire Detection Module 4
Fire Suppression and Costs 5
Fire Effects 6
Resource Changes 6
Fire Occurrence 7
Valuation of Resource Changes 8
Outlook for Model Implementation 10
References 10

GLOSSARY

A_x	Program for fire management activity type x.
a	Fire size class (general).
a_I	Fire size class after initial attack.
a_E	Burned area vector after escaped fire analysis, with a component for each affected resource.
B	Set of fire behavior variables.
b	Vector of values for variables in B.
b_I	b following initial attack calculations.
b_E	b in escaped fire analysis with a vector for each affected resource.
C	Fixed yearly cost of fire management programs.
c	Variable suppression costs.
D	Present value cost plus net value change.
d	Fire area at detection.
E_α	Set of inferred parameters for fire management activity, α.
e_α	Value vector for set E_α.
e	Value vector for union of all E_α.
EFA	Escape fire analysis (also large fire analysis).
F	Vector function relating resource value changes to physical changes (inverse of f, (2)).
F_B	Fire behavior function.
FEES	Fire Economics Evaluation System.
FMS	Fire management situation.
FMM	Fire management mix.
f	(1) Fuel model. (2) Vector function relating physical resource changes to dollar values.
f_t	Fuel type used on fire report forms.
G	Set of physical fire effects variables for resources.
g	Vector of values for G.
h	Fire type number designating cause and access class.
IAA	Initial attack analysis.
IPC	Inferred parameter cell.
m_f	Fuel moisture vector for dead fuel particle size classes and live fuels.
N	Number of fires.
P	Probability function.
PL	Program level (presuppression budget).
q_t	Resource change vector per unit burned area in year t.
Q_T	Total resource change vector per unit burned area through year T.
R	Resource management emphasis indicator.
r	(1) Fire rate of spread. (2) Resource type.
S	Set of fire management situation parameters.
s	Value vector for S.
T	(1) Topography descriptor (FMS parameter). (2) Years of fire effects accumulation.
t	Time—years.
t_d	Time of day class.
t_I	Suppression time in IAA.
t_y	Time of year class.
u	Slope class for terrain.
$\hat{u}$	Slope-aspect-elevation class.
V	(1) Vegetation class (FMS parameter). (2) Resource value change vector.
v	Vegetative cover type.
w	Windspeed.
Z	(1) Climate zone (FMS parameter). (2) Years of fire occurrence for effects accumulation.
Γ	Array of prefire resource characteristics needed to calculate fire effects.
Ω^t	Postfire resource management program through year t after a fire.
Φ^t	Set of given parameters and programs through year t.

Increasingly, wildland fire management programs are being judged by their economic efficiency. The use of that criterion to evaluate programs is relatively new, but the application of economic theory to fire management dates from the 1920's (Sparhawk 1925).

The variable nature of wildfires has stimulated planners to recognize that a probabilistic approach to fire management analysis and planning is needed. Only recently, however, have probability concepts been explicitly incorporated into fire analysis and planning systems—and then only in a limited way (Hirsch and others 1979; U.S. Dep. Agric., Forest Serv., 1981b).

At the Pacific Southwest Forest and Range Experiment Station, a multidisciplinary team at Riverside, California, is developing an analytical and planning approach called the Fire Economics Evaluation System (FEES) (Mills and Bratten 1982). Framework for the system is provided by a theoretical probability model designed to analyze program alternatives in wildland fire management. This model includes submodels or modules for predicting probabilities in fire behavior, fire detection, initial attack and large fires, fire effects, resource changes, fire occurrence, and resource values. Generally using state-of-the-art technology and available data, these modules are designed to be modified or replaced in the future as new research dictates.

This report describes the mathematical structure of the probability model and the logic for assembling the modules into an overall system for analyzing wildland fire management.

DESIGN OF THE MODEL

Early in the design phase, the research team decided to follow an approach that would not be site-specific. The system uses two kinds of parameters: *area*, to identify planning situations and *point*, to identify factors that affect fire behavior, occurrence, and effects.

Fire Management Situations

Area parameters serve to identify *fire management situations* (FMS)[1]—generalized physical locations with characteristics similar to actual planning areas. A FMS is shown in *fig. 1* with an indefinite boundary to indicate the nonspecific site concept. The probability model currently uses these area parameters:

- Climate zone (Z): one of 14 fire weather regions in the United States (Schroeder and others 1964).
- Topography class (T): general topography, such as flat, moderate, or steep land.
- Vegetation class (V): classes derived from standard classification schemes.
- Resource management emphasis (R): relative management importance of various land resources in the area.
- Occurrence types (H): the most important occurrence types defined by combinations of cause and access classes.
- Occurrence levels (N): average number of fires per year per million acres for occurrence types (H).

For each FMS, the planner determines a fire management mix (FMM). Such a mix is a combination of well-defined mixes of fire suppression units and activities, budget or program levels (PL), program emphasis, and treatment.

Inferred Parameter Cells

Point parameters describe the kind of fire environment that could be expected in the fire management situation being analyzed (*fig. 1*). Within a FMS are many kinds of fire sites. The point parameters that describe these sites are necessary for analyzing fire behavior, occurrence, management, and effects. A set of values for these parameters, and hence for a particular kind of fire site, is called an *inferred parameter cell* (IPC).

To predict fire behavior in the model, values for parameters of fuel, weather, and slope of the terrain are used. These and other parameters that determine them comprise the inferred parameter subset E_B. Similarly, E_D is the subset needed to calculate fire detection probability; E_S for calculating fire suppression; and E_R for calculating fire effects on resources.

The entire set of inferred parameters, i.e., the union of subsets E_B, E_D, E_S, and E_R is called E. Some of the parameters in E represent quantities that physically have continuous value ranges. However, for purposes of analysis, each of these ranges is partitioned into a small number of class intervals. The class intervals are numbered for each parameter, and these reference numbers become the range of the parameter. Other parameters, for example, cover type, are basically categorical, and these categories are assigned reference numbers. A vector of reference number values for set E is designated e, or e_α for sets E_α (α = B, D, S, or R), and such a vector defines an IPC.

[1]The glossary lists symbols, and their definitions, used in this publication.

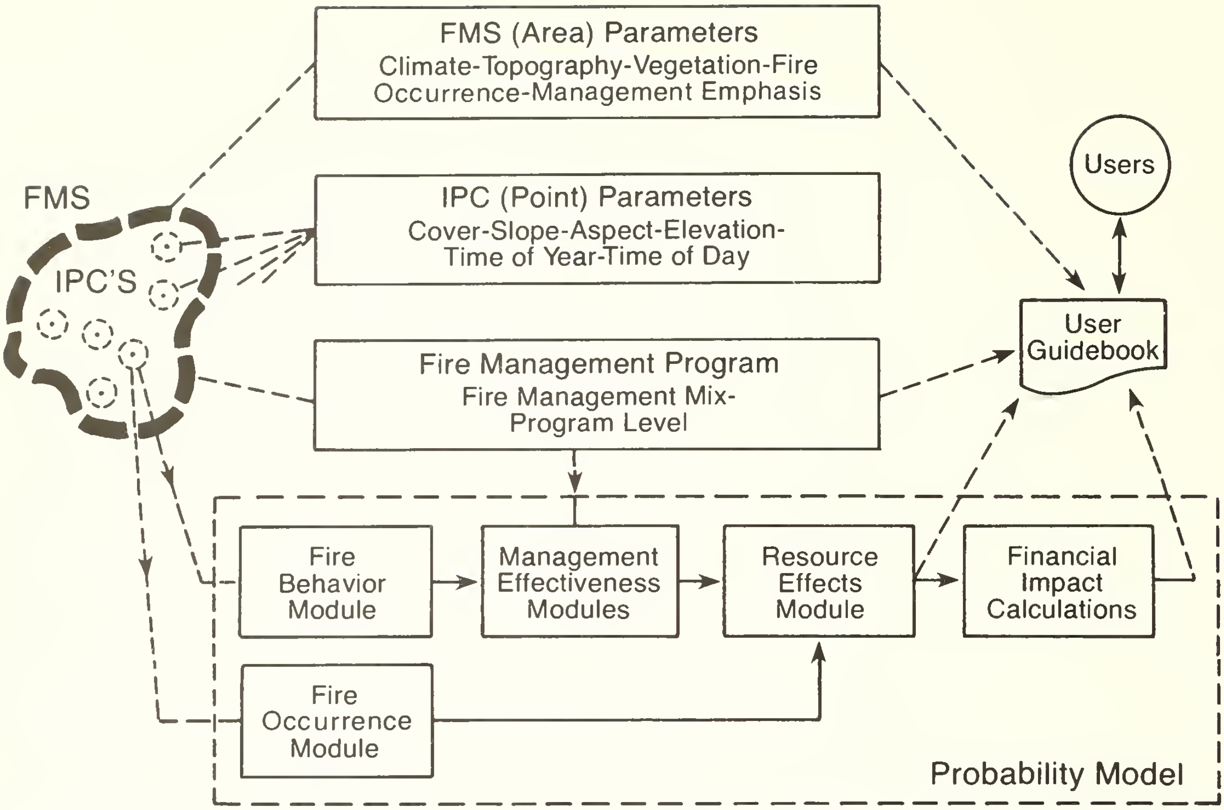


Figure 1—The probability model provides the mathematical framework for the Fire Economics Evaluation System now under development by the Forest Service. Fire management situations (FMS) are generalized physical location; inferred parameter cells (IPC) are particular kinds of fire location or site.

The IPC's in set E are basic elements of the analysis space. In each IPC, the analysis process will yield probabilities for fire effects on land resources and for variable costs of the specified fire management activities. The effects and costs for any IPC will be realized only if a simulated fire occurs in that cell. This fire occurrence is a random event in the real world and in the model. In any year or fire season, a fire chosen at random will fall in a given cell. This process can be interpreted as a random occurrence of an IPC, or more specifically, of the parameter values defining the IPC. In this sense, e and $e_{\alpha,s}$ for the modules are random vectors.

Fire Management Program Options

A range of fire management programs will be analyzed for each FMS. These programs will be described by well-defined fire management mixes (FMM) of kinds of units and activities, and a range of budget or program levels (PL). The PL represents the total annual budget for the FMS. An FMM is a set of rules for allocation of the PL dollars, first between the various kinds of inputs (fuel treatment, initial attack, etc.) and then between various kinds of expenditures within the input categories.

Outputs

For any combination of FMS, FMM, and PL, the FEES probability model will calculate two basic kinds of outputs. The first is a joint probability distribution for the fire induced changes in several kinds of forest resource outputs, measured in resource quantities (e.g., timber volume) per million acres per year over a 10 year planning period. These changes can be either positive or negative, including both beneficial and detrimental effects of fires.

The second output will be a probability distribution for the economic effiency measure, *cost plus net value change* (C + NVC). Here the resource changes over time will be given dollar values which, along with the time stream of fire and resource management costs, will be discounted to present values and summed. Expected values of this "bottom line" output will provide an economic risk-neutral basis for choosing between FMM's and PL's for a given FMS. The probability distributions will provide opportunities for choices based on other kinds of risk preference and consideration of inputs other than FEES to the decision making process.

Model Structure

A more detailed diagram of the probability model is shown in *figure 2*. Information flows between the modules generally from left to right. Logically, the first module to consider is fire behavior. Fire behavior variables include rate-of-spread, intensity, and other quantities derived primarily from these two. Probabilities for fire behavior depend explicitly on the IPC parameters and implicitly on weather data used to estimate the probabilities.

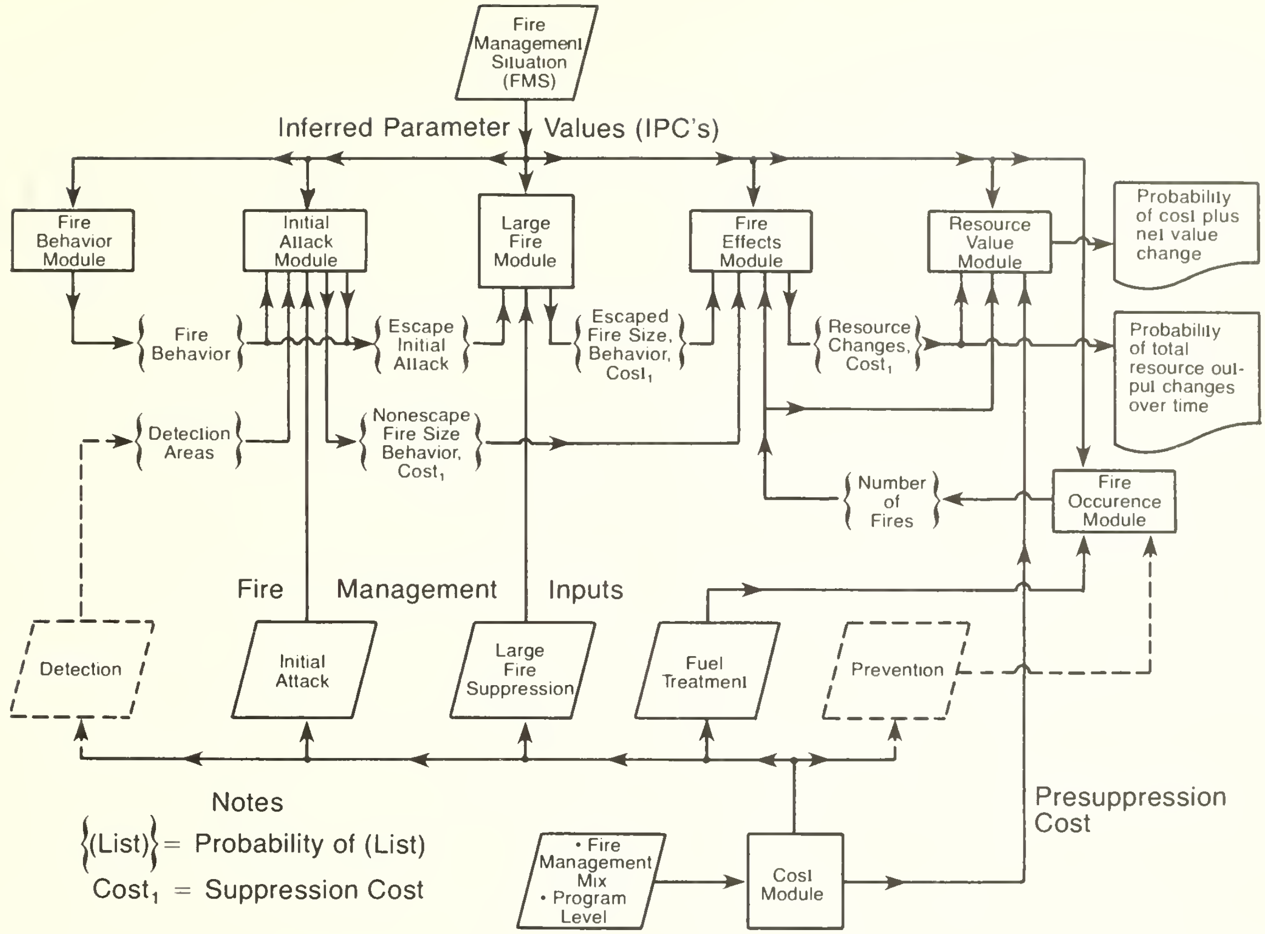


Figure 2—Modules or submodels form the theoretical probability model. They deal with various aspects of the fire management analysis procedure. Information flows between modules generally from left to right. The modules for fire prevention and detection are shown in dashed lines because they will not be included in the Fire Economics Evaluation System now being developed.

Cost-effectiveness models for fire prevention and detection are not presently available, so these inputs are shown as dashed line boxes in *figure 2*. In initial FEES development, detection and prevention activities are assumed to be those historically used in an FMS. The historical dollar expenditures in these areas are subtracted from the PL before using the FMM rules to allocate the remaining dollars to the other inputs. Consistent with these assumptions, probabilites for detection areas and numbers of fires are estimated from historical fire data and used as inputs to the model.

Given detection area and fire behavior probabilities along with the initial attack inputs or available attack units, the *initial attack module* calculates probabilities for initial attack outcomes for each IPC. These outcomes include a probability for "escape," which is defined as any result from the initial attack or fire behavior calculations in which fire size or intensity exceed values beyond which the initial attack model is invalid. For escape conditions, a *large fire module* combines subjective and computer techniques to estimate probabilities for final fire sizes, behaviors, and costs.

Given results from these two modules, the *fire effects module* first calculates joint probabilities per fire for suppression costs and resource changes over time in each IPC. Then costs and resource changes and their joint probabilities are combined over all IPC's in the FMS to, in effect, get probabilities for time streams of effects and costs per fire for any fire in the FMS. Probabilities for annual numbers of fires in the FMS are then used to estimate probabilities for total annual resource change and suppression costs in the FMS. The probabilities for total resource output changes over time which are available at this point in the calculations form one part of the model output for use in the "guidebook" of results.

Dollar values are assigned to each single IPC time stream of resource changes in the resource value module. These values and the suppression costs are appropriately discounted, and their probabilities are combined to provide probabilities for present values of resource changes and suppression costs for a single IPC. These probabilities for present values are combined over all IPC's, and probabilities of numbers of fires are used to get probabilities for total suppression costs and net value changes in the FMS. Presuppression costs from the cost module are added to arrive at the "bottom-line" output, for the "guidebook," of probabilities for cost plus net value change.

THE PROBABILITY MODEL

The probability model description uses functional and informal set notation. Symbols used and their definitions are listed in the Glossary. Submodels for estimating fire effects, fire behavior, and other model functions are represented here only as conditional probability distributions in generalized functional notation. Independent and dependent variables or sets are included along with the independent parameters. Random variables and parameters comprising inputs and outputs of the various modules are assumed to be discrete valued. The use of class intervals for defining ranges of the FMS and inferred parameters was described earlier. Similar partitioning is assumed for random variables that are internal to the model.

The following functional notation conventions are used to distinguish between random variables and deterministic parameters, and for other purposes:

P(x) is the probability that discrete random variable X has value x. The convenient procedure of simply writing P(x) with no further explanation will be followed. The domain of the function will be given explicitly only when this is not obvious.

P(x;a) is the probability of x as described above, given deterministic independent parameter a. Similarly, P(x;a,b) has given parameters a, b, and so forth.

P(x|z) is the conditional probability for values of discrete random variable X, given value z for discrete random variable Z. Then, P(x|z;a) is the conditional probability for x, given z and parameter a, and so forth.

$P_n(x)$ uses subscripts on P, as $P_1(x)$ to denote a particular functional form for P and $P_2(x)$ for a different form. Occasionally, letter subscripts are used in the same way.

The modules and their interactions are described in the logical sequence shown in *figure 2*. Then, fire occurrence weighting will be used to give the final model outputs.

Fire Behavior

For each IPC, the fire behavior module will calculate probabilities for quantities such as fire spread rate, intensity, and tree crown scorch height needed to calculate effectiveness of detection and suppression activities and fire effects on resources (Salazar 1981).

Let B represent the desired set of fire behavior descriptors and β a value vector for B. Then, current modeling capabilites (Albini 1976, Rothermel 1972) can be represented by the function:

$$\beta = F_B(u,f,w,m_f) \qquad (1)$$

where

u = slope of terrain

f = fuel model (a set of fuel characteristics)

w = windspeed

m_f = fuel moisture vector for dead fuel particle size classes and live fuels

This function is useful in the model only if fire occurrence probabilities can be defined for the independent variable cell $[u,f,w,m_f]$. Data availability does not permit this directly. The weather-dependent variables w and m_f are not recorded, in general, in historic fire records and the fuel model may have to be inferred from other data sources. It appears feasible to use proxy variables which are included in occurrence data and weather records to get probabilities:

$$P_w(w,m_f|t_d,t_y,\hat{u},v;s)$$

where

t_d = time of day class

t_y = time of year class

s = value vector for FMS parameter set S

$\hat{u}$ = [slope, aspect, elevation]

v = vegetative cover type

Direct fuel model information also is missing from historic fire records, so that f must be inferred from other information. A vegetative cover type (v) is generally included in individual fire reports. We assume that a probability function $P_F(f|v;s)$ can be defined from available data to give probabilities for fires in fuel model f, given that they have occurred in vegetative cover type v in FMS(s).

Then probabilities for sets $\tilde{b}$ of values for the fire behavior parameters B are calculated by summing the product of P_W and P_F over all values of (w,m_f,f) for which β from equation 1 lies within $\tilde{b}$. That is

$$P_1(\tilde{b}|t_d,t_y,\hat{u},v;s) \qquad (2)$$

$$= \sum_{(w,m_f,f)\epsilon C_1} P_w(w,m_f|t_d,t_y,\hat{u},v;s)P_F(f|v;s)$$

where $\tilde{b}$ is a set of values for B and C_1 is the set of (w,m,f) values such that the β calculated by equation 1 falls within $\tilde{b}$. Using the notation previously explained, P_1 can be written

$$P_1(\tilde{b}|e_B;s)$$

where

$e_B = (t_d,t_y,\hat{u},v)$

Fire Detection Module

Fire detection activities A_D result in probabilities at the time of report for fire size classes d. Intuitively, these probabilities depend on fire type h, fire beavior $\tilde{b}$, and a parameter value set e_D. Assume a probability function:

$$P_2(d|\tilde{b},e_D;h,A_D,s)$$

where

e_D is assumed to be the same as e_B

h = fire type, i.e., cause and access class

It is useful to combine P_1 and P_2 to get

$$P_3(d,\tilde{b}|e_D;h,A_D,s) = P_2(d|\tilde{b},e_D;h,A_D,s)P_1(\tilde{b}|e_B;s) \qquad (3)$$

Size at detection (d) and fire behavior ($\tilde{b}$) are used in the next section as independent variables for fire suppression calculations.

It should be noted that no comprehensive model of the kind assumed here for fire detection is currently available. Simplified assumptions will be made in the initial FEES development (Salazar 1981). The FEES model will provide a means for sensitivity analysis of the detection assumptions.

Fire Suppression and Costs

Analyses of fire suppression require that fires be described by both intensive and extensive variables. The fire suppression modules (*fig. 2*, initial attack and large fire modules) use primarily fire intensity and rate of fire spread, which are lumped into "fire behavior" here. Fire size at the time of beginning suppression action also is important; this can be related to d, the size at the time of report. Another kind of variable used in suppression analyses deals with effectiveness of suppression forces and activities. Examples are dispatching rules and fireline construction rates.

Fire suppression activity analysis is of two kinds: *initial attack anlaysis* (IAA) and *escaped fire analysis* (EFA). IAA uses computer modeling to produce joint probabilities for final fire sizes, suppression times, fire behavior, and suppression costs. For a given IPC, limits are set on fire size and suppression time beyond which IAA methods are invalid and the fires are said to have "escaped initial attack." For IPC's with a significant escape probability, EFA uses a combination of subjective and computer methods to estimate probabilities for final fire sizes, behaviors, and costs. EFA methods also are required for IPC's with significant probabilities for fire behavior parameters or fire size when reported which exceed certain limits. Behaviors and/or sizes beyond these limits predetermine a very high probability of escape from initial attack, making IAA unnecessary.

For IAA, assume a probability function

$$P_4(a_I,t_I,c_I|d,\tilde{b}_I,v,u,t_d;h,A_S,s)$$

where

a_I = fire size class resulting from IAA

t_I = suppression time class for IAA

$\tilde{b}_I$ = fire behavior, assumed constant during IAA

c_I = suppression cost calculated in IAA (Gonzalez-Caban 1981)

u = slope class

A_s = suppression program including kinds and quantities of suppression resources

Other quantities are as previously defined.

Deterministic versions of initial attack models of this kind are currently being used in the FOCUS fire planning model (Bratten and others 1981) and in the Forest Service's national fire analysis system for forest planning (U.S. Dep. Agric., Forest Serv. 1982).

A major source of variability not shown explicitly in P_4 is fire force productivity (e.g., fireline construction rates) (Haven and others 1981, Hunter 1980). Another source is arrival time of attack units. The FEES initial attack module will include these kinds of variability along with the explicit input distributions for detection area and fire behavior (Hunter 1980).

The notation for the IAA probability function is shortened to

$$P_4(a_I,t_I,c_I|d,\tilde{b}_I,e_S;h,A_S,s) \qquad (4)$$

where

$$e_S = [v,u,t_d] \qquad (5)$$

In the fire effects and cost calculations to follow, a_I, $\tilde{b}_I$, and c_I are needed, but d is no longer needed. Similarly, fire rate of spread r, a component of b_I, is no longer needed. P_3 and P_4 are combined and summed on d and r to give for IAA:

$$P_5(a_I,t_I,b_I,c_I|e;h,A_D,A_S,s) \qquad (6)$$

$$= \sum_d\sum_r P_3(d,\tilde{b}_I|e_D;A_D,s)P_4(a_I,t_I,c_I|d,\tilde{b}_I,e_S;h,A_S,s)$$

where b_I is $\tilde{b}_I$ without the r component and e is the union of sets e_D and e_S. That is

$$e = [\hat{u},v,t_d,t_y] \qquad (7)$$

Define a special fire size-suppression time class Ψ_{Ie} as the "escape" class of IAA results for IPC (e), which will indicate further analysis using EFA methods (Hunter 1981). EFA also may be required for a set of initial size and fire behavior conditions Ψ_o which will exist with a known probability prior to IAA. For IPC (e) let

$P_{EI}(\Psi_{Ie}|e;h,A_D,A_S,s)$ = the probability for escape in IAA

$P_{EO}(\Psi_o|e;h,A_D,s)$ = the probability of prior conditions requiring EFA.

Then the total probability for requiring EFA in IPC (e) is

$$P_6(EFA|e;h,A_D,A_S,s) = P_{EO}(\Psi_o|e;h,A_D,s) \qquad (8)$$

$$+ (1-P_{EO}(\Psi_o|e;h,A_D,s))\, P_{EI}(\Psi_{Ie}|e;h,A_D,A_S,s)$$

We evaluate P_{EO} and P_{EI} by summing probabilities over sets Ψ_o and Ψ_{Ie}. P_{EO} is calculated by summing P_3 over set Ψ_o:

$$P_{EO}(\Psi_o|e;h,A_D,S) = \sum_{d,\tilde{b}\epsilon\Psi_o} P_3(d,\tilde{b}|e;h,A_D,S) \qquad (9)$$

Similarly, P_{EI} is further defined using P_5:

$$P_{EI}(\Psi_{Ie}|e;h,A_D,A_S,s) \qquad (10)$$

$$= \sum_{a_I,\, t_I\epsilon\Psi_{Ie}} \sum_{b_I} \sum_{c_I} P_5(a_I,t_I,b_I,c_I|e;h,A_D,A_S,s)$$

In IAA, homogeneity of the simulated fire situation is assumed. That is, a single fire behavior and IPC will apply throughout the analysis, and a single fire size affecting all resources will result. The invalidity of this assumption after the fire attains a certain size or elapsed time is precisely what makes EFA necessary. In EFA, a fire may move through several IPC's or equivalent before containment. Therefore, it is necessary to describe the results in inhomogeneous terms. The means used here is to describe fire behaviors and burned areas by vectors with a component for each affected resource. Let

a_E = escaped fire burned area vector, with a component for each affected resource

b_E = escaped fire behavior array, with a behavior vector for each affected resource

c_E = escaped fire cost class, including cost of prior IAA if pertinent.

Then we assume that EFA will give probability functions of the form:

$$P_7(a_E,b_E,c_E|e;h,A_D,A_S,s) \qquad (11)$$

Suppression time t_I was used in the IAA escape probability calculations (Equations 6, 10), but will not be needed in further calculations. We define (a_I',b_I',c_I') as the class of nonescape IAA results, i.e., without Ψ_{Ie}. We sum P_5 over t_I to give:

$$P5a(a_I',b_I',c_I'|e;h,A_D,A_S,s) \qquad (11a)$$

$$= \sum_{t_I} P_5(a_I,t_I,b_I c_I|e;h,A_D,A_S,s) \div [1-P_{EI}(\Psi_{Ie}|e;h,A_D,A_S,s)]$$

Let

$$\alpha_I = (a_I',b_I',c_I')$$

$$\alpha_E = (a_E,b_E,c_E)$$

where the a,b,c,'s are as previously defined. Also, assume α_I and α_E to be mutually exclusive. Then, using P_5, P_6, and P_7, the final suppression area, behavior, and cost probability function is

$$P_8(\alpha|e;h,A_D,A_S,s) \qquad (12)$$

$$= \begin{cases} P_{5a}(\alpha|e;h,A_D,A_S,s)\,(1-P_6(EFA|e;h,A_D,A_S,s)), & \alpha \epsilon\, \alpha_I \\ P_7(\alpha|EFA,e;h,A_D,A_S,s)\, P_6(EFA|e;h,A_D,A_S,s), & \alpha \epsilon\, \alpha_E \end{cases}$$

Fire size and behavior are used in the next section to calculate probabilities for fire effects on land resources.

Fire Effects

The effects of fire on land resources and the measures of productivity vary greatly between resources. Calculations of the immediate impacts of fire on resource quantities require transformations from the physical effects of fire (Peterson 1981). For example, a physical effect is area of grazing range burned; the corresponding resource effect is animal grazing capacity lost. The immediate resource effects must be further evaluated, over time, to obtain the final fire impacts: total animal-unit-months lost or gained, for the range example.

The FMS parameter set S includes R, the resource management emphasis vector with a component for each resource type. Fire effects are calculated for types having nonzero emphasis. In fire effects valuation, e.g., deriving dollar values for fire effects, the component values in R imply specific prefire and postfire management procedures.

Immediate physical resource effects probabilities are given by the FEES fire effects module in the form:

$$P_9(g|a,b,e;\Gamma(s),s) \qquad (13)$$

where

g = vector of immediate physical effects per unit burned area for emphasized resources

$\Gamma(s)$ = array of prefire resource characteristics needed to calculate fire effects in s

Other quantities are as previously defined. In particular, it should be recalled that a and b are fire area and behavior vectors with components corresponding to those of g.

Probabilities P_8 and P_9 are combined and summed on b, which is no longer needed, to give P_{10} which will be used later after defining probabilities for resource changes. Then

$$P_{10}(a,g,c|e;h,A_D,A_S,\Gamma(s),s) \qquad (14)$$

$$= \sum_b P_8(a,b,c|e;h,A_D,A_S,s)P_9(g|a,b,e,;\Gamma(s),s)$$

Resource Changes

Persistence or delay of fire effects on resources from year to year implies that resource changes in any year t, from a particular previous fire, must be correlated with changes from that fire in preceding years. However, we assume that resource changes from any fire are independent of those from all other fires. Then, the probability of resource change per unit burned area in year t after a fire in e with effects g is of the form:

$$P_{11}^t(q_t|q_{t-1},\ldots,q_1,g,e,a;\Gamma(s),\Omega^t(s),s) \qquad (15)$$

where

q_t = resource change vector per unit burned area in year t after a fire causing effects g in year 1

$\Omega^t(s)$ = postfire resource management program for years 1 through t for the fire-affected resources

In the mathematical development of the model which follows, the year t of resource changes is treated as an integer variable up to some year T. In application of the model, fire effects on resources are confined generally to a small number of years. In considering fire effects on timber output, for example, the effects of a single fire can be lumped into, say, 2 years—the year of positive effect due to salvage, if any, and the future year of negative effects on planned or actual harvest. One or two thinning harvests may be included between. The point is that even though a total time span T of 50 or 100 years may be involved, the effects are null in all but a few years.

Similarly, significant effects on range, recreation, wildlife, or watershed are confined generally to a small number of years following a fire.

The conclusions are that computational problems which may appear insuperable for t = 1, 2, ..., 100, say actually are tractable because only a few years are of significance. The probabilities of effects g are obtained by summing P_{10} on costs (which are not needed for resource change calculations). The result is combined with P_{11} and summed over the range of effects g and fire area vector a (as it affects resource changes per unit fire area):

$$P^{t}_{12}(q_t|q_{t-1},...,q_1,e;h,\Gamma(s),A_D,A_S,\Omega^t(s),s) \tag{16}$$

$$= \sum_a\sum_g[P^t_{11}(q_t|q_{t-1},...q_1,g,e,a;\Gamma(s),\Omega^t(s),s) \times \sum_c P_{10}(a,b,c|e;h,A_D,A_S,\Gamma(s))]$$

To shorten notation, the "given" parameters and programs indicated following the semicolon and h in the expression for P_{12} will be abbreviated using the notation $\Phi^t(s)$. That is

$$\Phi^t(s) = [\Gamma(s),A_D,A_S,\Omega^t(s),s] \tag{17}$$

Resource output changes are assumed to be additive over the years following a fire. Given a set of resource change vectors $[q_1, q_2, ..., q_T]$ over T years, the cumulative total change per unit burned area is

$$Q_T = \sum_{t=1}^{T} q_t \tag{18}$$

The probability for a particular Q_T is just the probability of the corresponding set of q_t values. Using P^t_{12} from equation 16, the joint probability for the q_t's is

$$P^T_{13}(q_T,...,q_1|e;h,\Phi^T(s)) \tag{19}$$

$$= \prod_{t=1}^{T} P^t_{12}(q_t|q_{t-1},...,q_1,e;h,\Phi^t(s))$$

To gain computational efficiency, we rewrite equation 19 in recursive form, for k = 2, 3, ..., T:

$$P^k_{13}(q_k,...,q_1|e;h,\Phi^k(s)) \tag{20}$$

$$= P^{k-1}_{13}(q_{k-1},...,q_1|e;h,\Phi^{k-1}(s)) \times P^k_{12}(q_k|q_{k-1},...,q_1,e;h,\Phi^k(s))$$

with

$$P^1_{13}(q_1|e;h,\Phi^1(s)) = P^1_{12}(q_1|e;h,\Phi^1(s)) \tag{21}$$

From the definition of Q_T (equation 18), we note that

$$q_t = Q_t - Q_{t-1}$$

for $t>1$, and $q_1 = Q_1$ so that we can write:

$$P^k_{14}(Q_k,...,Q_1|e;h,\Phi^k(s)) \tag{22}$$

$$= P^k_{13}(Q_k-Q_{k-1},...,Q_1|e;h,\Phi^k(s))$$

with

$$P^1_{14}(Q_1|e;h,\Phi^1(s)) = P^1_{13}(Q_1|e;h,\Phi^1(s)) \tag{23}$$

$$= P^1_{12}(Q_1|e;h,\Phi^1(s))$$

Then, equations 20 and 21 can be rewritten entirely in terms of the Q's:

$$P^k_{14}(Q_k,...,Q_1|e;h,\Phi^k(s)) = P^{k-1}_{14}(Q_{k-1},...,Q_1|e;h,\Phi^{k-1}(s)) \tag{24}$$

$$\times P^k_{12}(Q_k-Q_{k-1},...,Q_1|Q_{k-1}-Q_{k-2},...,Q_1,e;h,\Phi^k(s))$$

with

$$P^1_{14}(Q_1|e;h,\Phi^1(s)) = P^1_{12}(Q_1|e;h,\Phi^1(s)) \text{ and } k = 2, 3, ..., T.$$

When P^T_{14} has been calculated, we can sum on the Q_t's for $t<T$ to get the probability for total resource change per unit burned area, Q_T, over T years following a fire in e:

$$P^T_{15}(Q_T|e;h,\Phi^T(s)) = \sum_{Q_1}...\sum_{Q_{T-1}} P^T_{14}(Q_T,...Q_1|e;h,\Phi^T(s)) \tag{25}$$

Total resource change vector Q^*_T is calculated by multiplying the resource change per unit area by the fire area, i.e., $Q^*_T = Q_T a$. Then the probabilities for Q^*_T are given by

$$P_{16}(Q^*_T|e;h,\Phi^T(s)) \tag{25a}$$

$$= \sum_t[P^T_{15}\frac{Q^*_T}{a}|e;h,\Phi^T(s))\sum_b\sum_c P_8(a,\tilde{b},c|e;h,A_D,A_S,s)]$$

where P_{16} is defined for values of Q^*_T such that (Q^*_T/a) is in the domain of P^T_{15} and a is in the domain of P_8.

We now have probabilities for total resource changes due to fires in each IPC for years 1 through T, where year 1 is the year of fire occurrence. We must combine these changes and probabilities over all IPC's in the FMS, and then use probabilities for annual numbers of fires to get probabilities for total annual resource changes in the FMS.

Fire Occurrence

Assume a function $P_{17}(e;h,x,A_P,A^x_1,s)$, giving the probability that a fire of type h, in year x, occurs in parameter cell e, given prevention program A_P and fuels treatment program A^x_1 through years 1 to x.

The probability of total resource change vector Q_{Txh} over T years, following a fire of type h in year x is

$$P_{18}(Q_{Txh};h,x,T,\Phi^T(s,x)) \tag{26}$$

$$= \sum_e P^T_{16}(Q^*_T|e;h,\Phi^T(s))P_{17}(e;h,x,A_P,A^x_f,s)$$

where A_P, A^x_f, and $\Phi^T(s)$ have been included in $\Phi^T(s,x)$.

Given a total of N_{xh} fires of type h in year x and assuming independence of effects between fires, the distribution of these fires over the Q_{Txh} values is given by

$$P_{19}(N_{QTxh}|N_{xh};h,x,T,\Phi^T(s,x)) \tag{27}$$

$$= M(N_{QTxh}|N_{xh};P_{18}(Q_{Txh};h,x,T,\Phi^T(s,x)))$$

where N_{QTxh} is the number of fires in year x of type h giving resource changes Q_{Txh} over T years. M is a multinomial distribution of the N_{xh} fires over the Q_{Txh} values which have probabilities P_{18}.

Assume a probability distribution $P_{20}(N_{xh};h,x,A_P,s)$ for N_{xh}, the number of fires of type h in year x with fire prevention program A_P. Then, the total probability per year for N_{QTxh} is

$$P_{21}(N_{QTxh};h,x,T,\Phi^T(s,x)) \tag{28}$$

$$= \sum_{N_{xh}} P_{19}(N_{QTxh}|N_{xh};h,x,T,\Phi^T(s,x))P_{20}(N_{xh};h,x,A_P,s)$$

where prevention program A_P is included in $\Phi^T(s,x)$ in P_{21} and hereafter.

Let N^j_{QTxh} represent a vector (j) of numbers of fires over the Q_{Txh} values. Then, the total resource change vector for this number vector is $\tilde{Q}^j_{Txh}$ given by multiplying each component of the resource change vector by the corresponding number of fires. We assume that the effects of individual fires are independent and additive.

$$\tilde{Q}^j_{Txh} = Q_{Txh}N^j_{QTxh} \tag{29}$$

(Formally N^j_{QTxh} should be a diagonal matrix here rather than a vector. We assume that the meaning is clear.)

The probability for $\tilde{Q}^j_{Txh}$ is just the probability for fire number vector N^j_{QTxh}:

$$P_{22}(\tilde{Q}^j_{Txh};h,x,T,\Phi^T(s,x)) \tag{30}$$

$$= P_{21}(N^j_{QTxh};h,x,T,\Phi^T(s,x))$$

These probabilities are aggregated and summed over arrangements j to give

$$P_{23}(\tilde{Q}_{Txh};h,x,T,\Phi^T(s,x)) \tag{31}$$

$$= \sum_{\tilde{Q}^j_{Txh} \in \tilde{Q}_{Txh}} P_{22}(\tilde{Q}^j_{Txh};h,x,T,\Phi^T(s,x))$$

The year of fire occurrence x and the number of years T over which fire effects are accumulated have been treated as parameters. We now wish to form an expression for resource changes due to fires of type h occurring in years 1 through Z, say. Let $\hat{Q}_{Zh}$ be this vector of changes. Then

$$\hat{Q}_{Zh} = \sum_{x=1}^{Z} \tilde{Q}_{(Z-x+1)xh} \tag{32}$$

Let $\tilde{Q}^k_{(Z-x+1)xh}$ be a particular set of values for $\tilde{Q}$ over years x = 1 to Z in an arrangement k. Then the probability for $\tilde{Q}^k_{Zh}$ resulting from this set of values is

$$P_{24}(\hat{Q}^k_{Zh};h,z,\Phi^Z(s,Z)) \tag{33}$$

$$= \prod_{x=1}^{Z} P_{23}(\tilde{Q}^k_{(Z-x+1)xh};h,x,Z-x+1,\Phi^{Z-x+1}(s,x))$$

Aggregating and summing on arrangement k gives

$$P_{25}(\hat{Q}_{Zh};h,Z,\Phi^Z(s,Z)) \tag{34}$$

$$= \sum_{\hat{Q}^k_{Zh} \in \hat{Q}_{Zh}} P_{24}(\hat{Q}^k_{Zh};h,Z,\Phi^Z(s,Z))$$

Finally, we sum over fire types h to get

$$\hat{Q}^m_Z = \sum_h \hat{Q}^m_{Zh} \tag{35}$$

for arrangement m. Then the probabilities for sets of values $\hat{Q}^m_Z$ are given for this arrangement by

$$P_{26}(\hat{Q}^m_Z;Z,\Phi^Z(Z)) = \prod_h P_{25}(\hat{Q}^m_{Zh};h,Z,\Phi^Z(s,Z)) \tag{35a}$$

Summing probabilities on m and aggregating gives

$$P_{27}(\hat{Q}_Z;Z,\Phi^Z(s,Z)) = \sum_{\hat{Q}^m_Z \in \hat{Q}_Z} P_{26}(\hat{Q}^m_Z;Z,\Phi^Z(s,Z)) \tag{36}$$

Function P_{27} gives probabilities for the total resource change vector $\hat{Q}_Z$ over Z years. Marginal distributions for individual resource components of $\hat{Q}_Z$ are easily obtained by summing P_{27} over the other components. Expected values are calculated by the usual procedures.

Valuation of Resource Changes

The financial impacts of resource changes due to fire are calculated using a process quite similar to that outlined above for amounts of resource changes. The differences are that suppression costs must be carried through the calculations and that dollar values are discounted to present values.

We pick up the previous calculations at equation (16) where the summation on c is omitted, giving a probability function:

$$P^t_{28}(q_t,c|q_{t-1},\ldots,q_1,e;h,\Phi^t(s)) \tag{37}$$

where $\Phi^t(s)$ is defined in equation 17. Expression (37) gives the joint probability for resource changes per unit burned area in year t following a fire and suppression costs for the fire, given resource changes for previous years and parameter set e for the fire location.

Let $\tilde{v}_t$ be the dollar value vector per unit burned area for resource change vector q_t (Althaus and Mills 1982). Assume a function f_t such that $\tilde{v}_t = f_t(q_t)$, and the inverse function F_t giving $q_t = F_t(\tilde{v}_t)$.

Discounted changes, due to fire, in the dollar values of resource outputs are assumed to be additive over the years following a fire. Given a set of resource change vectors (q_1, q_2, ..., q_T) over T years, the total present value vector (in year 1) for the sum of these changes using discount rate I is:

$$V_T = \sum_{t=1}^{T} f_t(q_t)/(1+I)^{t-1} \tag{38}$$

The probability of a particular V_T is just the probability of the corresponding set of q_i's. Using P_{28}^{t} from equation 37:

$$P_{29}^{T}(q_T,\ldots,q_1,c|e;h,\Phi^T(s)) \tag{39}$$

$$= \prod_{i=1}^{T} P_{28}^{i}(q_i,c|q_{i-1},q_{i-2},\ldots,q_1,e;h,\Phi^i(s))$$

In recursive form:

$$P_{29}^{k}(q_k,\ldots,q_1,c|e;h,\Phi^k(s)) \tag{40}$$

$$= P_{29}^{k-1}(q_{k-1},\ldots,q_1,c|e;h,\Phi^{k-1}(s))P_{28}^{k}(q_k,c|q_{k-1},\ldots,q_1 e;h,\Phi^k(s))$$

for k = 2, 3, ..., T, and with

$$P_{29}^{1}(q_1,c|e;h,\Phi^1(s)) = P_{28}^{1}(q_1,c|e;h,\Phi^1(s)) \tag{41}$$

From equation 38,

$$f_i(q_i) = (V_i - V_{i-1})(1+I)^{i-1}$$

so that

$$q_1 = F_1(V_1)$$

and

$$q_i = F_i[(V_i - V_{i-1})(1+I)^{i-1}]$$

for $i \geq 2$. Then we can write

$$P_{30}^{k}(V_k,\ldots,V_1,c|e;h,\Phi^k(s)) \tag{42}$$

$$= P_{29}^{k}(F_k[V_k - V_{k-1})(1+I)^{k-1}],\ldots,F_1(V_1),c|e;h,\Phi^k(s))$$

with

$$P_{30}^{1}(V_1,c|e;h,\Phi^1(s)) = P_{29}^{1}(F_1(V_1),c|e;h,\Phi^1(s)) \tag{43}$$

Equations 40 and 41 can be written entirely in terms of the V's, using equations 42 and 43:

$$P_{30}^{k}(V_k,\ldots,V_1,c|e;h,\Phi^k(s)) \tag{44}$$

$$= P_{30}^{k-1}(V_{k-1},\ldots,V_1,c|e;h,\Phi^{k-1}(s))P_{28}^{k}(F_k[(V_k - V_{k-1})(1+I)^k],c|$$

$$F_{k-1}[(V_{k-1} - V_{k-2}) \times (1+I)^{k-1}],\ldots,F_1(V_1),e;h,\Phi^k(s))$$

for k = 2, 3, ..., T and with P_{30}^{1} given by equation 43.

After P_{30}^{T} is calculated, the probabilities are summed over the V_i's for $i < T$ to give the probability of total dollar impact of resource changes per unit burned area over T years, discounted to the year of the fire:

$$P_{31}^{T}(V_T,c|e;h,\Phi^T(s)) \tag{45}$$

$$= \sum_{V_{T-1}} \ldots \sum_{V_1} P_{30}^{T}(V_T,\ldots,V_1,c|e;h,\Phi^T(s))$$

From this point in the calculations, the development parallels that under Fire Occurrence in the previous section from after equation 25 through equation 31. The equivalent of function P_{23} here is

$$P_{32}(\tilde{V}_{Txh},\tilde{c}_{xh};h,x,T,\Phi^T(s,x))$$

This function gives the joint probability of resource value change vector $\tilde{V}_{Txh}$ and suppression cost $\tilde{c}_{xh}$ for a fire of type h, where the value changes include the time stream from year x to year x+T, discounted to the year of the fire, x.

The resource change values and suppression costs in year x are further discounted to present values:

$$V_{Txh} = \tilde{V}_{Txh}/(1+I)^{x-1} \text{ and } c_{xh} = \tilde{c}_{xh}/(1+I)^{x-1} \tag{46}$$

The corresponding probabilities, using P_{32} are

$$P_{33}(V_{Txh},c_{xh};h,x,T,\Phi^T(s,x)) \tag{47}$$

$$= P_{32}(V_{Txh}(1+I)^{x-1},c_{xh}(1+I)^{x-1};h,x,T,\Phi^T(s,x))$$

Resource change values and suppression costs are all discounted to present values and can now be summed over all years of fire occurrence x. If the sum is through year Z, the number of years for accumulation of values, T, is Z−x+1 for each x. Then

$$\hat{V}_{Zh} = \sum_{x=1}^{Z} V_{(Z-x+1)xh} \text{ and } \hat{c}_{Zh} = \sum_{x=1}^{Z} c_{xh} \tag{48}$$

Let $V^{j}_{(Z-x+1)xh}$ and c^{j}_{xh} be a particular set of values, in an arrangement j. Then the probability for the corresponding sums is

$$P_{34}(\hat{V}^{j}_{Zh},\hat{c}^{j}_{Zh};h,Z,\Phi^Z(s,z)) \tag{49}$$

$$= \prod_{x=1}^{Z} P_{33}(V^{j}_{(Z-x+1)xh},c^{j}_{xh};h,x,Z-x+1,\Phi^x(s,x))$$

These probabilities are summed over all arrangements j and aggregated along with $\hat{V}^j$ and $\hat{c}^j$ to give

$$P_{35}(\hat{V}_{Zh},\hat{c}_{Zh};h,Z,\Phi^Z(s,Z)) \tag{50}$$

$$= \sum_{\substack{\hat{V}^{j}_{Zh} \in \hat{V}_{Zh} \\ \hat{c}^{j}_{Zh} \in \hat{c}_{Zh}}} P_{34}(\hat{V}^{j}_{Zh},\hat{c}^{j}_{Zh};h,Z,\Phi^Z(s,Z))$$

Resource value change vectors and costs are next summed over fire type h to give

$$\hat{V}_Z = \sum_h \hat{V}_{Zh} \text{ and } \hat{c}_Z = \sum_h \hat{c}_{Zh} \tag{51}$$

If $(\hat{V}^k_{Zh}, \hat{c}^k_{Zh})$ is a particular arrangement k of values, the probability for the corresponding sum is

$$P_{36}(\hat{V}^k_Z, \hat{c}^k_Z; Z, \Phi^Z(s,Z)) = \prod_h P_{35}(\hat{V}^k_{Zh}, \hat{c}^k_{Zh}; h, Z, \Phi^Z(s,Z)) \tag{52}$$

Summing over arrangements k and aggregating:

$$P_{37}(\hat{V}_Z, \hat{c}_Z; Z, \Phi^Z(s,Z)) \tag{53}$$

$$= \sum_{\substack{\hat{V}^k_Z \epsilon \hat{V}_Z \\ \hat{c}^k_Z \epsilon \hat{c}_Z}} P_{36}(\hat{V}^k_Z, \hat{c}^k_Z; Z, \Phi^Z(s,Z))$$

This function gives the probability for present value of suppression costs and value change for each resource type over a planning period of Z years. The "bottom line" FEES model output is "total cost plus net value change" (Mills and Bratten 1982). To get this quantity, the components of $\hat{V}_Z$ must be added to suppression costs $\hat{c}_Z$ and the present value of fixed costs associated with $\Phi^Z(s,Z)$ added to the total.

Let $\hat{V}_{Z1}$, $\hat{V}_{Z2}$, ..., $\hat{V}_{ZN}$ be the components of $\hat{V}_Z$ for resources 1, 2, ..., N. Then, net value change plus suppression cost is

$$\hat{V}_Z = \sum_{i=1}^{N} \hat{V}_{Zi} + \hat{c}_Z \tag{54}$$

Let $\hat{V}^j_{Zi}$ and $\hat{c}^j_Z$ be a particular arrangement j of values. Then, the probability for the corresponding sum is

$$P_{38}(\hat{V}^j_Z; Z, \Phi^Z(s,Z)) = \prod_i P_{37}(\hat{V}^j_{Zi}, \hat{c}^j_Z; Z, \Phi^Z(s,Z)) \tag{55}$$

Summing over arrangements and aggregating gives

$$P_{39}(V_Z; Z, \Phi^Z(s,Z)) = \sum_{\hat{V}^j_Z \epsilon V_Z} P_{38}(\hat{V}^j; Z; \Phi^Z(s,Z)) \tag{56}$$

Let the present value, fixed cost of the programs in $\Phi^Z(s,Z)$ be C(s,Z). Then, adding these costs to $\hat{V}_Z$ gives total cost plus net value change

$$D_Z = \hat{V}_Z + C(s,Z)$$

and

$$P_{40}(D_Z; Z, \Phi^Z(s,Z)) = P_{39}(D_Z - C(s,Z); Z, \Phi^Z(s,Z)) \tag{57}$$

The expected value for D_Z is

$$\overline{D}_Z = \sum_{D_Z} D_Z P_{40}(D_Z; \Phi^Z(s,Z)) \tag{58}$$

OUTLOOK FOR MODEL IMPLEMENTATION

The overall probability model has been defined in functional mathematical form. The independent and dependent variables and parameters for the various modules have been specified to the degree possible.

Implementation of the model could proceed using various methods and levels of completeness for the modules. For example, the initial attack module could be constructed as an analytical model, assuming the availability of data or physical models for the required probability functions. Alternatively a Monte-Carlo procedure could be used to calculate the probabilities using a deterministic model with stochastic inputs.

Some of the functions and relationships may require interpretation to fit unforeseen situations. In particular, the escaped fire analysis procedures and some of the fire effects analyses will become more clearly defined as additional research efforts proceed. The overall model has been defined in sufficiently general terms that it should readily adapt to the final forms taken by these and the other modules.

REFERENCES

Albini, Frank A. **Estimating wildland fire behavior and effects.** Gen. Tech. Rep. INT-30. Ogden, Utah: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1976. 92 p.

Althaus, Irene A.; Mills, Thomas J. **Resource values in analyzing fire management programs for economic efficiency.** Gen. Tech. Rep. PSW-57. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 9 p.

Bratten, Frederick W.; Davis, James B.; Flatman, George T.; Keith, Jerold W.; Rapp, Stanley R.; Storey, Theodore G. **FOCUS, a fire management planning system—final report.** Gen. Tech. Rep. PSW-49. Berkeley, Calif: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1981. 34 p.

Gonzalez-Caban, Armando. **Fire management program economic cost: initial attack and large fire suppression.** 1981. Unpublished draft supplied by author.

Haven, Lisa; Hunter, T. Parkin; Storey, Theodore G. **A compilation and extrapolation of existing fireline production rates.** 1981. Unpublished draft supplied by authors.

Hirsch, Stanley N.; Meyer, Gary F.; Radloff, David L. **Choosing an activity fuel treatment for southwest ponderosa pine.** Gen. Tech. Rep. RM-67. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 15 p.

Hunter, T. Parkin. **Initial attack module, problem analysis.** 1980. Unpublished draft supplied by author.

Hunter, T. Parkin. **Large fire module, problem analysis.** 1981. Unpublished draft supplied by author.

Mills, Thomas J.; Bratten, Frederick W. **FEES: design of a *F*ire *E*conomics *E*valuation *S*ystem.** Gen. Tech. Rep. PSW-65. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 26 p.

Peterson, David L. **Fire effects module, problem analysis.** 1981. Unpublished draft supplied by author.

Rothermel, Richard C. **A mathematical model for predicting fire spread in wildland fuels.** Res. Paper INT-115. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972. 40 p.

Salazar, Lucy. **Fire behavior model and fuel treatment, problem analysis.** 1981. Unpublished draft supplied by author.

Schroeder, Mark J. and others. **Synoptic weather types associated with critical fire weather.** Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1964, 492 p.

Sparhawk, W. N. **The use of liability ratings in planning forest fire protection.** J. Agric. Res. 30(8):693-762; 1925.

U.S. Department of Agriculture, Forest Service. **FSH 5109-19—Fire management analysis and planning handbook.** Washington, DC: Forest Service, U.S. Department of Agriculture; 1982.

Bratten, Frederick W. **Probability model for analyzing fire management alternatives: theory and structure.** Gen. Tech. Rep. PSW-66. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 11 p.

A theoretical probability model has been developed for analyzing program alternatives in fire management. It includes submodels or modules for predicting probabilities of fire behavior, fire occurrence, fire suppression, effects of fire on land resources, and financial effects of fire. Generalized "fire management situations" are used to represent actual fire management areas. The model serves as the framework for the Fire Economics Evaluation System now being designed at the Pacific Southwest Forest and Range Experiment Station. Outputs from the model will consist of probability distributions for changes in resources caused by fire and for a measure of economic efficiency over a planning period.

Retrieval Terms: Fire Economics Evaluation System, fire economics, fire management, probability model

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

General Technical
Report PSW-67

Living More Safely in the Chaparral-Urban Interface

Klaus W. H. Radtke

The Author:

KLAUS W.H. RADTKE, at the time this report was prepared, was senior deputy forester, Department of Forester and Fire Warden, County of Los Angeles. He earned a bachelor's degree in forest management (1968) and a master's degree in natural resource management (1980) at Humboldt State University, Arcata, California, and a doctorate in wildland resource science (1981) at the University of California, Berkeley.

Acknowledgments:

This report was prepared under Cooperative Agreement 21-436 between the Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, and the Department of Forester and Fire Warden, County of Los Angeles.

I thank the following persons for their assistance in making this publication possible: **C. Eugene Conrad**, of the Station research staff, for providing insights in the ecological aspects of chaparral management; **May E. Huddleston**, formerly of the Station staff, for technical publishing assistance; **Arthur M. Arndt**, formerly of the Department staff, for his strong support of the research work reported herein; and **James R. Sweeney**, San Francisco State University, **Paul J. Zinke**, University of California, Berkeley, and **Ronald H. Wakimoto**, University of Montana, Missoula, for their helpful suggestions in reviewing earlier drafts of the manuscript.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

June 1983

Living More Safely in the Chaparral-Urban Interface

Klaus W. H. Radtke

CONTENTS

Introduction 1
The Chaparral Environment 1
Chaparral Vegetation 1
Fire and Chaparral 2
Problems in Watershed Management 5
Dry-Creep, Wet-Erosion Cycle 5
Fire-Flood Cycle 7
Erosion Factors 9
Soils 9
Climate 9
Topography 10
Vegetation 11
Animals 11
Human Interference 13
Coping with Watershed Problems 14
Maintaining Slope Stability 14
Controlling Drainage 15
Controlling Animal Activity 16
Landscaping for Fire and Erosion Control 17
Establishing Greenbelts 20
Maintaining Compatibility of Plants 21
Choosing Low-Growing Species 22
Ice Plants 27
Coyote Brush 27
Rosemary 27
Prostrate Acacia 28
Rockrose 28
Periwinkle 28
Ivy 28
African Daisy 28
Watering Plants 28
Water-Saving Plants 28
Water Requirements 30
Overhead Impact Sprinklers 32
Planning for Home Safety from Fire 32
Reducing Fuel Load 33
Understanding Fire Behavior 34
Promoting Fire Safety 37
Clearing Brush Around Homes 40
Treating Newly Burned Chaparral Slopes 40
Direct Seeding 41
Annual Ryegrass 41
Barley 42
Check Dams 43
Boards 43
Jute Matting 44
Chain Link Fence 44
Sandbags and Deflector Barriers 44
Drains 45
Dry Walls 45
Plastic Sheeting 45
Guniting 46
What to Do When Caught in a Wildfire 47
Before Fire Approaches 47
When the Fire Front Arrives and Passes 47
When Caught in the Open 48
Evacuation and Road Closure 48
Appendix: List of Species Mentioned 49
References 50

In recent years, urban development has extended into rural areas around many of our larger cities. Where the topography is relatively flat and open, this encroachment presents no great difficulty, but where the cities are surrounded by steep, brush-covered slopes, development has resulted in all-too-frequent loss of life and property. Although intense efforts have been made to deal with this problem, one pressing need is clear: greater coordination in planning for fire control and for the prevention of flooding, landslides, and erosion.

The brushland fire-flood-erosion sequence is particularly well known in chaparral areas of southern California. Urban encroachment accelerates the cycle and adds the potential for tragedy. Unless adequate measures are taken in new developments, fire protection and flood control agencies are hard pressed to safeguard life and property.

When hazardous conditions come about through improper land use or lack of planning, they are extremely difficult to correct by either private or public action. Government agencies should therefore work together to adopt comprehensive protection plans before permission is granted for wildland development. These plans must resolve the problem presented by new construction in ecologically sensitive areas, so that added services for safeguarding such developments are not paid for by society as a whole.

Living in the urban-wildland interface creates biological and social problems which cannot be readily resolved. Logically, zoning ordinances should exclude development on steep chaparral wildlands and in areas where flooding is a common occurrence. But these are also the areas most desirable to potential home buyers because they offer a view or serve as secluded, wooded hideaways. Most of the pioneer homeowners who initially settled in these areas were aware of the danger of fire and flood and were able to live in closer harmony with natural conditions. Most modern homeowners, however, are ill equipped to live in the wildlands and have come to depend on private and public organizations for support and safety. Today's homeowners want to live in natural surroundings, but often do not know how. To live more safely in the mountains, they must regain the pioneering spirit of self-help, neighborhood teamwork, and an understanding of nature's ways. Too often, home buyers fail to realize that fire protection agencies may not be able to save the "home" from fire, and that building and safety and flood control agencies may be powerless to save them from floods and mudslides.

This report is intended to bring about greater understanding of a fragile ecosystem—chaparral. It describes preventive maintenance measures that should help reduce the damage from fire and flood. The information provided here is addressed to homeowners, home buyers, developers, landscape architects, land use planners, wildland managers, zoning agencies, city and county boards of supervisors, and other interested persons.

Although the report sometimes deals with them separately, protection from fire and prevention of erosion go hand in hand. Fire protection that weakens slopes and causes slides, or slope protection that increases fire hazard, can give us only a dangerous illusion of safety. From a realistic view, the price we must pay to live in the chaparral is high; it can be lowered only through wise planning and management.

THE CHAPARRAL ENVIRONMENT

Chaparral is a plant community in California that has adapted over millions of years to summer drought and frequent fires. Similar vegetation is found in regions of Mediterranean climate throughout the world. These regions lie along the western edges of the continents, roughly between 28° and 37° latitude in the Southern Hemisphere and between 30° and 43° latitude in the Northern Hemisphere. Except in the Mediterranean Sea, the ocean water in these regions is comparatively cool; cold currents flow toward the equator, and local upwelling brings cold water to the surface. In summer, high-pressure systems bring dry air to these regions, but in winter, rain-producing fronts move in.

Mediterranean regions are found in the countries of Europe, Africa, and Asia that border the Mediterranean

Sea; in southwest Australia and South Africa; and in Central Chile, Mexico, and the State of California. The climate is characterized by hot, dry summers and wet, moderate winters. Rainfall ranges from about 10 inches (250 mm) to above 32 inches (800 mm). The mixtures of plant species within these areas are determined by such factors as aspect and steepness of slope, soils, elevation, fire frequency, and local climate.

Chaparral Vegetation

Two distinct subformations of chaparral called "hard chaparral" and "soft chaparral" are clearly distinguished in recent ecological literature and are commonly referred to as chaparral and coastal sage scrub communities, respectively (Paysen and others 1980, Westman 1982). This distinction is important for both fire and slope management.

The coastal sage scrub community or "soft" chaparral is rapidly becoming an "endangered" habitat because it is commonly found in California's coastal zone, where most urban expansion is taking place. It is generally restricted to the more xeric sites at lower elevations, because of orographic effects, and at higher elevations because of shallow soils (Miller 1981). The dominant species that compose the coastal sage scrub community are of smaller stature than those in the chaparral community and provide a more open habitat that encourages more herbaceous species including the sages, California sagebrush, and deerweed.[1] The chaparral community as a whole is drought-tolerant. In comparison with hard chaparral species, which tend to start growth in winter, coastal sage species tend to start growth soon after the first significant autumn rains. Additionally, both annual plant productivity and wildfires in this community tend to be related to the amount of rainfall, whereas hard chaparral species are more independent of rainfall in these respects (Minnich 1983).

Generally, plant adaptations to drought include thick leathery leaves, reduced leaf size, and summer dormancy, a condition which enables the plant to reduce its metabolic functions and drop leaves under prolonged drought. Two adaptations to fire are sprouting and fire-stimulated germination of seeds. Sprouting produces new shoots from the roots or root crown after the top has been injured by fire, browsing, pruning, or other means (Sampson 1944). It may begin soon after a fire if soil moisture is available to the deep root system. After an early summer fire, sprouts may grow more than a foot tall before the first rains come in the fall.

Both sprouting and nonsprouting plant species germinate prolifically after fires. The seeds of many chaparral species remain viable for a long time; often a thick seed coat protects the endosperm from drying out. Fire often injures this seed coat so that seeds germinate under proper conditions of moisture and temperature. In the air-dried state, many seeds can tolerate temperatures higher than 302° F (150° C) for 5 minutes within the seed zone (top half-inch of soil layer), but tolerance to high temperatures is sharply reduced when seed moisture content is high (Sweeney 1956). Seeds of some plant species may germinate readily with or without fire, whereas other species with a hard seed coat, such as certain *Ceanothus* species and many legumes, often require very hot fires to germinate. Nature has developed a set of survival mechanisms for the varying fire and environmental conditions in the chaparral region.

Besides the sprouts and seedlings of the perennial chaparral species, seedlings of herbaceous species are abundant in the first few seasons after fire. Seeds of many of these species lie in the soil for years awaiting stimulation by fire for germination. Fire-dependent annuals and perennials are responsible for the beautiful array of wildflowers that can be seen everywhere the first few seasons after a fire. They provide a natural vegetative cover that helps temporarily to reduce the heavy erosion that can be expected from steep mountain slopes once existing protective cover has burned off. These short lived, fire-adapted species convert mineral nutrients to organic form, thus conserving nutrients that could be lost by leaching and erosion. Some species, such as deerweed, are able to obtain mineralized soil nitrogen from symbiotic bacteria and may be an important means of returning it to the soil in an available form for other plants. Nitrogen is the plant nutrient most easily lost during a fire.

Many chaparral plants exude chemical inhibitors, commonly called allelopathic agents. These volatile or water-soluble antagonistic chemicals are carried by the heat of the day or by water to the soil and other plants, where they may effectively stunt growth and reduce or eliminate seed germination (Muller 1966, Muller and others 1968, Rice 1974). Allelopathy is widespread in nature and the chemical agents probably accumulate in the soil from one year to the next. Allelopathy may function as a plant defensive mechanism that assures availability of the limited moisture and nutrients to the dominant plants on the site. By removing litter and burning the soil surface, fire acts to reduce the effects of these chemical inhibitors in the soil.

Plant species diversity peaks in the first few seasons after a fire, but is reduced when, in the years after a fire, the fire-dependent annuals and short-lived perennials fail to reproduce. In hard chaparral, shrub species such as bush poppy and *Ceanothus* may decline in vigor after 10 and 20 years, respectively, and provide dry, dead fuel for future fires. Chaparral fires aid in the continued survival of these species. The oldest stands of hard chaparral generally have the lowest species diversity and tend to be even-aged. In contrast, most mature coastal sage stands are uneven-aged and have greater species diversity because of seedling

---

[1]Common names of plants and animals are used throughout this publication. For scientific names, see Appendix: List of Species Mentioned.

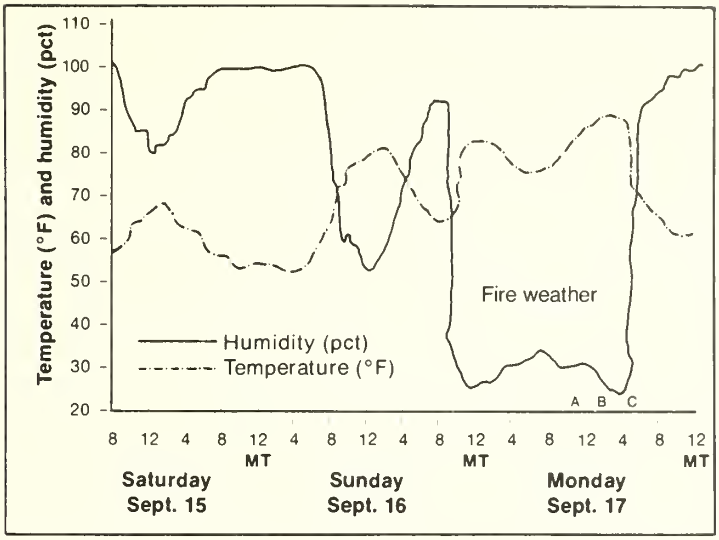


Figure 1—The 1923 Berkeley Fire—considered the most devastating in California's history—broke out in Wildcat Ridge (*A*), reaching the city (*B*) before finally coming under control (*C*). Wind velocity on September 17 was 40 mph (64.4 kph). (Source: Emanuel Fritz, University of California, Berkeley).

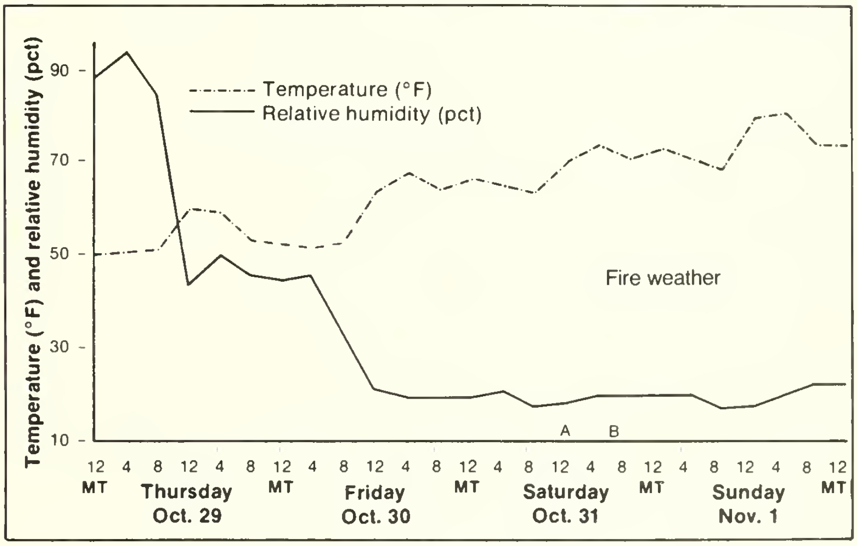


Figure 2—The Oat Fire in Los Angeles County, which started on October 31, 1981 (*A*) and burned 15,500 acres, was contained during the night (*B*) despite dangerous fire weather conditions characterized by low relative humidity. Young age classes (average: 11 years) of woody chaparral species offered relatively high resistance to fire spread.

establishment in the absence of fire and also greater herb diversity and cover.

Fire and Chaparral

Wildfires in California can occur at almost any time of year but are most prevalent during the dry season. Extreme fire conditions normally exist from September through December or until the winter rains end the dry season. Fires are more likely to occur during strong Santa Ana winds; these winds, also known as Santana, foehn, devil, or fire winds, blow from the north to northeast out of the Great Basin of Utah, Colorado, and surrounding northern States. As the air is compressed and forced southwestward to lower elevations, it becomes hot, dry, and gusty. When Santa Ana winds meet the local mountain winds, unpredictable weather patterns are often set up, making erratic fire fronts and spotting ahead of fires a common occurrence.

The rapid changes in temperature and humidity before, during, and after the 1923 Berkeley Fire illustrate the effects of fire winds on local climate (*fig. 1*). It was the most devastating fire in California history, with 624 houses burned in a single conflagration. High winds and wood shingles were the major factors in the heavy structural losses. Within 1 hour of the onset of the Santa Ana winds at 8:30 p.m., humidity had dropped from 92 to 25 percent. By midnight, temperature had increased from 63° F (17.2° C) to 82° F (27.8° C).

In southern California, humidity may approach 10 percent, as it did in the 1981 Oat Fire in Los Angeles County (*fig. 2*). Most major fires in the chaparral areas of southern California occur during this extreme fire weather. Under Santa Ana conditions, wildfires are extremely difficult to control unless the fuel supply is exhausted or the wind subsides. Studies of fire problems in Los Angeles County, particularly the coastal Santa Monica Mountains, point this out (Radtke 1978, 1982; Weide 1968). A study of frequency of fires burning more than 100 acres in the Santa

Monica Mountains from 1919 to 1982 indicates that the greater portion of wildland areas have burned at least once in the last 60 years; some have burned more than four times (*fig. 3*).

In the interior mountain ranges of Los Angeles County, fire frequency and number of acres burned are high in the summer months because of high summer temperatures and occasional lightning strikes. In the coastal ranges, fire frequency is lower in the summer, and lightning strikes are almost unknown as causes of fire. The number of acres burned is lower than in the interior ranges because the Catalina eddy, a marine breeze characterized by cool, moist air, penetrates the coastal mountains, primarily during June and July. This cool air is also responsible for the abnormal air circulation pattern of upslope instead of downslope winds during the evenings and into the night. In both the inland and coastal regions, the great toll of acreage burned from late September through December is the result of the Santa Ana wind, which has its highest frequency from September to February and is almost absent in July and August.

The pressure for urbanization of wildlands and open space is significant in the Santa Monica Mountain range. Before intensive settlement began, the north-facing slopes (those facing the San Fernando Valley) were relatively free from fire, but in the last 35 years large fires have greatly increased here. Presently the estimated fire-start probability in coastal sage scrub is about once in 14 years and in chamise chaparral once in 16 years (McBride and Jacobs 1980). This large increase in fire starts is the result of the population influx: almost every fire is started accidentally or deliberately by man.

The areas of highest fire frequency are at the fire perimeters, where fires burn together. In such a high-fire-frequency area, only the first fire burns hot because the quantity of fuel remaining for subsequent fires is reduced. The fire boundaries are determined by fire suppression activities, fuel types and their age classes, topography, fuel modification attempts (firebreaks, roads, and subdivisions), and wind conditions. Once a fire perimeter is established, it normally defines a portion of the boundaries for fires that burn as much as 20 to 30 years later (*fig. 3*). This becomes clear when we realize that chaparral fire intensity depends on the mixture and age of the individual chaparral species. The ratio of dead to live fuel is much greater in old than in young chaparral and varies from species to species. Past fire frequencies suggest that under natural conditions chaparral does not become highly fire-prone for about 15 to 20 years, or until some of the shorter-lived chaparral components die and increase the dead fuel (Philpot 1977). Coastal sage scrub, because of its shorter lived species and greater mixture of herbaceous species, can become highly fire-prone after 5 to 8 years.

The major flammable vegetation types found in the Santa Monica Mountains, namely chaparral, coastal sage scrub, and grassland, also have a direct bearing on fire

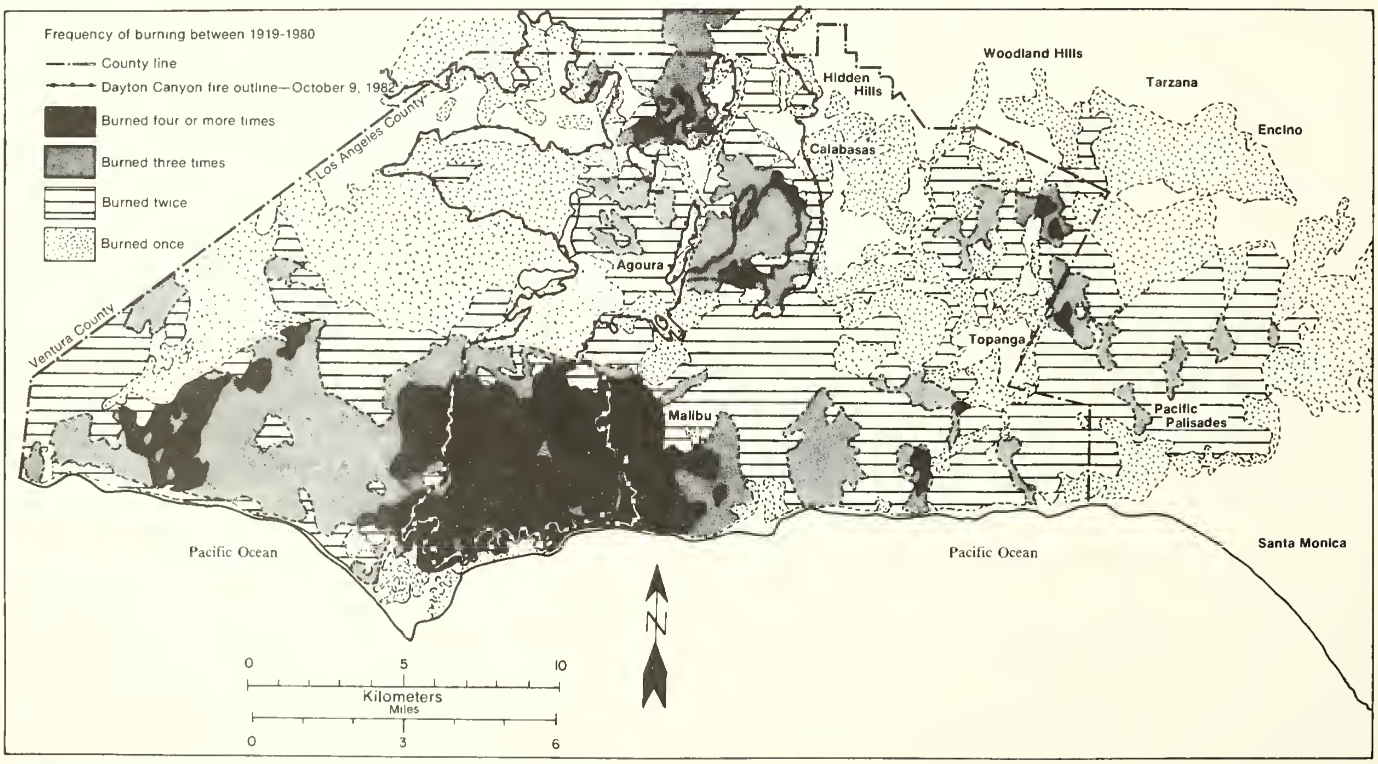


Figure 3—Frequency of fires exceeding 100 acres (40 hectares), in the Santa Monica Mountains (Ventura County line to the San Diego Freeway), southern California, 1919 to 1982. The outline on the left shows the extent of the Dayton Canyon Fire, October 1982.

frequency and fire intensity because of their different fuel loads and ease of ignition. For example, the flashy annual grassland fuel seldom exceeds 5 tons per acre (11.2 t/ha) whereas mature chaparral can exceed 30 tons per acre (67 t/ha). Grassland fires may be more frequent but are also more easily extinguished; however, they often carry the fire into the coastal sage scrub and chaparral. In any event, the fuels dictate the ease of fire starts and spread rates and this has a direct bearing on fire frequency. When the grasslands were grazed, reducing fuel loads, the highest fire frequency was found in coastal sage. With reduction in sheep grazing, fires in annual grassland, especially along roads and rights of way, have become the major source of fire starts. Nevertheless, fire starts have been historically concentrated in the coastal sage areas, where development has been greatest.

The predictable direction of fire spread in the Santa Monica Mountains during Santa Ana winds is south to southwest. This spread pattern is primarily influenced by fire winds and secondarily by topography. Because canyons in the eastern part of the Santa Monica Mountain range run in a south to south-westerly direction or parallel with the fire winds, fire is channeled up the canyons, spreads out as it reaches the ridges, contracts again as it is funneled downhill through the canyons, and may fan out in either direction as it reaches the beaches. The western portion of the Santa Monica Mountains does not have this pronounced linearity of canyons and fire winds, however. Fires therefore are more influenced by the direction of the winds and are more irregular in shape (Weide 1968).

PROBLEMS IN WATERSHED MANAGEMENT

A watershed is generally understood to be all the land and water within the confines of a drainage area. Vertically, it extends from the top of the vegetation to the underlying rock layers that confine water movement. A homeowner's watershed is the area of land whose drainage directly affects the safety of that person's property. Frequently this area includes adjacent properties over which the homeowner has little control. The drainage conditions may vary widely. Some homeowners have a well-manicured property adjacent to a street where all runoff is channeled into rain gutters. Others are in a watershed that includes steep slopes where most runoff finds its way eventually into intermittent stream beds. Sometimes the steep slopes are undercut by either natural stream channel erosion or development activities. To know how to safeguard their properties, homeowners should understand the erosional processes affecting a watershed, and the changes brought about by wildfire and their own actions.

Dry-Creep, Wet-Erosion Cycle

In chaparral, preserving the stability of the slopes is a major problem. Most chaparral in southern California grows on geologically young mountains where the steep slopes range from 25° to more than 70°. About 25 percent of the chaparral watershed exceeds the angle of repose, that is, the angle between the horizontal and the maximum slope that a particular soil or other material assumes through natural processes. On slopes that exceed the angle of repose, gravitational forces are likely to cause soil and rocks to slide or fall downhill unless anchored by plants. The angle of repose increases with the compaction of the material, with the average size of fragments, with the surface roughness and cohesion of soil particles, and, in sand, with an increase in moisture content up to the saturation point. For loosely heaped soil particles the standard angle of repose is approximately 9° for wet clay, 11° to 20° for dry sand and mixed earth, 21° to 25° for gravel, and 23° for moist clay (Van Burkalow 1945). Under natural conditions and where soil is anchored by deep-rooted plants, the angles of repose are much steeper than those given. Occurrence of landslides in chaparral is strongly related to the angle of repose for different soils, once cover, root depth, and root strength are taken into consideration.

On steep, harsh southern exposures, plant cover is sparse, and dry creep and dry ravel (downhill soil and debris movement during the dry season) become major erosional forces, especially where slopes beyond the angle of repose have been undercut. During low rainfall years, this dry creep and dry ravel often exceed wet erosion rates during the winter months. The debris settles at the foot of the slopes, where it is flushed out by the rainstorms of higher-than-usual intensity, which occur about every 5 years. Dry creep and dry ravel can also be greatly accelerated by animals, such as deer, rodents, and birds.

The dry-wet cycle on these slopes begins when summer drought encourages dry creep and dry ravel. The onset of the first light winter rains gives the soil cohesion and greatly reduces dry erosion. If further rains do not follow before the soil dries out, dry creep and dry ravel again accelerate. With heavier rains, dry erosion finally stops completely, so that erosion is at a minimum during the first part of the rainy season. As the rainy season continues, however, the soil mantle becomes saturated and rill and gully (overland) erosion accelerates. Toward the end of the rainy season and until the soil surface dries out and loses its cohesiveness, erosion is again low (Anderson and others 1959).

The erosion cycle is influenced by topography and vegetation. A north-facing slope is less exposed to the sun than a south-facing slope, and is therefore more moist for the greater part of the year. On north exposures, deeper soils and more dense plant cover of different species have developed over time, and these greatly reduce dry creep and overland erosion. Dry ravel occurs sporadically but may

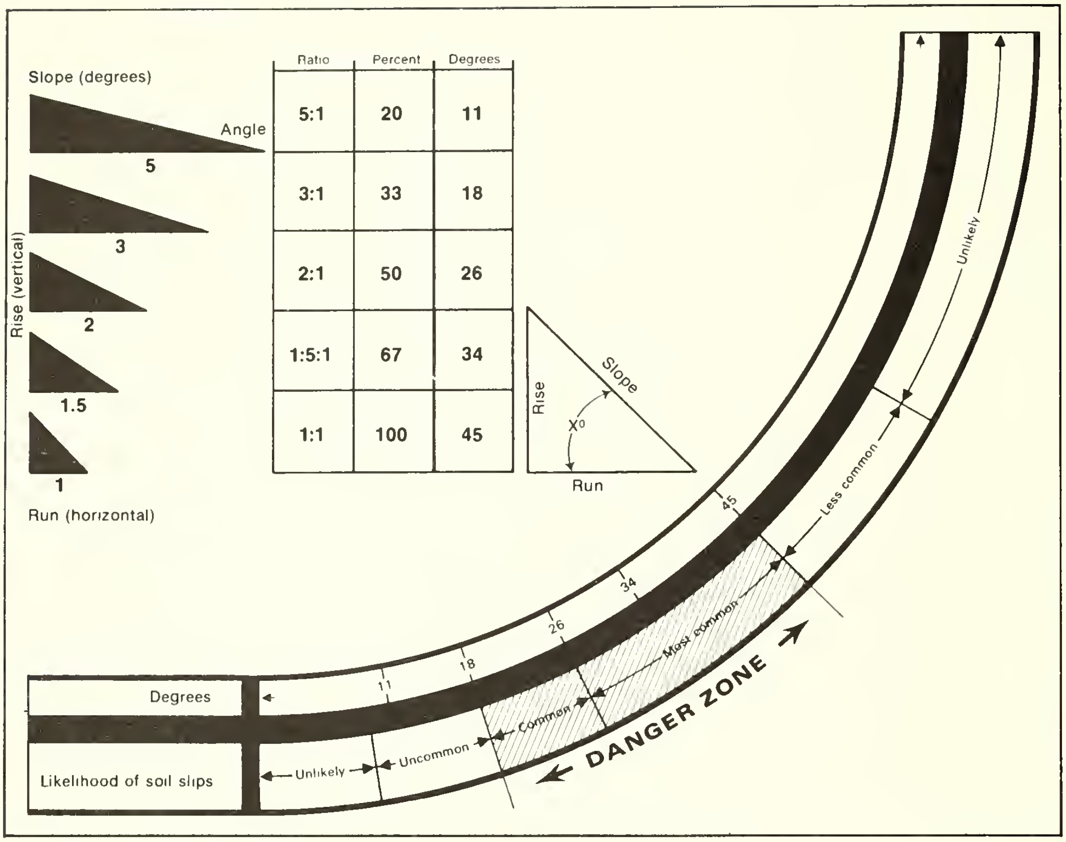


Figure 4—Slope ratio, percent slope, and degree of slope are shown for some hillsides of varying steepness. On natural slopes, the danger of soil slip failures is related to slope angles. The angle may be expressed as the ratio of run to rise, either as a percent (rise/run) or in degrees (angle between run and slope) (Campbell 1975).

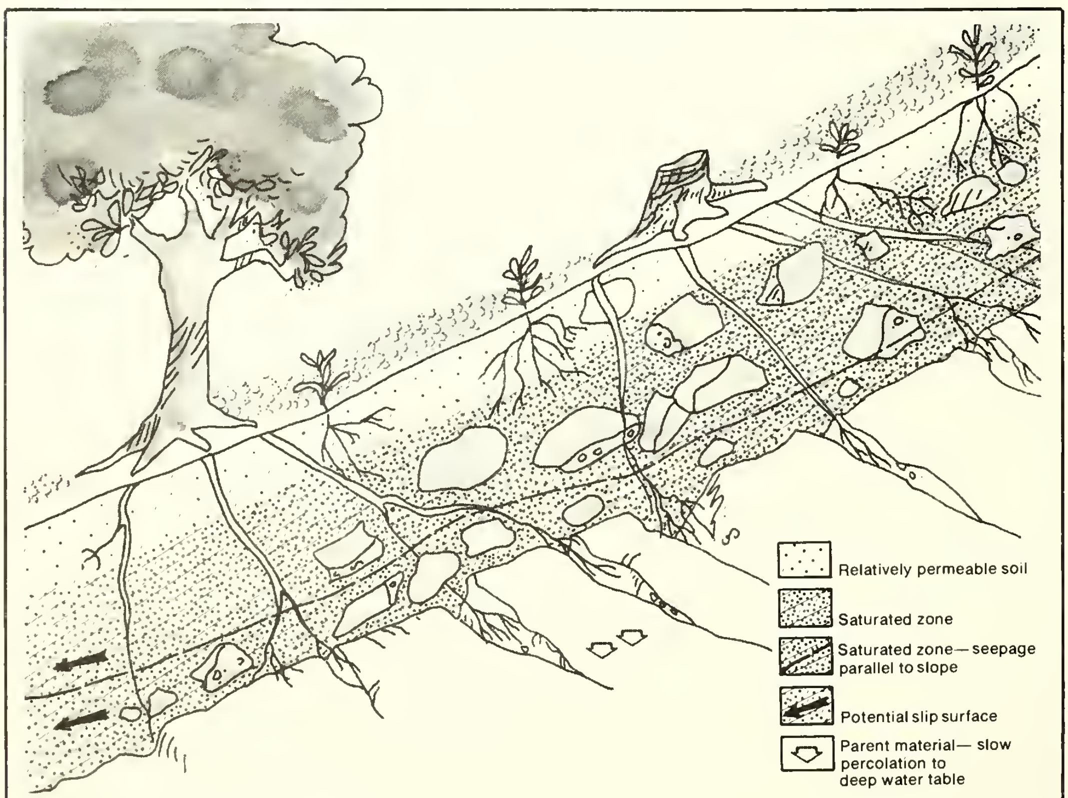


Figure 5—During heavy rains, the amount of water that infiltrates the soil layer may exceed the capacity of the parent rock material to transmit water. A zone of supersaturated soil may develop, with a potential slip surface as the lower edge. The chances of slope failure are increased when deep-rooted native vegetation is replaced by more shallow-rooted plantings. Even though little or no runoff and little erosion may occur at the surface, slope strength at the deeper levels is reduced.

be high during or immediately after a fire; plants that were anchoring the debris on their uphill side are burned off, and gravitational forces are again influential.

Dry creep is more continuous and at times almost imperceptible, but soil slips and slumps (landslides)—the major wet erosional processes on mature chaparral watersheds—are readily visible. A soil slip is a miniature landslide caused by downslope movement of soil under wet or saturated conditions. Slips and slumps account for almost 50 percent of the total erosional processes on a watershed (Rice 1974).

Soil failures are most common on slopes that range from 25° to 45° (*fig. 4*). As the slopes become steeper, the thickness of the soil mantle decreases and rockslides become more common. The minimum angle of soil failure is steeper for chaparral vegetation than for grasses. Slides occur primarily during rainfall of high intensity, after the soil has been saturated from a single major storm or from several medium- to high-intensity storms in close succession. In such cases, the rate of water infiltration into the soil mantle exceeds the rate of percolation into the underlying bedrock. This results in supersaturated soils (*fig. 5*).

Slips and landslides occur more readily when the interface of the soil and the parent material is low in shear strength (resistance to separation), but this is not easy to predict for a particular region. Slides may not add much to the immediate amount of downstream sediment eroded from a particular watershed because the eroded material may accumulate at the base of the slope. The sediment effect of slides is magnified after a fire because even moderately heavy storms can create high-velocity overland flow of water over bare hillsides, carrying away the accumulated sediment. Because flow velocity is further increased in the streambeds, the water can transport greater amounts of debris.

Fire-Flood Cycle

The amount of erosion after a fire depends on the storm intensity and the time elapsed since the fire (*table 1*). Postfire erosion may be more than 50 to 100 times greater than on a well-vegetated watershed. Understanding of the fire-flood cycle is vital to watershed management because the peak flows created by fire-denuded hillsides are responsible for accelerated erosion and flood damage.

Table 1—*Amount of erosion related to age of chaparral and maximum 24-hour precipitation*

Years since fire	Erosion at maximum 24-hour precipitation of . . .		
	2 inches	5 inches	11 inches
		Yd³/acre	
1	5	20	180
4	1	12	140
17	0	1	28
50+	0	0	3

Source: Kittredge 1973

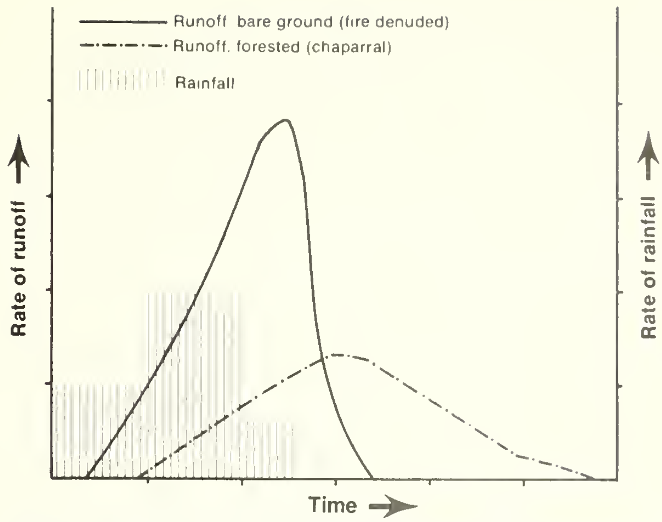


Figure 6—Water runoff from a watershed denuded by fire reaches a higher peak than that from a forested watershed.

Peak flow is the point of maximum streamflow, the result of precipitation that is added to the base streamflow after immediate losses for interception, infiltration, and soil moisture recharge have been satisfied. On bare ground, peak flow increases drastically as the rate of rainfall increases, and reaches its maximum about the same time as rainfall (*fig. 6*). As the rain stops, runoff is greatly reduced and is eliminated within a very short period thereafter. As shown in the graph, runoff on a well-vegetated watershed is often not noticeable until the storm is well underway. A much reduced peak runoff is normally reached at the end of the storm, and the constantly diminishing flow is fed for a considerable period of time. Grassland watersheds have greater peak flows than forested watersheds.

A well-vegetated watershed thus greatly reduces peak streamflow by increasing the time before runoff begins, and by spreading it over a longer period of time. This eliminates or greatly reduces watershed damage, as follows: Increasing the infiltration rate and lag time by as much as four times decreases the peak discharge rate (peak flow) by almost four times. On the other hand, a decrease in lag time and infiltration rate, caused by bare soils, produces a geometric increase in sediment-carrying capacity. Thus, as the velocity of the water (v) is doubled, its erosive power is increased 4 times (v^2) and its carrying capacity is increased 32 times (v^5). This carrying capacity dictates the quantity and size of material that can be carried by a given amount of water and adds to its destructiveness (Leopold 1980).

Of the wet erosional processes, scouring out of stream channels after fires accounts for the greatest sediment yield. Overland flow causing rill and gully erosion is next in importance. The debris that clogs a stream channel bed and is scoured out has been accumulating since the last fire and was reduced by intermittent nonfire-related flood peaks. Thus, even during nonfire years, channel scour is a major source of sediment. Both channel scour and overland flow increase with storm intensity, channel scour being responsible for two to three times more sediment than overland flow in almost all situations. The amount of channel scour depends on stream discharge and, therefore, the capacity of moving water to hold and carry sediments. Overland flow depends on other factors, such as the infiltration rate of the soil (related to soil texture and aggregation), the percolation and water storage capacity (related to soil texture and depth), the steepness of the slope, the heat of the fire (which affects development of water-repellency in soil layers), and the splash effect during heavy rains (which clogs the pores of fine-textured soils).

The production of water-repellent (hydrophobic) soils by hot fires is an important factor in overland flow (*fig. 7*). In nature, many soils are water-repellent to some degree, as a result of the breakdown of organic material and the presence of certain chemicals in the plant litter. Often fire volatilizes these chemicals and the resultant gases penetrate into the soil, where they cool, coat the soil particles, and reduce water penetration through the soil layer that has been affected. Water-repellency is more acute in coarse (sandy) soils than in fine (clay) soils. Fine soils have a greater surface-to-volume ratio, so that more of the water-repellent gases per unit area of soil are needed to coat all soil particles effectively. Depending on the heat of the fire, the water-repellent layer may be found almost at the surface or down as far as 2 inches (5 cm) (DeBano 1969, Osborn and others 1967). Nonwettable soils reduce germination and establishment of plants on sloping ground because of the lack of adequate soil moisture.

Immediately after a fire, the water-repellent layer acts as mulch by preventing evaporation from the lower wettable layer. Chaparral that resprouts during the hot summer after a fire draws moisture from the rock crevices and the water remaining in the lower wettable layer. With the onset of rains, the surface wettable layer becomes saturated; further precipitation cannot infiltrate except through the breaks in the water-repellent layer. The resulting overland flow is magnified by successive storms. However, if the first few winter rains are light and the thin wettable surface layer does not dry out between rains (that is, in cool, overcast weather), then the water-repellent layer becomes wettable from slow absorption of moisture from above. Once moist throughout, it retains its infiltration and percolation capacity. Surface runoff from later storms is greatly reduced as long as the layer does not dry out and become nonwettable again. Mechanical disturbance breaks up the nonwettable layer even more readily than gentle rains. The effect of water repellency is much lower after the first year and becomes negligible after 5 to 10 years (DeBano and Rice 1973). Such changes in soil wettability may partly explain the great differences observed in overland flow after a fire.

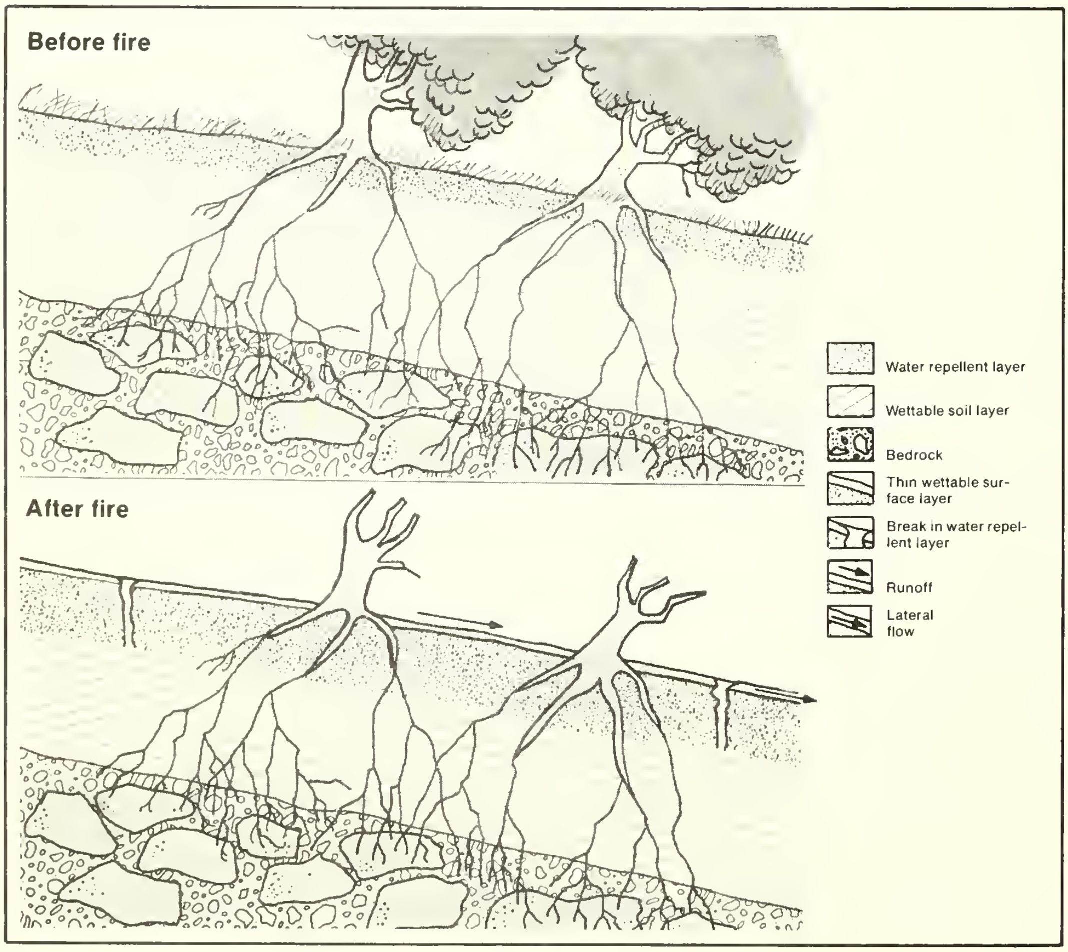


Figure 7—The effects of heat on the soil may increase the depth of the water-repellent layer, and increase repellency, so that water does not penetrate well to plant roots. Thus the establishment of seedlings is slowed down until the water-repellent layer is broken up. Water from frequent heavy rains flows overland, and rill and gully erosion is increased. With time, the water-repellent layer again becomes wettable.

During the season after a fire, if rainfall is low and storm intensities are light, overland flow and channel scour are lessened. Dry creep, dry ravel, and occasional landslides which started on steep slopes during the fire may then be the primary agents of erosion. On the other hand, dry erosion may be greatly reduced if the fire occurs immediately before the rainy period or between rainy periods.

Increases in landslides during the rainy period following a fire could be caused by well-spaced storms that permeate the nonwettable layer and completely recharge the water-holding capacity of the soil. Once the soil moisture is recharged, a high-intensity storm could quickly supersaturate the soil, thereby accelerating wet creep, starting slumps and slides, and greatly increasing overland flow. Under these conditions, postfire rainy season slumps and slides have a tendency to occur more frequently on a south slope than a north slope. On south slopes, a sparse prefire vegetative cover, coupled with thin soils and a smaller root network, provides less soil-binding and water-holding capacity.

Postfire slips and slumps during the first few years after a fire may be greatly reduced on nonwettable soils if high intensity storms follow each other in close order, thereby reducing rainfall penetration through the nonwettable layer. The soil below the nonwettable layer would remain dry, eliminating landslides, but the greatly increased overland flow would result in highly visible rill and gully erosion and would increase channel scour.

Erosion Factors

Erosion is the product of six factors: soils, climate, vegetation, animal activity, topography, and human activity. The climate, the degree of slope of the land, and the soil physical characteristics cannot be directly controlled to reduce soil erosion, but can be modified through soils engineering, whose principal aim is to change slope characteristics so that the amount and velocity of runoff is lessened.

Soils

Soil is developed through physical and chemical weathering of a thin surface layer of rock and mineral fragments (soil parent material). Soil texture, structure, depth, and fertility determine what kind of plant life a soil can support and what its infiltration rate, percolation rate, and water holding and water storage capacities will be. Soil texture and structure determine the erosiveness of soils. Texture is the proportion of mineral particles of various sizes in the soil; structure is the degree of aggregation of these particles.

In order of decreasing particle size, soil texture classes are sand, silt, and clay. Sand particles are visible to the naked eye; individual silt and clay particles are visible only under the microscope. Sandy soils are referred to as coarse textured, loamy soils as medium textured, and clay soils as fine textured. Generally, soils composed of coarser particles drain water more rapidly than soils composed predominantly of finer particles. Sandy soils allow fast water infiltration and percolation, but little storage; clay soils allow slow infiltration and percolation and greater storage. Sand, silt, and clay are easily eroded if the particles are not bound into stable aggregates. Organic materials and colloidal clays are primary cementing agents. Soils high in clay content and organic material are among the least erodible and most fertile soils. Sandy soils low in clay and organic material tend to have high erosion rates.

Good soil structure contains much airspace, which allows ready water infiltration into the soil, water percolation through the soil, and higher water storage capacity. Soils that have blocky or prismatic aggregates or that contain a high fraction of gravel (rock fragments larger than 2 mm) have higher infiltration rates than soils that are platy, such as most clay soils, or granular, such as some loamy soils.

Although geological relationships are too complex to analyze here, review of some geologic terms and principles should clarify the direct implication of geology in slope management. The type of rock and parent material present are good indicators of the weathering of rocks, the soil-forming processes, and erosion. The rock hardness, the size of the crystals, and the degree of crystal bonding and cementation are all important factors. For example, many granitic rocks erode rapidly because of weak crystal cohesion and large crystal size. This makes our granitic soils highly erodible. Rhyolite rocks weather more slowly, producing finer crystals, and soils derived from these rocks are therefore less erodible. Basalt rocks have even finer crystals that weather very slowly and soils derived from these rocks are less erodible still.

Generally, metamorphic rocks (rocks that were altered in form under extreme heat and pressure) are harder than igneous rocks (rocks formed by cooling and solidification of molten lava) and sedimentary rocks (rocks which were broken down by weathering and deposited by water, wind, and gravity and then consolidated by heat or pressure or cemented by silica, lime, or iron solutions).

Climate

The major climatic factors in erosion are precipitation, temperature, and wind. Precipitation, viewed as the interplay of amount, intensity, and duration, rather than as average rainfall, is the greatest erosional factor. The first rainfall after a dry period saturates a bare soil surface, causing little erosion. After that, raindrops hit the soil-water surface, causing breakdown of the soil aggregates. Splashing causes muddy water, in which the smaller soil particles are held in suspension. When this muddy water enters the soil, the pores become clogged; infiltration slows down and may almost stop. Amount and velocity of runoff are increased, causing surface erosion, rills, and finally gullies. If the runoff water is concentrated long enough on a particular portion of a slope, the soil becomes saturated and mud flows result.

Temperature and wind have some erosional effects. High temperatures have an indirect effect in creating a harsh environment for plants, so that revegetation is slow and there is little soil binding. Wind erosion at the surface is most critical on fine-grained dry soils devoid of vegetation. When large areas become exposed, as on recently tilled fields or sandy deserts, or in dry, overgrazed regions, wind erosion may become the dominant process.

Topography

Topography can be directly controlled or permanently altered to reduce soil erosion. Changes in topography influence climate (rainfall), soils, and vegetation. Degree and length of slope, the two most important factors that determine the amount of runoff and soil erosion (*table 2*), can often be manipulated. Cover crops, such as grasses, help to offset the effect of slope on surface erosion and contours can be very effective in reducing soil erosion and runoff. Rains of high intensity cause much greater amounts of erosion than do low intensity rains under similar slope conditions. Two rules of thumb emphasize these important relationships: doubling the degree of slope increases the erosion two to three times, and doubling the horizontal length of the slope increases erosion two to three times.

To visualize the amounts of sediment carried away by erosion, note that 1 mm (0.04 inch) of soil erosion approximates 2 tons of topsoil per acre (4.6 t/ha) or up to 4 cubic yards (3 m^3) of wet soil. Thus, 0.04 inch (1 mm) of soil erosion per acre equals about one large dump truck of debris. These estimates would be affected by the type of soil and the rainfall intensity. During high intensity rains, runoff and erosion increase with length of slope and shallowness of soil, because at high intensities there is less time for infiltration and water storage. For low intensity rains, runoff and erosion decrease greatly (*table 2*). If the soil has a low infiltration rate and low water storage capacity, excessive runoff and slope damage can be reduced only through engineering practices, such as installation of ter-

Table 2—*Effects on erosion and runoff produced by slope characteristics, protective cover, and rainfall intensity*[1]

Erosion factor, soil, location, time period, crop	Annual rainfall	Slope steepness	Slope length	Annual soil loss	Water loss
	Inches	*Degrees*	*Feet*	*Tons/acre*	*Pct rain*
Slope					
Steepness	40	2	91	20	29
(Shelby loam, Montana, 1918-35, corn, clean tilled):	35	5	73	69	28
Length (Shelby silt loam,	33	5	90	24	19
Montana, 1934-35, corn,	33	5	180	54	21
clean tilled):	33	5	270	66	24
Direction (Marshall silt loam, Iowa, 1933-35, corn, clean tilled):					
On contour	27	5	—	0	0.1
Up and down	27	5	—	12	12
Protective cover					
Palouse silt loam, Washington, 1932-35 wheat):					
Fallow	22	17	—	9	9
Bare	22	17	—	28	25
Rainfall intensity					
(Marshall silt loam, Iowa,					
1932-34)	(2)	5	158	9	11
	(2)	5	315	18	18
	(2)	5	630	33	20
	(3)	5	158	8	28
	(3)	5	315	6	17
	(3)	5	630	6	14

Source: Bennett 1939.

[1]Rainfall in southern California is generally more concentrated and of higher intensity than in Montana or Iowa, and often causes more erosional damage than indicated here.

[2]High intensity = rains considerably exceeding infiltration capacity of the soil.

[3]Low intensity = rains twice the duration of high intensity rains and only slightly above the infiltration capacity of the soil.

races and drains which take the water off the slope before it can do any damage. Compaction of the soil reduces infiltration and surface roughness increases it.

Terracing reduces the length of the slope, mitigates the degree of slope, and disperses the water at a lower velocity, thereby reducing its cutting action. The greatly reduced runoff reduces the amount of soil eroded. Significant reduction in total runoff from terraced land compared with that from nonterraced land can be achieved; the soil becomes more permeable because the reduced velocity of the runoff allows more time for infiltration (*table 2*).

Spacing of terraces is determined primarily by the slope of the land. Spacing is also influenced by the ability of the soil to absorb water and transmit it through its profile, and by the plant material that covers the slopes. Permeable soils of high water storage capacity, erodible soils, soils underlain by weak bedrock, and soils on steep slopes require close spacing of terraces. In areas of intense rainfall, and in residential areas, concrete terraces (bench drains) and down drains are used to channel the water off the slope, but may not prevent slippage. During the intermittent high-intensity rains that occurred in southern California in the spring of 1978 and 1980, I noted many slope failures on manmade slopes despite concrete terraces. Slope failures often occurred on permeable soils on steeper slopes that were planted to grasses and shallow-rooted vegetation instead of deep-rooted plants. In areas of high-intensity rains, both concrete terraces and deep-rooted vegetation are therefore necessary. Bench drains, generally, should not be installed on natural slopes steeper than 20° because there may be weakening of slope stability at the steeper angles.

Contour planting, a system of small earth terraces constructed around the slope so as to follow the contour of the land, is used as a soil conservation measure. It is most successful on permeable soils during average storms of medium duration. Heavy, intense storms allow contours to break and permit the water to concentrate in channels down the slope. Grains such as barley have been used successfully for over 50 years in initial contour stabilization of highly erosive fill slopes of good permeability until deep-rooted, woody plant material has become established.

Vegetation

A good vegetative cover can greatly offset the effects of climate, soil, and topography on erosion. Vegetation achieves this effect by intercepting rainfall, and by decreasing the velocity of runoff and the cutting power of water, thus allowing more time for water to infiltrate. In addition, vegetation increases soil particle aggregation and porosity. Roots bind the soil particles and anchor the soil to the parent material. Transpiration through the leaves dries out the soil, enabling it to absorb more water.

Different types of vegetation reduce erosion to different degrees. Plants with interwoven rhizomes, plants that form a tight mat, or those that produce much litter and have tight aerial crowns normally decrease surface erosion more than plants that lack these characteristics. Most grasses are therefore well suited for surface erosion control, and deep-rooted woody plants for permanent slope stability especially on slopes with deep soils. This fact was reemphasized in studies which showed that during moderate- to high-intensity storms, soil slippage (shallow mass soil movement) was inversely related to the rooting pattern, size, and density of vegetation (Bailey and Rice 1969, Rice and others 1969, Rice and Foggin 1971). Analysis of the soil slips by vegetative types showed slippage on about 25 percent of the barren or sparsely covered natural slopes situated on harsh southern and eastern exposures. The roots of the sages, the predominant vegetation on these sites, are shallow and spread laterally through shallow soil instead of into bedrock. Slippage occurred on 12 percent of the area converted from brush to perennial grasses, but on only 6 percent of the area converted to annual grasses. Apparently a higher density and greater below-ground root biomass of annual grasses compared with perennial grasses more than compensates for their more shallow root system. On slopes converted from chaparral to grass, soil slip patterns were thus related to root patterns, whereas on natural slopes they were related to soil factors.

In all chaparral vegetation types combined (chamise, oak, broadleaf) there was slippage in less than 2.5 percent of the area. These vegetation types are characterized by plants with deep tap roots. California scrub oak with roots extending more than 30 feet (9 m) deep and occupying mesic northerly and easterly aspects, is one of the vegetative types least susceptible to slippage. Overall, dense broadleaved chaparral, which prefers the more mesic northern exposures, is much less susceptible to slippage than the more sparse chamise chaparral predominantly found on harsher southern exposures.

Vegetation, in general, increases the moisture storage capacity of the soil, particularly when plants are vigorously growing and transpiring. Most chaparral plants are evergreen and active in winter, thereby increasing the capacity of the soil for greater soil moisture storage during the critical winter period.

Any good vegetative cover will greatly reduce erosion during intense rainfall of short duration or extended rainfall of low intensity. In southern California's Mediterranean climate, however, almost yearly storms of high intensity and long duration are characteristic. Therefore, the most effective plant material possible is needed, along with proper land use planning. In chaparral, nature has provided a watershed cover that has become effectively adapted to dry, hot summers and long periods of summer drought. Modifying this cover for fire protection creates many problems.

Animals

The influence of animals on erosion is closely linked to that of vegetation. For example, beneficial soil fauna such as earthworms and beetles are more abundant under a good vegetative cover. They greatly improve soil structure by mixing humus with subsurface soil layers and by creating channels in the soil which increase soil permeability. A moderate number of rodents, such as pocket gophers, are also useful for this purpose. Too many rodents can be a nuisance, however, creating soil instability by damaging root structure, tunneling large underground waterways, and concentrating water in sections of hillsides. These conditions can induce slippage problems.

Animals, like plants, require a definite set of habitat conditions. A change in habitat often directly affects population dynamics. In an informal study made of a 90- by 150-foot (27.4 by 45.8 m) chaparral-covered urban watershed that was fenced but had not burned in 40 years, various changes in animal populations were observed. The chaparral was pruned for fire safety in 1977 and 1978 and the understory was thinned, thereby destroying the habitat for pack rats. The resident rattlesnake, measuring 44 inches (111.8 cm), was removed from the site. The understory was planted to low fuel plants, which were readily clipped by pack rats and mice that reinvaded from surrounding areas. California quail moved onto the site, but no California ground squirrels were sighted.

Within a year after the partial brush clearance, the October 1978 Mandeville Canyon Fire denuded the study area and surrounding watersheds. This prompted a rat invasion into nearby residentia areas and created the open habitat preferred by ground squirrels. During July and August, 1979, 17 ground squirrels were trapped within the study area, accounting for 100 percent of the population sighted. Four rattlesnakes were also removed during the summer months. One rattlesnake was killed onsite; its stomach contained the remains of four gophers. With the removal of the rattlesnakes, the gopher population exploded with serious detriment to the reestablishment of the low fuel plants. Three western racers, two gopher snakes, and one mountain kingsnake were spotted during 1979, but these are no match for a mature gopher in its natural underground habitat.

From July 1 to August 15, 1980, 39 ground squirrels were trapped, accounting for every ground squirrel within the study area at the time. Trapping was continued on September 1 and an additional 15 ground squirrels were caught within the next 2 weeks. The great influx of ground squirrels into the area was supported by juvenile animals that moved into areas of low population densities created through trapping. It is estimated that 90 percent of the adult ground squirrels would need to be trapped every year to maintain effective population control. Rabbits were sighted for the first time, and along with rats and mice, are heading towards a population explosion. A coyote was observed to raise a litter each year during 1978-80, near the study area.

In this example, human interference changed the balance of nature by changing the natural habitat. The changes in the predator population resulted in increasing the gopher, rat, mouse, ground squirrel, and rabbit populations. This had an immediate detrimental effect on the watershed through reduction of ground cover and undermining of slope stability.

The detrimental effect of rodents on slope stability is also pointed out in hillside grading guidelines (Los Angeles County 1975) which specify that "fill slopes steeper than 2:1 (20 percent, 11°) with a grading project located next to undeveloped land infested by burrowing rodents, shall be protected from potential damage by a preventive program of rodent control."

Observations by the Los Angeles County Agricultural Commissioner's Office in Calabasas Park confirmed that ground squirrels were at least a significant contributing cause of a massive slope failure that cost more than $500,000 for rehabilitation. Control of rodents affecting sloping land is therefore a cost-effective undertaking.

Trapping and population control is most successful when the life history of the animal is known. The California ground squirrel causes extensive hillside damage (*fig. 8*) because it digs burrows from 5 to 39 feet (1.5 to 12 m) long, almost 5 inches (13 cm) in diameter and up to 4 feet (1.2 m) deep (Grinnel and Dixon 1918). Colonial burrows used by both sexes and their young may be more than 130 feet (40 m) long. At any time there are more burrows than individual squirrels, because the squirrels construct new burrows from time to time to have additional escape routes and probably to leave most of their fleas behind in the old nest. These fleas can be the carrier for the bacillus of the bubonic plague. Minimal handling of ground squirrels is therefore advisable.

The California ground squirrel was an asset to the Indians because both its fur and meat could be used. The squirrel became a pest when the settlers drove out the Indians and destroyed many other natural enemies such as the golden eagle, redtailed hawk, coyote, badger, wildcat, weasel, rattlesnake, and gopher snake. The importance of natural enemies for population control is well documented. One study showed that a nest of golden eagles consumed 6 ground squirrels per day for a total of about 540 squirrels during a 3-month period (Grinnel and Dixon 1918). Intensive agriculture also supplied a dependable food source for the ground squirrels; thus two primary factors of population control, seasonal scarcity of food and natural enemies, were greatly reduced or eliminated.

In the wildlands, ground squirrels gather almost any seeds and fruits available, but prefer the young leaves and seeds of alfilaria, star thistle, and bur clover. The animals are also fond of prickly pear. In urban areas and agricultural lands they gather grain and grass seeds. Successful revegetation methods with grasses can therefore contribute to population explosions by providing a plentiful seed source from early ripening seeds. Among cultivated nuts, ground squirrels prefer almonds and walnuts, and among fruits they like apples, prunes, peaches, apricots, figs, and olives. Poultry and wild bird eggs, as well as potatoes, are also sought after. Grapes, if harvested while ripening, are normally safe from ground squirrels.

The breeding season of the California ground squirrel extends from about February until April. At higher altitudes and in colder climates, the breeding season is later and shorter. A litter varies from 4 to 11 and averages 7 or 8. Under favorable conditions of climate and food supply, two litters are produced in 1 year. The gestation period lasts about 30 days and the young are born towards the end of March. They may appear above ground near their burrows towards early May. They start digging their own burrows within 4 to 6 weeks thereafter, and fend for themselves from then on. If the population density is too high locally, they migrate by July and August. By September, the young have matured.

Human Interference

The homeowner must remember that on steep terrain almost every stone and plant has its place. Anything that changes the natural relationships of soil, vegetation, and runoff may create a potential hazard. Random clearing or tunneling or other disturbance of the soil may channel overland flow or groundwater seepage in such a way as to weaken slopes and eventually lead to failure of an entire slope. Undercutting of the toe of a slope is one of the major reasons for eventual slope failures. Development above such slopes should be severely restricted unless the slope can be totally restabilized by mechanical means. Restabilization should be a logical prerequisite for issuing a building permit. With the rapid mobility of the urban population, the original owner and builder are seldom faced with the hillside problems and financial losses they helped create.

The urban hillside homeowner normally lacks the knowledge necessary and year-round commitment to property management, so that small problems magnify and watershed deterioration progresses from year to year. For example, a bench drain—a concrete sidehill drain—that is partially blocked by soil, or a pipe filled with leaves, will eventually cause uncontrolled overland runoff, supersaturated soils, and slope failures. Slopes cleared of deep-rooted vegetation but not properly replanted will slowly weaken because the strength of the remaining root system is steadily deteriorating. Root decay starts rapidly with the death of the plant and is completed in about 10 years (Rice and others 1982). Since landscape plants that replace native plants take a longer time to provide an equal biomass of live roots to the soil, it is therefore best to thin and prune, leaving deep-rooted native plants alive as permanent specimens or at least until the replacement vegetation is well anchored.

A row of water-demanding landscape plants, such as roses or fruit trees, planted along the edge of a slope may be responsible for supersaturated soils during intense rains. Backyards that are leveled to accommodate lawns may be responsible for channeling water over the slope. A broken or leaky pipe or sprinkler system or improperly laid out drains are causes of slope failures, especially in older developments. Improper or loosely compacted fill may settle, thereby often breaking drainage pipes laid across or through them. The displacement of natural enemies of slope-damaging rodents increases their population and also accelerates their damage potential. Any hillside development has the potential for creating serious problems for

Figure 8—Hillsides in southern California are often damaged by ground squirrels that burrow deep into the soil and dig for distances up to 40 feet (12.2 meters).

lower-lying homes; however, the unwillingness of a downslope or sideslope resident to provide drainage easement may affect the drainage patterns of the whole watershed, and dangerously undermine its stability.

On a larger scale, the hydrologic characteristics of a watershed can be altered in two ways by urbanization (Strahler and Strahler 1973):

1. The percentage of surface runoff made impervious to infiltration is increased through the construction of buildings, driveways, and so on. This leads to increased overland flow (runoff) and greater discharge directly into streams, increased flood peaks, and reduced recharge of groundwater.

2. Storm sewers allow storm runoff from paved areas to be taken directly to the stream channels (or the ocean) for discharge.

The effects of these two changes combine. Runoff time to the stream channels is shortened at the same time that the proportion of runoff is being increased. The lag time between precipitation and runoff is reduced, thereby increasing peak flow and frequency of floods.

Two basic methods of control are possible to decrease peak flows that exceed the stream channel capacity (Satterlund 1972):

1. Increase the capacity of the channel to handle excess flow, as by dredging, building levees to increase bank height, widening the channel or straightening it to increase speed of flow.

2. Decrease the volume of water so that it does not exceed the capacity of the channel, as by means of reservoirs, spreading grounds, and diversion overflows.

Sometimes it is possible to shift a problem from one place to another. This approach is useful if the problem is shifted away from a high value area to a low value area. Problems arise, however, when determining what can be done if homes are located at the edge of a streambed, at the mouth of a channel, or on a flood plain. In such flood-hazardous locations proper flood control then becomes impractical if not impossible and should be thought of as flood reduction rather than flood control.

COPING WITH WATERSHED PROBLEMS

Maintaining Slope Stability

If slopes on a particular property range from about 25° to 45° (47 to 100 percent), landslides may be the major long term erosional process (Campbell 1975). They can be reduced by maintaining deep-rooted woody vegetation, such as chaparral, on the hillside. The deep roots serve the dual function of anchoring the soil and pumping the water out of the deeper soil layers. Woody chaparral vegetation is more deeply rooted than any other low-fuel plant vegetation that could replace it, and also has an extensive, strong lateral root system. Therefore, chaparral should not be grubbed out. Occasionally the volume of fuel should be reduced through pruning that removes dead material, trims lower branches, and tops larger branches, and through occasional thinning of crowded plants. The chaparral plants should be interspersed with deep-rooted, drought-tolerant low-fuel plants of somewhat similar water requirement or tolerances that will form low-growing, dense ground covers. Sprinkler irrigation may be necessary until the low-fuel plants are well established; after that, they can be given a few deep waterings in the summer. Proper watering of new plantings may have to be continued throughout the winter season if rainfall is sparse or intermittent. If drought-tolerant landscape plants are heavily watered, they may not be able to use all of the water so that the soil mantle is partially saturated at the start of the rainy season, with greater likelihood of soil slips and slides. Water-demanding plants should therefore not be used for hillside planting.

When chaparral is thinned or removed for fire protection, great care must be taken not to remove plants over more area than can be safely replanted and covered with low-fuel plants the same season. Any disturbance or removal of the native vegetation represents at least a temporary instability in a particular portion of the watershed. Erosion during brush conversion can be severe on even moderately steep slopes of about 15° (27 percent). First-year erosion rates on such slopes can exceed 1 inch (2.54 cm) of loose topsoil. On an acre basis (1 acre = 0.4 ha), this would amount to as much as 100 cubic yards (76 m^3) of soil (enough to fill up to 25 dump trucks) that would find its way into properties at the base of the slope. Such heavy soil loss can be greatly reduced through the use of erosion netting, such as jute matting, which is very effective in protecting soil from washing away. Erosion netting should be used at planting time whenever it is anticipated that heavy rains will return before a plant cover can be reestablished. The loss of topsoil in itself is very critical because topsoil contains more nutrients, has better structure, a greater infiltration rate, and more water storage capacity than subsoil and is therefore more capable of producing vigorous, rapidly growing plants.

Brush conversion on slopes approaching 30° (58 percent) should not be attempted unless appropriate soils engineering practices such as terracing are used or unless the slope is short. In some instances slopes are steeper than the natural angle of repose for the geologic material. For most standard soils on natural slopes, this angle is about 34° (67 percent), but it depends on the many factors discussed earlier. Because of internal static friction, the angle of maximum slope (angle at which slope failure occurs) may be up to 10° greater than the angle of repose. Los Angeles County Grading Guidelines (1975) also emphasize the maximum slope angle by stating the "cuts shall not be steeper than 1.5:1 (34°) unless the owner furnishes a soils engineering or soils geology report. . .certifying that a cut at a steeper slope will be stable and not create a hazard to

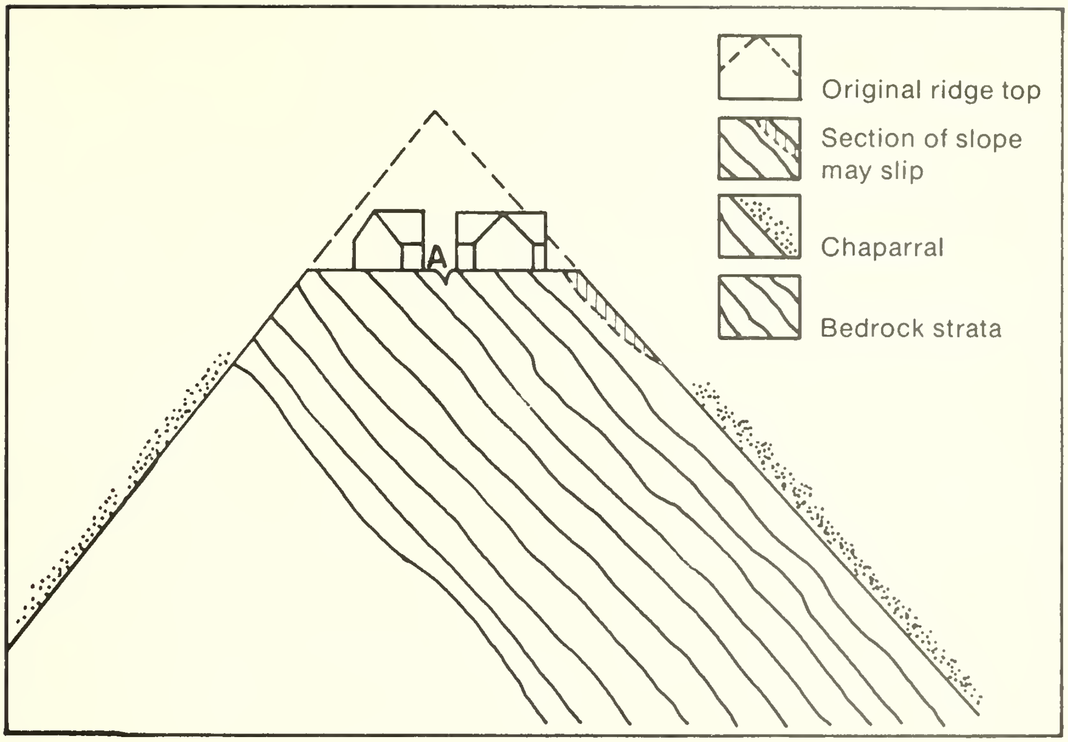


Figure 9—Rock strata can contribute to hillside problems. A break in the pavement next to the house (*A*) caused by sewer or water lines can lead to major slippage. More slippage occurs on the right side of this hill than on the left.

public and private property." Even so, the building inspector has the right to insist on a more gentle slope if necessary for stability and safety. Large-scale brush conversion for fire safety should not be attempted on slopes beyond the angle of repose, because the soil will slide under the force of gravity once the plant cover is removed. Most landscape plants cannot establish themselves unless the hillside is reshaped. If this cannot be done, permanent accelerated erosion results, leading to eventual large-scale slope failures if the underlying parent material is unstable.

The bedrock from which most soils are derived is important to slope stability. For example, fractured rocks, or rock layers that are parallel to the slope, especially on a northern exposure, cause more hillside problems than consolidated rock or rock layers at right angles to the slope (*fig. 9*). Soil stability can be greatly reduced by an underlying clay bed; this acts as a lubricating agent once it is wet. High rates of water infiltration cause local soil saturation that may result in mudflows and major slides, especially when they occur on geologically unstable material. Therefore erosion and slope problems will be accelerated if water is concentrated on any particular portion of a slope, unless the water finds its way immediately into storm drains or rain gutters.

Controlling Drainage

Homeowners must understand the purpose of grading regulations and should not defeat their intent through ignorance or lack of maintenance. Much of the hillside damage in the Los Angeles area in the 1978, 1980, and 1983 floods could have been reduced by homeowners through preventive maintenance and by following the grading requirements spelled out in the Los Angeles County grading guidelines, summarized below:

- A 2 percent overall gradient must be maintained from the rear of the lot to the curb or drainage structure.
- A berm must be installed at the top of the slope to prevent water from draining onto the slope.
- A 1 percent flow line is required around the house to a drainage structure or the street.
- No roof drainage over slopes is permitted.
- Any gradient greater than 5 percent that carries yard drainage must have a paved swale (wide open drain with low center line) or V driveway.
- When fill is used to repair even a small slip on a slope, benches are required if the natural slope exceeds 5:1 (20 percent or 11°).
- Cut slopes more than 5 feet (1.5 m) high or fill slopes more than 3 feet (0.9 m) high must be planted with grass or ground cover. Slopes more than 15 feet (4.6 m) in vertical height must also be planted with shrubs not more than 10 feet (3 m) on center or trees not more than 20 feet (6 m) on center, or a combination of shrubs and trees at equivalent spacing in addition to grasses or ground covers.
- Irrigation must be provided covering all portions of the slope.

To protect the homeowner from damage caused by nearby developments, the guidelines stipulate that "no grading permit shall be issued for work to be commenced between October 1 of any year and April 15 of the following calendar year unless the plans for such work include details of protective measures, including desilting basins or other temporary drainage or control measures or both as may be necessary to protect adjoining public or private property. . . ." Additionally, a standby crew for emergency work must be made available by the builder at all times during the rainy season, and necessary materials must be available immediately when rain is imminent. Furthermore, all removable protective devices must be in place at the end of each working day when the 5-day rain probability forecast exceeds 40 percent. A guard must be on site whenever the depth of water in any device exceeds 2 feet (61 cm). A 24-hour emergency phone number of the person responsible for the project must be listed when submitting the temporary erosion control plans. (It is wise also to post this number on the construction site at all times.)

A field inspector visits building sites periodically, but would not be aware of any accelerated erosion problems unless requested by a homeowner to make an emergency inspection of a property, or unless an inspector is checking the building site to make sure that drainage plans have been adhered to. Concerned neighbors may also call the field inspector to point out erosion problems on construction sites. A final inspection is done at the time the land is occupied, and the inspector does not return unless requested to do so or unless a construction permit is taken out for improvements. Under these circumstances, new owners may not be aware of the consequences of any additional work they are doing, however minor. For example, major slope failure affecting several properties was observed after the heavy 1980 rains. The homes had an adequate setback from the slopes and the canyon below, but the large backyards and lawns sloped more than 1 percent toward the rear, thereby draining all excess water down the hill. Chances are that the backyard landscaping was done after the final inspection and the result was a disastrous financial loss to the owners. In another newer home extending over a hillside, part of the roof drained onto the slope, Apparently this was a late change in the design, or it would not have passed inspection. Again, the result was major slope failure with great financial loss.

Even gently sloping hillsides are not immune from slope failure. Therefore, hillsides sloping more than 5 percent for any appreciable distance should not be planted to lawns. The slope should be broken up by terraces or stone walls so that the actual lawn is level or has a very gentle slope.

Weakening the slope structure through undercutting of its toe, as for further development below a steep property, should be avoided at any cost. Retaining walls may reduce slide hazard, but are very costly and rarely can duplicate the stability of the natural toe of a slope. If a slope is being undercut by a small stream, it may be possible to rechannel the stream and reduce its velocity in the affected area. Streambank control is often a more feasible alternative.

Vegetation, as described earlier, can reduce both wet and dry erosion. Overland erosion in the form of rills and gullies can be greatly reduced by maintaining a thick ground cover on the slopes and allowing plant litter to accumulate. Once gullies have started, they cut rapidly into the soil mantle and should be immediately controlled through small check dams, stacking of cut brush, and temporary soil-binding cover, such as grasses. Dry creep and dry ravel on steep slopes where vegetation is sparse can be reduced by use of plants adapted to harsh sites with thin soils; these add cohesion to the soil.

The annual weed clearing of hillsides down to mineral soil for fire hazard reduction is a source of accelerated erosion. Weedy flash fuels such as introduced annual grasses and wild mustard are well adapted to the climate and soils of southern California. Clearing them on a yearly basis with handtools removes much valuable soil while establishing an excellent seedbed for the next weed crop, which becomes quickly established with the onset of winter rains. Motor-powered machines that use nylon filaments for weed trimming cause less erosion than handtools do, because a small stubble of the plant is left to protect the soil surface. Nevertheless, yearly eradication of annual flash fuels around homes is a never-ending task; such areas should be planted to low-growing, drought-tolerant ground cover, interplanted if necessary with deep-rooted vegetation such as chaparral or carefully selected introduced trees and shrubs.

Controlling Animal Activity

Rodent activity should be reduced and controlled. It adds to slope instability by reducing the cover of low-fuel plants while weakening their root system. Water is concentrated on the particular parts of the slope where rodents have been active. Hillside animal pests can be controlled most effectively by their natural enemies. If these are not present, cats can effectively control rodents, including gophers and ground squirrels. Cats and dogs also manage to keep the rabbit population under control.

Occasionally, the homeowner must act to minimize hillside damage by animals. Instruments that send shock waves through the soil, such as noisemaker windmills attached to metal rods that send out electrical impulses, have been used with varying success on hillsides for rodent control, especially for gophers. They may be worth trying because they require little maintenance once installed. Control of pests that have reached epidemic proportions, such as ground squirrels, is best achieved through poisons placed in strategically located bait stations. Gopher poison placed directly into the rodent runways is effective. Advice on the use and availability of poisons is available from the local office of the Agricultural Commissioner; in Los Angeles County, these offices provide rodent control service for a minimal fee based on the size of the problem and the followup service required. Some poisons can be bought without a license, but in using these poisons, extreme care must still be taken to ensure that natural predators and domestic animals are not affected.

Trapping is often effective in animal control. To catch gophers, small box traps work occasionally and Macabee[2]

[2]Trade names and commercial enterprises or products are mentioned solely for information. No endorsement by the U.S. Department of Agriculture or the County of Los Angeles is implied.

traps have worked well. The Macabee traps are used to block both sides of the major underground tunnel; the small box traps are placed at the end of a side tunnel. Larger box traps placed above ground and baited with apples work well for rabbits; ground squirrels prefer peanut butter or nuts but can also be caught with fruits, especially when these are not in season. For catching rabbits, the traps should be hidden under larger shrubs; for catching ground squirrels, they can be left in plain view. These traps also easily catch young gophers and other underground rodents when they wander above the ground in search of food. Rats, mice, occasionally a bird, and even a young curious cat, may enter the traps. Live traps such as the "have-a-heart" traps (standard size, 30 inches long by 7 inches high) are also effective for the small, curious ground squirrels. The larger traps are better suited for larger animals.

Effectiveness of traps tends to vary with the season, the animal, and the bait used. Maintenance of these traps requires frequent walking on hillsides which accelerates soil erosion. Daily disposal of the animals is a chore that falls upon the trapper.

Shooting, where permissible, is also an effective way to control most animal pests. Homeowners must be aware of the danger of firearms and must comply with local ordinances concerning their ownership and use.

Raptor (bird of prey) roosts are used effectively by Los Angeles County foresters to control rodents in young tree plantations. In areas where no natural resting sites, such as trees, are present, the roosts serve for sighting, attacking, and devouring of prey. A homemade raptor roost is easily installed and should consist of a vertical post or pipe at least 15 feet (4.6 m) tall on which a wooden crossbeam 3 to 5 feet (0.9 to 1.5 m) long is mounted horizontally. The pipe should be in one piece, or it may break at a joint from wind action. (A completed roost looks like an elongated letter T.)

Eradication attempts by homeowners are normally of short duration and poorly organized. Continuous effort is necessary for long-term population control and hillside safety, as demonstrated by the following projection for ground squirrels:

The projection assumes that one litter of eight young is raised each year, there is no natural mortality, plenty of food is available, and the rodents can freely emigrate. A mated pair of ground squirrels present on a watershed in early spring will then increase its population to 10 by summer. If an eradication program is 80 percent efficient, 2 animals are left at the end of the first season. If there is no followup campaign, the population climbs back to its original 10 at the end of the second season, to 50 the third season, 250 the fourth season, 1250 the fifth season, and 6250 the sixth season. Because, during a lifespan of 5 years, the original pair could be responsible for 6250 offspring, the initial intensive eradication campaign was responsible for limiting the population to 1250 at the end of the fifth season; a difference of 5000 animals. However, even the relatively low number of 50 animals on an acre of urban watershed could greatly undermine the hillsides. Neighborhood teamwork is therefore essential to keep hillside pests under control and eliminate the breeding population on a regular basis. Just eliminating the young will not prevent reinfestation.

LANDSCAPING FOR FIRE AND EROSION CONTROL

When a community greenbelt or a homeowner's undeveloped acreage is to be planted for minimum maintenance and little irrigation, the most important consideration should be low fuel volume. On hillsides, low-fuel landscape plants should form a solid cover; they should therefore have a spreading and not mounting growth habit. This will suppress weeds and reduce the dry flash fuel. Drought tolerance and resprouting ability are other important considerations. Ground covers like ivy and vincas, low-growing shrubs like coyote brush, hedges such as oleander and myoporum, and even a conifer like Canary Island pine (the only fire-sprouting conifer readily available from nurseries) do not need to be replanted. They all readily sprout after fires, thereby assuring that the greenbelt reestablishes itself at little or no cost. The resprouting ability of ground covers is extremely important on steep slopes. Chances are that with additional watering after a fire, ground cover that was well established can partially reestablish itself within 3 or 4 months, often in time for the winter rains. Chaparral plants should not be overlooked in this respect. All are drought tolerant and most resprout.

Scrub oak, *Ceanothus* species, chokecherry, and sugarbush can be readily shaped into beautiful short-stemmed trees. At distances of about 25 feet (7.6 m) or more apart they can be kept relatively fire retardant by occasional pruning. Oak, California pepper, Brazilian pepper, California laurel, sycamore, and black locust, to name a few, are trees that can be effectively blended into a landscape setting. They all resprout after fire. However, trees generally have greater fuel volume than shrubs and receive less pruning. For fire safety, trees can be planted farther apart than shrubs.

Often overlooked in landscaping are the vinelike low-growing natives, such as honeysuckle, which are quite drought tolerant, have a low fuel volume, and are excellent for slope stabilization. They will resprout after fire. Resprouting ability also allows the plant to recover from gopher and other rodent damage.

The choice of plants for landscaping is related directly to fire safety and protection from erosion. All plants burn during extreme fire weather conditions, specifically, high temperatures, strong winds, and low relative humidity. The labeling of plants as *highly flammable*, *fire retardant*, or *fire resistant*, is therefore misleading. For many years, the term "fire resistant" or "fire tolerant" has been used in ecological literature to denote plants that are adapted to fire and can survive it. For example, a nonsprouting pine such as ponderosa pine is called fire resistant because trees at maturity are protected from firekill by their thick bark. Coast live oak is a fire-resistant (fire-tolerant) tree because it readily resprouts from dormant shoots underneath the bark; however, a mature oak located next to a home, because of its fine dead aerial fuel that consists of twigs and branchlets, can readily catch fire and produce flames that are two or more times greater than its height and diameter. Some plants that do not sprout, such as Mediterranean *Cistus* species (many of which are highly flammable but used in landscaping), and also many native *Ceanothus* species are fire adapted, because they readily reestablish themselves from seeds stimulated by fire. Thus, if properly used and maintained, plants can reduce the spread of fire; if improperly used, they may increase fire spread. Proper choice of plants for landscaping depends on specific conditions, but must be combined with measures to improve the fire safety of the structure itself.

The term *fire retardant,* as used in a flammability context, means that the plant so described is less flammable than another that contains the same amount of fuel. This difference may be due to the proportions of live and dead fine fuel present, to the oil and mineral content (ash) of the foliage, to the percent fuel moisture, or to the age of the plants. For example, the needles of plants like pines, cham-

Table 3—*Chemical composition of 11 low-fuel plant species*

Species and plant part[1]	Length, type[2]	Moisture content[3]	Ash[4]	Crude fat[4]	Crude protein[4]	Crude fiber[4]
				Percent		
Prostrate acacia						
Leaves		275	2.5	5.8	16.2	15.7
Stems	12 in., H to SW	215	1.9	6.4	10.9	30.7
Twin peaks coyote brush[5]						
Leaves		335	4.3	9.8	14.7	11.7
Stems	4 in., H to SW	277	3.9	5.2	8.3	21.1
Carmel creeper						
Leaves		225	2.6	4.3	10.8	14.1
Stems	H to SW	200	2.3	2.5	5.7	26.5
Green galenia[6]						
Leaves		221	10.9	3.5	18.2	9.7
Stems	8 in., H to SW	198	10.0	1.5	12.1	17.8
Descanso rockrose						
Leaves		226	7.1	3.3	10.1	26.5
Stems	H to SW	187	2.6	2.1	5.7	13.5
Purple rockrose[7]						
Leaves		239	7.2	4.5	10.5	13.1
Stems	H to SW	226	5.3	4.2	6.4	28.9
Prostrate rosemary[5]						
Leaves		349	4.3	12.1	8.8	15.1
Stems	8 in., H to SW	242	3.2	4.2	3.3	47.3
Chilean saltbush[6]						
Leaves		337	10.5	3.3	24.3	6.3
Stems	SW	216	3.3	1.4	13.1	29.1
Green saltbush[7]						
Leaves		527	9.2	1.9	27.1	8.3
Stems	Green to H	401	6.5	1.1	12.3	26.4
Mueller's saltbush[5]						
Leaves		392	10.5	2.5	20.6	7.3
Stems	4 in., H to SW	353	8.1	1.8	12.5	24.7
Gray santolina[3]	Composite	322	9.1	11.1	16.4	16.6

[1]Late fall growth of tip cuttings consisting of leaves and small twigs was analyzed. Large seasonal variations in moisture content and fat, protein and fiber contents are often encountered.

[2]H = herbaceous, SW = semiwoody, W = woody, Composite = herbaceous to semiwoody tip cuttings consisting of leaves and stems.

[3]Moisture content of the living plant sample as percentage of its oven dry weight.

[4]Percentage of dry residue in relation to the total oven dry weight of plant sample.

[5]Plants that are inherently flammable (high oil content) but low in fuel volume.

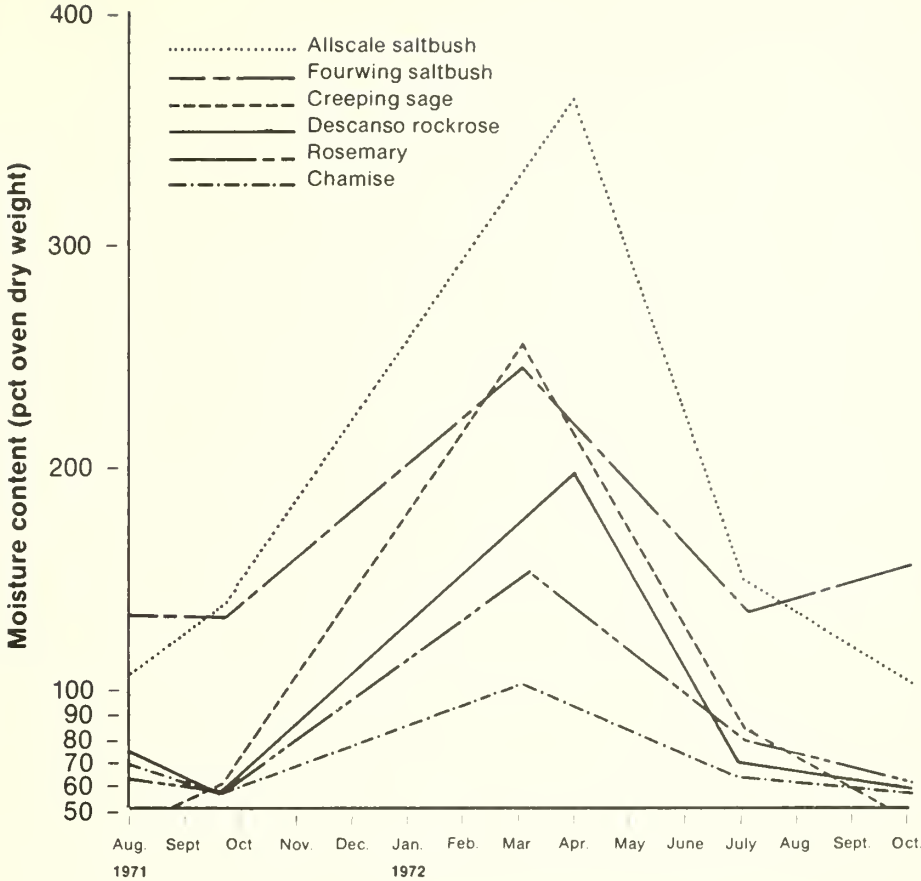
[6]Fire retardant plants: low in fat (oil) and high in ash.

[7]A related species, gum rockrose, which grows 6 to 8 feet tall, is often recommended for low fuel planting, but it has a high crude fat content (14.9 percent) and is highly flammable.

Table 4—*Heat values of four wildland fuels*

Species, fuel type	Heat value	
	Kcal/g	Btu/lb
Annual grass		
Early green	0.418	753
In bloom	1.668	3,005
Mature, dry	3.956	7,128
Blue gum eucalyptus		
Leaf litter	5.732	10,328
Bark	4.616	8,317
Duff	5.454	8,272
Branches/twigs	4.591	8,272
Chamise		
Leaves	5.439	9,800
Twigs	5.009	9,025
Branches	4.742	8,544
Scrub oak		
Leaves	4.571	8,236
Twigs	4.480	8,072
Branches	4.490	8,090

Source: Agee and others 1973



'igure 10—Seasonal fuel moisture content of foliage (leaves and current year's stem growth) of seven native and introduced shrub species varies widely among species, and by season.

se, and rosemary have a high oil content and fine fuel characteristics. They are therefore inherently more flammable during the fire season than saltbushes, which have broad leaves and lower oil content, with higher ash content (*table 3*). Other plants fall into intermediate categories.

Some other plants used in landscaping may be just as flammable as chamise, one of the most flammable chaparral species. The heat content of bluegum eucalyptus is comparable to that of chamise (*table 4*). So, once ignited, both species may burn equally hot, and the eucalyptus may present added problems of greater fuel volume and litter production. During the 1977 Santa Barbara Fire, 244 houses were lost when sundowner winds (downhill evening wind patterns) carried the fire from tree to tree and from one wood shingle roof to another.

Live fuel moisture is important because plants with higher fuel moisture ignite less readily. For example, the live fuel moisture of many saltbushes that are recommended as "fire-resistant plants" is higher than that of most chaparral species except for succulents. Live fuel moisture content of such wildland fuels may be low from June to November and high from December to April (*fig. 10*). The late summer and fall Santa Ana (fire winds) coincide with this period of low fuel moisture. Within a few hours the dry, hot winds can reduce fuel moisture of fine dead plant material to the critical level for ready ignition and can further decrease live fuel moisture by a few percentage points over several days. The amount of fine, dead fuels determines rate of fire spread because such fuels dry rapidly, ignite quickly, and preheat live fuels to the ignition point.

It is clear, then, that inherent fire-retardant characteristics of landscape plants cannot be depended on to prevent ignition during severe fire weather. Young plants and new shoots on pruned plants have a high moisture content, and can be considered slow burning (fire retardant), but as these plants become older and more woody and the amount of dry fuel and dead litter increases, they become more flammable. This fact may explain some of the contradictory literature about "fire retardant" plants. For example, old man saltbush is often recommended in California as a fire-resistant plant. In Tunisia, the plant is grown as firewood because it is excellent for baking bread in the traditional domestic ovens and also for charcoal. In well-managed, nonirrigated plantations, it can produce up to 17 tons/acre (38.25 t/ha) of firewood during the first year after outplanting, and 30 tons/acre (67 t/ha) within 2 years (Franclet and LeHouerou 1974). With irrigation, the wood production is even higher. In Australia, where the plant is browsed periodically by sheep, it is kept vigorous, and does not readily contribute to fire spread.

Other plant species often mislabeled as fire resistant or fire retardant are rosemary, coyote brush, and rockrose. The foliage of these plants has a high oil content, and once ignited burns readily. Nevertheless, these plants are drought tolerant, esthetically pleasing, very versatile for landscaping, generally low growing (except for gum rock-rose), and well adapted to southern California's climate. Their rooting depth approaches that of coastal sage species. Prostrate coyote brush resprouts readily after a fire, and it is an excellent candidate for erosion control on the steeper hillsides as it does not require replanting after fire.

The fire resistance of plants is relative and depends on fuel moisture and the amount of dead fuel. Generally, a low-growing plant has an inherently lower fuel volume than a taller plant, and therefore has less fine dead fuel. Two key factors of fire control and fire safety are related directly to low fuel volume: *fuel discontinuity,* whereby the continuity of any flammable cover is broken up, and *reduction in fuel load,* whereby plants are pruned and dead fuel is cleared away.

The low fuel volume objective suggests creation of greenbelts around subdivisions and individual homes. As space permits, these areas could include flammable fuels such as chamise, eucalyptus, coyote brush, and rosemary, as well as relatively fire-resistant fuels such as ice plants. Aerial fuel (trees) can be kept reasonably fire retardant through periodic pruning; however, the general tendency is to leave them unpruned and they are therefore more flammable and carry fire more readily than low-growing plants. Conifers should not be planted close to a home, because their needles have a high resin content, provide fine fuels, are quite flammable, and are likely to be on the roof when fire strikes. However, both conifers and broadleaf trees planted a distance away from the home can serve the important function of channelling the initial convection heatwave away from a home and thereby perhaps saving it (assuming, of course, that the flames from the burning trees can be extinguished before they ignite the house).

Brush clearance ordinances are based on the low fuel concept and are good guidelines for reducing fire hazard. They are self-defeating if they do not take into account the increasing flammability of many landscape plants as they grow and mature, and ignore the danger of potential slips and slides on steep slopes owing to the removal of the deep-rooted chaparral vegetation.

Establishing Greenbelts

Homeowners trying to comply with the brush clearance ordinances and faced with a brush surcharge on their fire insurance policies should reduce the unwanted native vegetation in an ecologically sound way. They must realize that it may not be possible to reduce flammable fuels on slip areas and on erosive, steep, and unstable terrain to the point of receiving a favorable insurance rate. The added expense of paying the surcharge then becomes one of the costs of living with nature and may be much cheaper, even in the long run, than slope failures caused by improper or excessive clearing of native vegetation.

There are several alternative methods of reducing flammable fuels and establishing a greenbelt. The first is to eliminate the native vegetation and relandscape a greenbelt buffer strip of 100 to 200 feet (30.5 to 61 m) around the home. This practice may also be the only possible solution where the developer or builder has already eliminated most of the native plants, or where, because of harsh climate or site characteristics, only highly flammable vegetation exists. This method is effective if the native plants can be readily replaced by drought-tolerant vegetation of less fuel

Figure 11—Native plants can be used effectively as foundation plants in landscapes. To separate ground fuels from aerial fuels, prune the lower branchlets and thin the plant. Yearly light pruning can make it difficult for such plants to burn and support a fire.

volume and similar rooting characteristics. Moreover, more gentle terrain with deep soils is often well suited for the establishment of a wider greenbelt buffer zone that may include recreational facilities and commercial agriculture such as orange or avocado groves. This requires strong community support and long-range planning but may be the most effective way of separating wildland fuels from flammable structures.

A second alternative for landscaping in wildland areas is to reduce the fuels of the native vegetation and use the remaining plants as foundation plants in the landscape setting (*fig. 11*). To do this, an expert familiar with the native plants of the area should be consulted to oversee the selection of plants, thinning, pruning, and relandscaping. All native vegetation that is not to be removed during the initial thinning should first be identified. The unwanted vegetation should then be removed. The consultant who is selected should be well trained in the principles of pruning for fire safety and should oversee the pruning of all desirable woody overstory plants into upright short-stemmed trees. On multistemmed plants, several stems should be selected and the plant so pruned that a fuel separation is created between the overstory canopy and the ground cover that is to be planted next. This method works well in areas where the native vegetation has not been disturbed by fire for about 7 to 10 years, and where the fire frequency is low.

The careful selection of native plants as a foundation for landscaping is critical, because of differential watering requirements, differences in year-round appearance, growth, flowering habits, resprouting characteristics, and rooting depth. For example, native mountain lilacs (*Ceanothus* species) come in many shades of color from white to deep blue, and even the highly flammable chamise, left as a specimen plant, is delightful when displaying its attractive white flowers. Chokecherries, toyon, elderberry, and California walnut provide food for wildlife. When there is doubt about what plant to retain, it is best to choose a sprouting plant over a nonsprouting one.

Native understory plants can add accent to the landscape setting but can also act as ladder fuels to the woody overstory vegetation. Highly flammable plants such as sages (white, black, purple), buckwheat, California sagebrush, and deerweed should therefore be eradicated wherever permanent slope stability permits. Woody perennials such as fuchsias and gooseberries and even woody-based perennials such as sunflowers that die back to the base every year should be included in the landscape setting because they are low-fuel plants with showy flowers and provide food for wildlife. Perennial grasses should not be eradicated.

Once thinning and pruning of native plants is completed, erosion netting should be spread and anchored on steeper slopes and erosive soils. This is especially critical if slow-growing ground cover such as coyote brush is interplanted among the native plants or if the ground cover chosen will not grow fast enough to cover the soil surface by late fall. A "noncompetitive" protective cover crop such as alyssum can be sown in the fall for temporary control of surface erosion and rilling. When heavy first-year planting failures have occurred through such conditions as lack of proper maintenance, rodent activity, or browsing, it may be necessary to sow highly competitive annual grasses with the coming of the winter rains. These should be immediately eradicated in the spring, when replanting should begin.

Ideally, the greenbelt should be established early in spring, or even towards the end of winter, when soil moisture has been fully recharged through rainfall. Regular watering will be needed to get the plants established, especially the ground covers planted from flats, as these have a very shallow root system at first. Early establishment provides a better rooted cover before the hot weather and summer drought return. With this technique, less watering is required during the summer, and water can be withheld from plants earlier in the fall. The soil moisture is then well below field capacity when the winter rains return. Well-established plants several years old should not receive deep watering after mid-September. If plants are not established until summer, more frequent watering is needed and an abundant late weed crop may compete vigorously with the planted stock.

When planting is done in early spring at the end of the rainy season, weed killers or preemergent herbicides that selectively kill spring weeds can be used to full advantage. A reduced crop of winter weeds will still germinate and help cover the slope until the ground cover becomes fully established. Using selective weed killers for fall planting on hillsides is not advisable unless slopes are covered with jute matting, because the newly established ground cover will not prevent excessive erosion. For hillside use of preemergent herbicides or herbicides that kill the seedlings as they germinate, follow these four rules:

1. Select a herbicide that does not affect the planted stock.
2. Treat a small test area first.
3. Always use less than recommended.
4. Do not use a preemergent herbicide whose effectiveness lasts for more than one season.

Maintaining Compatibility of Plants

A critical concept when establishing a greenbelt is the compatibility of landscape species and native plants, especially in regard to watering and maintenance requirements.

Information on the compatibility of existing native plants and introduced species is scant, but the moisture and habitat requirements of native plants often provide a clue to their tolerance. In general, native plants found in moist canyons and draws have a higher tolerance to landscape irrigation than plants on north and east slopes. These, in turn, seem to have a higher tolerance than plants on harsh exposures such as south-to-west slopes and thin soils.

Among individual species, those with higher moisture requirements also seem to have greater tolerance to landscape irrigation than the most drought-tolerant species. The time and amount of watering also plays a critical role. Occasional deep watering during the summer at nighttime when the exotic plants show signs of wilting, such as drooping of leaves, is less damaging than intermittent, more shallow watering in the daytime. Heat and moisture both encourage root rot, so that plants growing in heavy soils, such as those with a high clay content, or in dark soils that heat up more readily, seem to be most affected. Examples to clarify the above points are given below.

Sumac species, such as laurel sumac, sugarbush, and lemonade berry, are quite drought tolerant and deep rooted. These native plants make excellent landscape specimens, but do not tolerate the watering required when interplanted with more water-demanding plants. The combination of sumacs with a surrounding groundcover of African daisy, ivy, or vinca is likely to result in root rot and death of the sumacs within a few years because regular watering is normally required to keep these ground covers alive. On the other hand, interplanting the sumacs with Twin Peaks coyote brush for groundcover may not adversely affect the sumacs if the coyote brush is watered only enough to keep it alive. Native oaks are also very susceptible to watering of an understory ground cover or surrounding lawns. A good technique which allows the use of more water-demanding plants is to keep an unplanted and unwatered buffer near the base of the intolerant shrubs and trees. However, situations can be found where the above-named plants seem to be compatible with landscape ground covers. Examples are long, steep slopes on north or east exposures, where, due to deep soils, water seepage from above and the shading of the native plants, the understory groundcover needs little or no watering. These situations are common when one owner has managed the property for many years. A change of ownership and a different management regime that results in increased watering may cause root rot and mortality of the woody native species. The soil around most native plants is normally well aerated and covered with litter and humus. Soil compaction around these plants may therefore also affect them more adversely than it would landscape plants.

Laurel sumac is of great interest in landscaping with native plants because it is an excellent soil binder on steeper slopes and harsher sites. Its prolific resprouting ability and fast growth enables it to survive in areas of repeated disturbance by fire and grazing. This resprouting ability from roots and root crowns makes it a nuisance plant in a landscape setting. However, once the soil surface around the plant is shaded with a noninvasive ground cover such as Twin Peaks coyote brush, and any disturbance has stopped, the resprouting will also greatly decrease or stop. This greatly reduces maintenance. When laurel sumac and sugarbush grow close to each other on nonerosive, moderately steep slopes, it may be better to select sugarbush as a foundation plant because it is usually much slower growing and does not require regular maintenance. It is also esthetically more pleasing throughout the year. Furthermore, laurel sumac is not cold-tolerant and freezes. All of the sumacs tend to be susceptible to insects and disease and pruning of dead material is therefore recommended.

On steep, erosive slopes, laurel sumac should not be replaced with landscape plants. For its fuel volume, the plant is one of the deepest rooted and most drought-tolerant plants available to the homeowner. Its reputation has been tainted by labeling as extremely flammable, because the species has been observed during wildfire as bursting into flames. Actually, in comparison to many other chaparral species of the same stature, fuel loading, and age, individual plants are quite fire-resistant. Except when the plant freezes, the dead-to-live fuel ratio is often much lower than that of other species. More important, perhaps, in fuel moisture it ranks among the highest of native plant species during the high fire weather conditions encountered in late fall. (Under wildland conditions, high fuel moisture of leaves and stems requires that the plant be preheated to higher temperatures, than for example, chamise, mountain mahogany, and most *Ceanothus* species, in order to ignite or burst into flames.) Once the surrounding fuels are removed and laurel sumac is pruned to treelike form, the understory vegetation rarely will preheat it to the ignition point. Leaves may be totally scorched by the heat of the fire, without the plant carrying the fire. Thus, the different ignition requirements of individual species and plants are the key to flaming and firespread.

Choosing Low-Growing Species

Ideally, plants should be selected for these qualities: (1) low growth habit, (2) drought tolerance, (3) fire retardance, (4) deep rooting habit, (5) esthetically pleasing effect, and (6) compatibility among different species (*fig. 12*). The usefulness of some commonly used low growing landscape plants and other plants in particular situations, with emphasis on southern California, was evaluated according to their suitability for various sites and conditions, growth characteristics, and fire retardance (*table 5*). The table is a general guide, but cannot substitute for onsite professional opinions rendered by expert consultants familiar with specific sites and problems. Homeowners who must deal with individual landscaping problems should make their own decisions from the table and descriptions, using the general advice on fire safety and more effective watershed management given elsewhere in this report.

The plant species listed, except where indicated, are able to form a solid ground cover for the slopes recommended. However, there is no guarantee that the species prevent slippage when the soil becomes saturated. Interplanting ground covers with shrubs and trees, as discussed earlier, will maximize slope stability. Landscape plants that require high maintenance or that are readily browsed, such as most prostrate *Ceanothus* species, are not included in *table 5*.

The columns in *table 5* headed "aspects," "soil depth," and "if irrigated" should be read as a unit. The values for soil depth apply to medium textured, loamy soils. Those for irrigation apply to coastal regions of southern Califor-

Figure 12—A greenbelt of coyote brush surrounds the house at the *top*. Trees provide added slope stability, but will increase the fire hazard as they grow. A greenbelt of African daisy plants provides minimal fire safety for the flammable house at the *bottom*. The probability of damage from fire and soil slippage is high.

Table 5—*Evaluation of 20 low-growing plants used in wildland-urban hillside landscaping*[1]

Species	Effective . . . On slopes (degrees) <25	25-35	>35	On aspects N-E	S-W	At soil depths (feet) . . . <1	1-3	>3	If irrigated summer to fall[2]	At elevations (feet)	Characterized by . . . Growth habit, height (inches)	Fire retardance	Re-sprouting ability	Rooting depth (ft) (effective)	Comments
Aaron's beard	X	X	Z	X		X			>2 M	Up to 4000	Spreading shrub, 12-24	Medium	If watered	<3	Low maintenance. Little foot traffic. Spreads by underground runners. Good soil binder. Invasive if well watered. Yellow flowers. Draws bees. Sun to shade.
				X			X		1 M						
				X				X	2-3 S						
					X	X			1 W						
					X		X		<1 W						
					X			X	1 M						
Acacia ongerup, prostrate	X	X	Y	X		X			<1 M	Up to 2000	Spreading shrub, 12-30	Low; decreases with increase in fuel	Poor	>6	Low maintenance. No foot traffic. Showy yellow flowers. Draws bees. Most drought-tolerant and quickest-spreading woody plant tested. Full sun. Spreads to more than 8 feet in diameter in full sun and deep soils.
				X			X								
				X				X	0						
					X	X			>1 M						
					X		X								
					X			X	1 S						
African daisy	X	Y	Z	X		X			2 M	Up to 2000	Trailing groundcover, <12	Medium to high	If watered	3	Moderate to high maintenance. Tolerates some foot traffic. Showy white flowers and other hybrid colors. Freezes at 25°F. Fertilize and water regularly. Full sun to partial shade.
				X			X								
				X				Y	<1 M						
					Y	X			1 W						
					X		X		2 M						
					X			X	1-2 M						
Algerian ivy (freeway ivy)	X	X	Y	X		X			1 W	Up to 2000	Trailing groundcover, 8-12	Medium	If watered	3-4	Low maintenance. Tolerates foot traffic. Excellent for minimizing erosion on long, steep cuts. Leaves will burn if watering is neglected. Excellent understory to a variety of trees. No flowers. Full sun to shade.
				X			X		1 M						
				X				Y	2 S						
					Y	Y									
					X		X		2 M						
					X			X	1 M						
Australian saltbush	X	X	Y	X		X			1 S	Up to 2000	Trailing groundcover, to 12	Generally high	Resprouts even on dry sites	3-4	Low to medium maintenance. Moderate foot traffic. Readily established from seeds. Naturalized on harsh rocky sites. May not form persistent solid cover because it is affected by disease if overwatered or crowded (variety *corta* may be disease resistant). Relatively short lived (5 years +). Full sun (no north slopes).
				X			X		0						
				X				Z							
					X	X			1-2 S						
					X		X		0						
					X			X	0						
Capeweed	X	Y		X		X			1-2 M	Up to 2000	Spreading groundcover, 6-8	High	If watered	1-3	Very low maintenance. Takes occasional foot traffic. Showy yellow flowers. Weedy in manicured setting. Frost sensitive. Draws bees. Spreads by runners. Full sun to partial shade.
				X			X		1 M						
				X				X	2 S						
					X	X			2 M						
					X		X		1 M						
					X			X	<1 M						
Carmel creeper ceanothus	X	X	Y	X		X			<1 M	Up to 4000+	Spreading shrub, 18-30	Low to medium; decreases with increase in fuel	If watered after light fire	6	Moderate maintenance (renovate occasionally by thinning old branches). No foot traffic. Readily browsed. Showy blue flowers. Draws bees. Full sun to partial shade.
				X			X		<1 M						
				X				X	2 S						
					X	X			1 M						
					X		X		<1 M						
					X			X	<1 S						

Table 5—*Evaluation of 20 low-growing plants used in wildland-urban hillside landscaping*[1] *(Continued)*

Species	Effective . . . On slopes (degrees) <25	25-35	>35	On aspects N-E	S-W	At soil depths (feet) . . . <1	1-3	>3	If irrigated summer to fall[2]	At elevations (feet)	Characterized by . . . Growth habit, height (inches)	Fire retardance	Re-sprouting ability	Rooting depth (ft) (effective)	Comments
Coyote bush (brush)	X	X	Y	X		X			<1 M	Up to 4000	Spreading shrub, 12-24	Low	Vigorous	6	Prune back every 5 years or less often. No foot traffic. Inconspicuous flowers. Hard to establish from flats in midsummer. Healthy green color. Sensitive to herbicides. Full sun. Spreads to more than 5 feet across in full sun and deep soils.
				X			X								
				X				X	0						
					Y	Y			>1 M						
					X		X								
					X			X	1 S						
Creeping sage	X	X	Y	X		X			>1 S	2000-6000	Trailing groundcover, <6	Medium to high	If watered	3-4	Low maintenance. Tolerates some foot traffic. Stem layers readily. Prefers acid soil. Excellent understory in pine plantations. Readily killed by overwatering and heavy soils. Sensitive to herbicides. Needs extensive seed scarification. Showy blue flowers. Draws bees. Sun to shade.
				X			X		0						
				X				X	0						
					X	Z									
					X		X		>1 S						
					X			X	1 S						
Descanso rockrose	X	X	Z	X		X			1 M	Up to 4000	Semi-upright shrub, 12-24	Low to medium	Poor	3-4	Medium to low maintenance. No foot traffic. Showy pink flowers; draws bees. Ground cover for easily accessible dry site areas. Attractive if watered; unattractive if not maintained. Full sun.
				X			X								
				X				X	0						
					X	X			<2 M						
					X		X								
					X			X	1-2 S						
Green lavender cotton	X	X	Z	X		X			1 M	Up to 4000+	Semi-upright shrub, 16-30	Low to medium	Resprouts even on dry sites	3-5	Medium maintenance. No foot traffic. Does not stem layer. Excellent for border effect. Clip back dead flower stalks every year to maintain higher fire retardance. Yellow flowers. Draws bees. Full sun to partial shade.
				X			X								
				X				X	0						
					X	X			2 M						
					X		X								
					X			X	1 S						
Ice plants	X	See text		X		X			<1 M	Up to 2000	Trailing groundcover, 4-18	Generally high	Depends on severity of fire	1-2	Low maintenance. No foot traffic. Showy multi-colored flowers. High foliage moisture and weak root system causes slippage on steeper slopes, especially fills. Full sun to partial shade.
				X			Y								
				X				X	0						
					X	X			1 M						
					X		Y								
					X			Y	'1-2 S'						
Lippia	X	Y	Z	X		X			2 M	Up to 2000	Trailing groundcover, <4	High	If watered	<3	Low maintenance. Tolerates foot traffic. Takes neglect and will recover with watering. Good soil binder among pruned shrubs. Excellent drysite lawn. Lilac to rose flowers. Draws bees. Mow off flowers to eliminate bees. Full sun to partial shade.
				X			X								
				X				X	<1 S						
					X	X			1 W						
					X		X								
					X			X	<1 M						
Periwinkle	X	X	Z	X		X			>2 M	Up to 4000	Trailing groundcover, <18	Medium	If watered	3	Low maintenance. Occasional foot traffic. Showy blue flowers. Does well under partial overstory where somewhat neglected. Excellent understory ground cover. Sun to shade.
				X			X								
				X				X	<1 M						
					Y		X								
					X			X	1-2 M						

[1]< = less than
> = greater than
X = suitable
Y = not totally suitable
Z = not recommended

[2]0 = None
1 = Once
2 = Twice
W = Week
M = Month
S = Summer
No entry = intermediate watering schedule (see entry above or below)

Table 5—*Evaluation of 20 low-growing plants used in wildland-urban hillside landscaping*[1] *(Continued)*

Species	Effective . . .										Characterized by . . .				Comments
	On slopes (degrees)			On aspects		At soil depths (feet) . . .			If irrigated summer to fall[2]	At elevations (feet)	Growth habit, height (inches)	Fire retardance	Re-sprouting ability	Rooting depth (ft) (effective)	
	<25	25-35	>35	N-E	S-W	<1	1-3	>3							
Point Reyes ceanothus	X	X	Y	X		X			<1 M	Up to 4000+	Spreading shrub, 8-24	Low to medium	Poor	6	Moderate maintenance (renovate occasionally by thinning old branches). No foot traffic. Readily browsed. Showy bright blue flowers. Draws bees. Full sun to partial shade.
				X			X								
				X				X	0						
					X	Y			1 M						
					X		X								
					X			X	1 S						
Prostrate ceanothus	X	X	Y	X		X			>1 S	4000-7000	Trailing groundcover, >4	Generally high	No	3-4	Low maintenance. Tolerates some foot traffic. Stem layers readily. At lower elevations in southern California plant prefers north slopes. Best on coarse textured soils. Needs extensive seed treatment. White to blue flowers. Draws bees. Sun to shade.
				X			X		1 S						
				X				X	0						
					X	Y			<1 M						
					X		X		0						
					X			X	0						
Prostrate myoporum	X	Y	Z	X		X			1 M	Up to 2000	Spreading groundcover, <6	Generally high	No	3	Low maintenance. No foot traffic. Stem layers. White flowers. Draws bees. Full sun to partial shade.
				X			X								
				X				X	2 S						
					X	X			2 M						
					X		X								
					X			X	<1 M						
Prostrate rosemary	X	X	Y	X		X			<1 M	Up to 4000+	Spreading shrub, 12-24	Low; decreases with increase in fuel	No	3-5	Low maintenance. No foot traffic. Stem layers readily. Hardy plant with dark green needle foliage. Showy blue flowers. Draws bees. Prefers full sun.
				X			X								
				X				X	1 S						
					X	X			2 M						
					X		X								
					X			X	<1 M						
Silver saltbush	X	X	Y	X		X			1 S	Up to 2000+	Spreading shrub, 16-30	Low to medium; decreases with increase in fuel	Without water after light fire	6	Moderate maintenance (renovate occasionally). No foot traffic. Stem layers, underground runners. Seeds germinate readily and are preferred by birds. Deer browsing maintains vigor, low growth, greater fire retardance (less fuel). Loamy to sandy soils. Flowers inconspicuous. For dry site landscaping away from house. Full sun.
				X		X	X		0						
				X				X	0						
					X	Y			2 S						
					X		X		0						
					X			X	0						
Wavy leaf saltbush	X	X	Y	X		X			1 S	Up to 3000	Semi-upright shrub, to 36	Low to medium decreases; with increase in fuel	Without water after light fire	6-9	Moderate maintenance (renovate occasionally). No foot traffic. Stem layers. Moderately browsed when young. Avoid heavy soils. Flowers inconspicuous. Good for dry site landscaping away from house. Full sun.
				X			X		0						
				X				X	0						
					X	Y			'2 S'						
					X		X		0						
					X			X	0						

[1] < = less than
> = greater than
X = suitable
Y = not totally suitable
Z = not recommended

[2] 0 = None
1 = Once
2 = Twice
W = Week
M = Month
S = Summer
No entry = intermediate watering schedule (see entry above or below)

nia and attempt to show relative watering needs of the plants listed. These values assume that soil moisture is recharged to 12-inch (30.5 cm) depth during watering. In reality, this goal is rarely achieved through overhead watering because of sprinkler design and time period necessary for irrigation. The effective rooting depths indicated in *table 5* are based on moisture withdrawal by roots after soil moisture has been depleted in the upper soil layers.

The term "fire retardance" as used in *table 5* reflects differences in fuel volume, inherent flammability characteristics of the plant, and ease of fire spread. For example, under extreme autumn fire conditions, on steep slopes with nongusting winds of 30 mph (48.3 kph), a 2-foot (61 cm) tall solid ground cover with "high" fire retardance is expected to produce a flame less than 10 feet (3 m) long and to reduce the rate of fire spread. Under similar conditions, a plant with "low" fire retardance may ignite readily, will carry the fire, and can produce flames approaching 25 feet (7.6 m) in length. For comparison, mature chaparral under these conditions can produce flames exceeding 80 feet (24.4 m) in length.

The following example for capeweed will illustrate the use of *table 5*. Column 1 shows that the species is most effective for planting on slopes not exceeding 25°, but may be used on a limited scale on slightly steeper slopes. The shallow root system of capeweed may trigger soil slippage. The next three columns of data are to be read as a unit and show the relationship between aspect, soil depth, and irrigation requirements. For example, the first line shows that on a north-to-east aspect with less than 1 foot of soil depth, established plants require summer irrigation once or twice a month.

The importance of microclimate should be kept in mind. A north or east slope provides an opportunity for using less drought-tolerant plants, such as vinca or ivy, whereas the harsh south- and west-facing slopes are best suited for the most drought-tolerant plants. Canyons and valleys provide for a wide choice of plant species, but may also increase the danger of frost due to cold air drainage.

Plants suitable to landscape needs can be identified by their performance in the neighborhood. Comparisons should take into account such variables as steepness and exposure of slopes, soil type and depth, and watering schedule. Further advice is available at nurseries and in literature on landscaping in California (Williamson 1976). The plants described in the rest of this section are rated according to the six qualities listed earlier.

Ice Plants

Ice plants (*Carpobrotus, Delosperma, Drosanthemum* spp.) generally are rated excellent in low growth habit, fire retardance, and esthetics, but fail in deep rooting habit. The coarse-leaved "freeway ice plants" (*Carpobrotus*, formerly classified as *Mesembryanthemum*) are recommended for soil binding of marginal, seldom-watered but not steep areas; white trailing ice plant (*Delosperma alba*) for soil binding of steeper slopes, and finally *Drosanthemum* species for soil binding of steep slopes even where soil is very poor (Williamson 1976). Professional landscapers recommend ice plants for extensive plantings on slopes as steep as 25° or more and these plants do an admirable job most of the time. However, when high-intensity storms occasionally follow each other in short order, dumping additional rain on supersaturated soils, by far the greatest proportion of soil slips in landscaped areas occurs on slopes planted with ice plant. As a general rule, a written opinion by a geologist should be obtained before ice plants are used extensively on landscaped slopes of more than 15°. Exceptions are extremely harsh slopes where only ice plants would grow anyway. Ice plants are so extensively used because the plants cover quickly, soon giving the appearance of a completed landscape job. Unfortunately, the combination of a weak root system with high foliage moisture that adds weight may produce slope failures (Ilch 1952).

Coyote Brush

Coyote brush (*Baccharis pilularis* var. *prostrata* or cultivar Twin Peaks) rates excellent in drought tolerance, deep rooting habit, and esthetics. Its flowers are inconspicuous. The plant is prostrate to semiprostrate but is deep rooted and quite drought tolerant. In coastal areas on deeper soils it requires little, if any, summer watering. Mature coyote brush is highly flammable once ignited but resprouts readily after fire. It is therefore recommended for steeper slopes even in chaparral areas because its high flammability is countered by its relatively low fuel volume. The plant should not be planted too close to the house, however. Initially slow growing and therefore hard to establish, a 5-year-old plant may measure 6 to 8 feet (1.8 to 2.4 m) in diameter on better soils, and its compact growth will eliminate weeds almost completely. Plants will mound after they have grown together and thinning out may be required. When coyote brush becomes overmature and quite woody (usually within 5 to 10 years, depending on soils, watering, and exposure) it should be cut back to a few inches above the base in the springtime toward the end of the rainy season. Regrowth will be rapid, and during the regrowth period the plant will be essentially fireproof. Most of the slope will again be clothed before the rains arrive; thus, occasional renovation of coyote brush should be considered. Only the prostrate variety is recommended. On slopes, it does not exceed 12 to 18 inches (30.5 to 45.7 cm) in height. Other varieties may grow to be more than 4 feet (1.2 m) tall.

Rosemary

The prostrate variety of rosemary (*Rosmarinus officinalis*) also rates excellent in drought tolerance, deep rooting habit, and esthetics, but does not spread as extensively as coyote brush and therefore should not be used for large-scale slope plantings where weed control is necessary. It is also highly flammable but has low fuel volume (semiprostrate). It will not resprout. Its blue flowers are quite attractive and lure bees.

Prostrate Acacia

Prostrate acacia (*Acacia rodelens* cultivar *ongerup*) rates excellent in drought tolerance, deep rooting habit, and esthetics. Mature plants are flammable and have a greater fuel volume than prostrate coyote brush. Where fire danger is not great, in many ways the plant is superior to coyote brush. In coastal regions it is the most drought-tolerant, quick-spreading, low-growing woody plant tested under wildland conditions. With adequate rainfall and good soils, it can form a thick mat 3 to 4 feet (0.9 to 1.2 m) in diameter within 1 year and up to 15 feet (4.6 m) in diameter within 5 years. In late spring the plant is covered with showy yellow flowers. It may mound to 4 feet (1.2 m) high (thereby greatly increasing fuel volume), if its growth is obstructed. Thinning is then required. This species is the most underrated and underplanted species for greenbelt establishment that our research has encountered in 5 years. Its one drawback is the lack of resprouting ability; however, some of its seeds develop true to the prostrate habit.

Rockrose

Many species of rockrose (*Cistus* spp.) are available. They are rated good in drought tolerance and esthetics, and have beautiful showy white or pink flowers. In growth form they range from semiprostrate to over 6 feet (1.8 m) tall. The genus is flammable but generally has low fuel volume; the major exception is gum rockrose, which has the highest oil content (crude fat) of any plant listed in *table 3*. The genus is recommended for border effect but not for mass planting because its semiprostrate-to-upright growth form does not eliminate weeds. It also aids fire-spread (Laure and others 1961, Martin and Juhren 1954, Olsen 1960).

Periwinkle

The *Vincas* (*Vinca major*, *V. minor*) are rated excellent in low growth habit, and esthetics. They are fairly deep rooted and somewhat drought tolerant. They form an excellent weed-free cover, will readily resprout after fire, and have showy flowers. *Vincas* are well adapted as an understory cover to deep-rooted vegetation, especially on northern and eastern exposures when deeper soils are present. Without an overstory, they may require frequent watering in the summer. The taller-growing periwinkle (*Vinca major*) is more drought tolerant and is a better soil binder on slopes than the smaller-growing dwarf running myrtle (*V. minor*). On fertile soils with ample soil moisture, periwinkle covers the soil faster than any other species discussed in this section. However, it can become an unwanted nuisance similar to ivy.

Ivy

Algerian ivy (*Hedera canariensis*) and English ivy (*Hedera helix*) are the two species of ivy most commonly used in landscaping. They form an excellent weed-free cover. Algerian ivy, known as freeway ivy, is more commonly planted and also more drought tolerant and more deeply rooted than the more dainty English ivy. Because of its aggressiveness, it may be considered a nuisance in manicured landscape settings and it chokes out other plants. However, because of its climbing habit, it can effectively cover old fences and keep them standing, and reduce erosion scars on very steep slopes as it climbs downward. It is excellent for erosion control and its fuel buildup with age is not considered a major problem if the plant is kept away from the home. Frequent watering is required in summer. The daintier-looking English ivy is more shallow rooted, and also needs constant watering in the summertime or its leaves will be sunburned. It should, therefore, not be planted on south slopes or in harsh areas and does best under partial overstory.

African Daisy

African daisy (*Osteospermum fruticosum*) is a trailing ground cover with very showy flowers. It is somewhat drought tolerant but is best planted in full sun and on moderate slopes with good soil and ample soil moisture. Overwatering in hot weather may cause disease. This plant is not suitable for harsh cut slopes or other harsh sites, such as south-to-west exposures with thin soils. It does best in the vicinity of the coast and freezes at about 25° F (-4° C). After fires, it reestablishes prolifically from seeds. Two to three years after establishment, it may require regular maintenance such as fertilization and thinning of dieback caused by drought, cold, and fungus.

Watering Plants

Proper watering is the key to maintaining healthy and functional plants anywhere, even in a drought-tolerant greenbelt in the chaparral-urban watershed. Ideally, such a greenbelt should require no supplemental irrigation, but even the most drought-tolerant plants require a minimum amount of rainfall for survival.

A practical rule of thumb is that most drought-tolerant landscape shrubs can survive on ½ inch (12.7 mm) of water per week during the hot summer months but may require a greater amount of water where esthetics are important. Most other landscape plants can survive on about 30 inches (762 mm) of supplemental irrigation per year. Since the average household uses more than 60 inches (1524 mm) of water per year for landscape irrigation, this represents a tremendous saving to the homeowner as well as to society. In California, where future water shortages are foreseen, such saving has great importance, and can be achieved simply by sharply reducing and thoughtfully regulating watering in the late winter and spring months when plants have plenty of ground water.

Water-Saving Plants

When soil moisture is recharged to field capacity late in the season, even chaparral plants can be moderately heavy water users. They can transpire more than 5 inches (127 mm) of water per month (*table 6*). Most chaparral plants are true water savers (hydrophytes), however, and are able to conserve water by restricting transpiration before permanent wilting occurs; they may become dormant in the summer (*table 6*). Miller (1979) showed that in a stand of chamise chaparral on a southern exposure, maximum transpiration was slightly over 1 inch (25.4 mm) in June, but dropped to less than ¼ inch (6.4 mm) in October before the fall rains. Maximum transpiration on north slopes was much higher than on south slopes; the maximum of 1.7 inches (43.2 mm) per month was reached a month later. The transpiration rates reached a minimum of 0.0024 inches (0.06096 mm) in October, primarily because the soil moisture had been used up.

In order to survive for several months on practically no soil moisture uptake, after being a moderately heavy water user just weeks before, water-saving plants have developed effective drought-adaptive mechanisms (Rundel 1977). These include

- Leaves which are small, thick, and leathery (having thick-walled cells) and high in oil content, all of which tend to reduce transpiration. Relative vertical orientation of leaves so as to present the edge but not the surface to the sun, as well as changes in the angle of leaves in response to sunlight regulate the uptake of solar radiation and water loss.
- Stomata (minute openings in the leaf surface) that open during the daylight only for a short period of time and are able to close quickly, thus reducing water loss; stomata may be recessed and have cavities covered with hairy protrusions, which aid in reducing water loss.
- Cutin (a waxy substance on the leaf) that reduces transpiration to a much greater degree after the stomata have closed.
- Reduction of exposed leaf surface, as through shedding, rolling, or folding of leaves.
- Reverse transpiration—the ability of leaves to take up atmospheric moisture.

In general, the major means of control of water loss are the stomata; the other mechanisms help control water loss even further. Additionally, the gradient of increasing aridity and lack of available ground water supply between evergreen shrub communities and summer deciduous

Table 6—*Rates of transpiration and evaporation on loamy soils, California*

Plant or surface	Location	Conditions	Time of year	Rate of transpiration	Source
				Inches/mo	
Lawn grasses	Coastal zone		Summer	4.0	Williamson 1976
Bermuda grass	Santa Ana River Valley	Water table:	Summer		
		2 ft		6.5	Blaney and others 1930
		3 ft		5.5	
Weedy herbs	Santa Ana River Valley	Level	Winter	2.0	Blaney and others 1930
Brush 5 ft tall: Chamise, sage, Yucca	San Bernardino	Soil moisture recharge to field capacity in May	Apr.	3.0	Blaney and others 1930
			June	3.9	
			July	5.2	
Reeds, tules	Temescal Creek, Corona	Streambed	Apr.-May	12.9	Blaney and others 1930
Mixed chaparral: Desert buckbrush, Scrub oak	Northern exposure	Before fall rain	July	1.7	Miller 1979
			Oct.	0.0024	
				0.0	
Chamise chaparral	Southern exposure	Before fall rain	June	1.1	Miller 1979
			Oct.	0.2	
Navel orange trees, mature, 10 ft spacing	Santa Ana River Valley	Level	Jan.	1.0	Blaney and others 1930
			Mar.	1.6	
			May	2.1	
			July	3.1	
			Sept.	2.0	
			Nov.	1.5	
Bare ground	Santa Ana River Valley	Water table:			Blaney and others 1930
		2 ft	Winter	0.3	
		2 ft	Summer	0.8	
		3 ft	Jan.-Apr.	0.1	
		4 ft	Summer	0.0	
Swimming pool	Coastal zone	—	Summer	5-10	Klaus W. H. Radtke
Evaporation pan	Coastal zone	—	—	[1]40.0	Strahler and Strahler 1973
	Riverside ("desert")	—	—	[1]67.0	Blaney and others 1930

[1]Per year

coastal scrub communities is reflected in a change from deep, penetrating roots to shallow, fibrous roots and an increase in shedding of leaves. Furthermore, some plants such as hoary-leaf ceanothus make more complete use of the available moisture by starting their active growing season early in the year during the cooler temperatures which normally coincide with the onset of the fall or winter rainy season. Chaparral plants that have deep root systems draw moisture even from deep rock crevices. Many drought-tolerant plants are also able to lower the soil moisture percentage well below the so-called wilting point, at which water absorption by roots theoretically stops and leaf turgor cannot be maintained even in the absence of transpiration.

Water Requirements

The ability of most chaparral plants to extract the maximum amount of moisture possible leaves the soil mantle and rock crevices dry to absorb moisture when the winter rains return. Proper watering of greenbelts should, therefore, be patterned after this natural water withdrawal-recharge cycle. The yearly irrigation requirements of landscape plants depend on the amount and distribution of rainfall and are governed by the timing of the last effective rain in the spring and the first effective rain in the fall. Such rainfall is sufficient to be absorbed by plants. The time of first summer irrigation depends on the amount of moisture stored in the soil at the end of the rainy season, and on the root depth and moisture requirements of plants (*table 7*). During years of well-distributed rainstorms, most of the water infiltrates the ground and recharges the soil moisture to field capacity throughout the plant root zone; moisture for evaporation and transpiration is thus supplied throughout the winter months. During years when the rainstorms come early and are more closely spaced, more water percolates below the root zone and is lost to the plant. Soil moisture recharge occurs less often and much available soil moisture is used up early in the season by evaporation and transpiration. On deep soils, less water penetrates below the root zone, but on coarse soils, there is greater moisture percolation to the underground water table. The approximate amount of water available per foot of soil is as follows (Stefferund 1957):

Soil type:	*Available water (inches/ft)*
Sand	0.25 - 0.75
Loamy sand	0.75 - 1.25
Sandy loam	1.0 - 1.5
Fine sandy loam	1.5 - 2.0
Clay loams	1.75 - 2.25
Clays	2.0 - 3.0

Table 7—*Hypothetical water use by nine species of chaparral plants and ground cover, based on soil moisture recharge to field capacity by March 15, coastal zone, California*

Plant	Effective rooting depth	Moisture available to roots	Transpiration		Date first watering needed	Response to drought
			Mar. 15 to June 15	June 16 to Aug. 15[1]		
	Feet	*Inches*	*Avg. inches/mo*			
Lawn grass	2	3.5	3.5	4.5	Apr. 15	Plant dies
Periwinkle	3	5.25	2.5	3.5	May 22	Leaves go limp, above-ground portions die, root systems usually survive
Algerian ivy	4	6.75	2.5	3.5	June 5	Plant dies
Descanso rockrose	5	8.25	1	2	Sept. 1	Plant goes partially dormant
Australian saltbush	6	9.25	1	0.5	None	Plant drastically reduces transpiration, "shuts down"
Coyote brush	7	10.25	1	1.5	None	Plant drastically reduces transpiration, "shuts down"
California buckwheat	8	11.0	1	1.5	None	Plant drastically reduces transpiration, "shuts down"
Prostrate acacia	9	11.75	1	1.5	None	Plant drastically reduces transpiration, "shuts down"
Laurel sumac	20	17.0	3	2.5	None	Plant drastically reduces transpiration, "shuts down"

[1]From August 15 to October 15 transpiration for all species increases drastically if soil moisture is readily available.

[2]See *table 8* for available moisture by soil profile.

Sandy soils have the lowest moisture-holding capacity and release the available water most easily. Clay soils have a greater water-holding capacity but do not release the water as easily because water is more tightly held by adsorption to the smaller soil particles. Plants compensate for the lower water-holding capacity of sandy soils with a wider root network, but are restricted in their root penetration and water withdrawal on shallow, compacted or heavy soils. Plants do not withdraw moisture at equal rates from all depths of the root zone, but initially concentrate withdrawal on the upper half of the root zone. When the available moisture is withdrawn from any appreciable part of the root zone, growth slows down. As more moisture is withdrawn, the soil layer reaches the point at which no further moisture uptake is possible by the plant roots of the particular species. Before this point is reached, however, most plants show that they require water. For example, temporary wilting of the plants during the daytime indicates water need; this wilting is readily apparent in the water-demanding plants such as periwinkle and ivy. Other plants may change leaf color from green to yellowish. Once plants are well established, irrigation should be sparing enough to reduce the available soil moisture to the point at which plant growth is reduced without permanent injury. Growth stops as the wilting point is approached, but again increases rapidly for most landscape plants after irrigation.

Because of the many variables, a specific watering schedule for each plant species cannot be given here. General watering recommendations for plant species (*tables 5, 7*) take into account such variables as soil depth, rooting depth, and transpiration rates. The minimum hypothetical transpiration rates and rooting depths given in *table 7* for ground covers and chaparral species suggest how soon after the last effective rains the landscape plants may need irrigation. Transpiration rates depend on the total leaf structure area of the plant as well as its growth rate, with greater growth resulting from a larger area and volume of foliage. Humidity, wind, and temperature are also important; for example, at constant relative humidity, transpiration of English oak was found to be five times greater at 104° F (40° C) than at 68° F (20° C) (Kittredge 1973). In general, transpiration is related to the species and age of the plant and to the site. Water requirements are less per unit volume on good soils, but the total transpiration is greater because the plants grow better and have more leaf surface area.

During dry years, or when rains have come late in the winter season, fairly complete soil moisture recharge is initially necessary through irrigation. One deep watering early in the summer may be required by the most drought-tolerant species. When late winter rains have recharged the soil to field capacity, no watering may be required at all, or a more shallow watering to perhaps 1 foot (30.5 cm) depth late in summer may be sufficient for plant survival. Moisture withdrawal by plant roots will then leave the soil dry, ready for heavy winter rains that may come early in the rainy season.

Under the conditions shown in *tables 7, 8,* Algerian ivy would require watering by about mid-May to remain turgid. This is within 9 to 10 weeks after the last storm (mid-March) recharged the soil moisture to field capacity within the root zone of the plant. By this time, approximately 3 inches (76 mm) per month of spring transpiration would have used up the 6.75 inches (171 mm) of available soil moisture to a depth of 4 feet (1.2 m). The plant would attempt to send out new roots into the deeper moist soil layer, but transpiration needs of the leaves would soon outstrip the capacity of the roots to expand. Moisture absorption for all practical purposes stops and the plant dies unless irrigated.

Periwinkle, like ivy, is a water loving plant, and its water needs also increase throughout the spring and summer

Table 8—*Water availability is determined by root depth and differences in moisture availability throughout the soil profile. Data are based on soil moisture recharge to field capacity by March 15 (see* table 7*)*

Soil profile (depth in feet)	Available moisture	Total available moisture	Species and root depth	
	Inches/ft soil	*Inches*		*Feet*
1	1.75			
2	1.75	3.5	Lawn grass	2
3	1.75	5.25	Periwinkle	3
4	1.5	6.75	Algerian ivy	4
5	1.5	8.25	Descanso rockrose	5
6	1	9.25	Australian saltbush	6
7	1	10.25	Coyote brush	7
8	0.75	11.00	California buckwheat	8
9	.75	11.75	Prostrate acacia	9
10	.75	--	--	
11	.75	--	--	
12	.75	--	--	
13	.75	--	--	
14	.75	--	--	
15	.75	--	--	
16	.75	17.0	Laurel sumac	20

months. On deeper soils, however, and especially in partially shaded areas, its root crown can survive without summer irrigation and can send out new shoots when winter rains return. It is, therefore, an excellent ground cover for neglected areas.

Prostrate acacia and coyote brush are two deep-rooted ground covers that have drought-adaptive mechanisms similar to chaparral plants and can drastically reduce transpiration as the wilting point is approached. Thus, once these plants are established, irrigation is hardly necessary. Prostrate acacia and coyote brush have the added advantage of being esthetically pleasing despite drought shutdown.

Overhead Impact Sprinklers

For both initial establishment and later maintenance of hillside ground covers, overhead impact sprinklers and drip irrigation systems are recommended. They are easy to install, maintain, and inspect. Overhead sprinklers are not efficient water users when compared to drip irrigation.

Great care should be taken in designing the irrigation system, so that it will evenly cover the affected areas without causing undue erosion. When there is doubt about how to design a hillside irrigation system, an expert should be consulted. A well-designed system will pay off over the years in water saved and possible damage to hillsides avoided.

The greatest efficiency rate or maximum spacing is normally achieved by spacing impact heads at 60 percent of their throw diameter. Thus, 60 percent of a 72-foot-diameter sprinkler would be 43 feet. For tight soils and initial establishment of ground covers, impact heads that deliver only about 0.1 inch (2.5 mm) of water per hour, or that rotate quickly, can be used. Such heads greatly reduce the impact of the falling water drops on the bare soil, preventing damage to soil structure and allowing for greater infiltration and therefore less runoff. These are important considerations for compacted fills that normally have a much lower infiltration rate than chaparral soils.

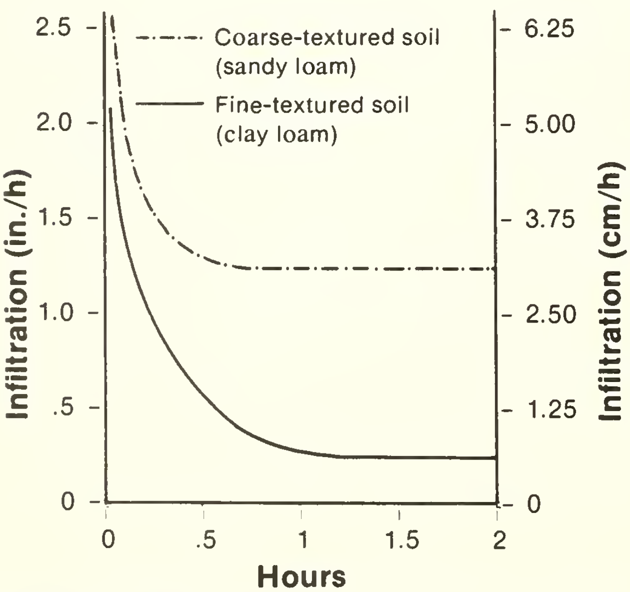


Figure 13—Infiltration rates for coarse-textured soils are higher than that for fine-textured soils.

Once the ground cover is well established, the nozzle of the impact head can be changed to deliver approximately 0.2 inch (5 mm) per hour. For soils that have a high infiltration rate, sprinklers are available to deliver as much as 0.4 to 0.5 inches (10 to 12.7 mm) per hour. When using these sprinklers, it may be advisable to irrigate several times a day to replenish soil moisture to the desired depth. Infiltration into soils is high during the initial watering period, but levels off very quickly as the soil surface becomes well moistened (*fig. 13*), as a result of closing of soil pores by soil particles or swelling of colloidal clays. For home use, high impact sprinklers are not normally recommended because they may saturate soil if left on too long. When sprinklers are automatically timed, there is danger that too much water may be applied and that a broken pipe may go unnoticed until hillside slippage occurs. Drip irrigation allows for deep watering with a minimum amount of water. Thus, a superior root system is developed.

To summarize, the proper watering of newly established greenbelts does not accelerate the natural erosion rates nor damage the soil structure. Deep watering is more beneficial to hillside plants than shallow watering because it recharges soil moisture more completely throughout the root zone and encourages some plants to develop a deeper root system. Water should be withheld from mature plants as much as possible to force slowdown of growth, which also results in reduction in transpiration. Water should be withheld towards the end of summer, allowing plants to harden off while they can still withdraw moisture from their root zones. Withholding water as fall approaches leaves the soil relatively dry at the onset of the rainy season and allows it to absorb water readily to greater soil depths. Constant shallow watering, on the other hand, only partially recharges the root zone, wastes water through evaporation, and may induce a more shallow root system that makes hillside plants less drought-tolerant. Deep watering should not be done after about mid-September. If effective rains do not occur until late in the season, occasional shallow watering may then be required to keep the more-water-demanding plants alive.

PLANNING FOR HOME SAFETY FROM FIRE

In most cases the fire safety of a home can be greatly improved. There are, however, special conditions of topography, wind, and heat patterns under which, in spite of all precautions, a home may literally explode in flames during a wildfire disaster. Through neighborhood teamwork, community action, and proper land use planning, the likelihood of such events can be reduced, but homeowners must realize that there is a risk in living in chaparral areas.

Reducing Fuel Load

Fire safety around a home is achieved by reducing the fuel load and breaking the fuel continuity, and by building a "fire safe" home in an area where it can be defended from wildfires. Landscaping to lessen the fire without fireproofing the home itself may be a futile effort. This was dramatically demonstrated during the June 22, 1973, Crenshaw Fire in Rolling Hills, Los Angeles County, where 12 homes burned, 11 of which had wood shingle roofs. The shingles caught fire, even though most homes were surrounded by an excellent green belt. The fire burned through 897 acres (359 ha) of light fuel which consisted of grass, mustard, and coastal sage.

The California State Resource Code 4291 is the basic vehicle for creating minimum fire safety by reducing the fuel load and breaking the fuel continuity. The code requires that all flammable vegetation must be cleared to a distance of 30 feet (9.1 m) around a structure. If additional hazards exist, the Director of the California Department of Forestry can require clearance up to 100 feet (30.5 m). Individual fire jurisdictions may differ as to the enforcement of the 30-to-100-foot-clearance law. For example, the County of Los Angeles brush clearance law (Section 27301 of the Los Angeles County Fire Code) requires a minimum of 30 feet legal clearance, but the Fire Chief can enforce clearance of up to 100 feet. The City of Los Angeles brush clearance law (Section 57.21.07) is more inclusive and requires the removal of all native brush (specimen plants excluded) and other flammable vegetation to a distance of 100 feet. The Chief Engineer has the authority to insist on more extensive brush clearance beyond 100 feet.

Homes burned in the 1961 Bel Air Fire showed the interdependence of brush clearance and roof type (Howard and others 1973). The destruction rate for homes with wood roofs ranged from 14.8 percent with brush clearance over 100 feet (legal clearance limit) to 49.5 percent with clearance of 0 to 30 feet. Nonwood roofs of approved types fared much better; the corresponding rates were 0.7 and 24.3 percent. With a legal brush clearance of 100 feet, a home with a wood roof therefore may be 21 times more likely to burn during a wildfire than a home with a nonwood roof. Gable roofs, large wooden overhangs (eaves), wood siding, large picture windows facing in the direction of the fire hazard, and houses located too close to a slope are some of the additional safety hazards that need to be eliminated in fire-prone areas. Pressure-treated wood shingles cannot be considered fire resistant indefinitely, because the safety edge wears off with time through weathering. Placing wood shingles over a layer of nonflammable material gives an individual home an added safety margin, but adds to fire spread by producing airborne incendiaries and creating radiation and convection heat that affects neighboring homes.

When a home with a nonwood roof and brush clearance of more than 100 feet (30.5 m) ignites, other conditions are

Figure 14—Winds tend to channel through chimneys, making narrow canyons and saddles particularly fire-prone.

responsible, the most critical being topography. Topography is becoming increasingly important as homes are being built in areas that are often indefensible from fire. Such areas include natural chimneys (narrow canyons that concentrate heat and updraft) (*fig. 14*), saddles (low points in a rolling landscape) (*fig. 15*), steep canyons, and ridges (*fig. 16*). Analysis of the apparently random burning of homes in the 1961 Bel Air Fire in Los Angeles showed that along Roscomare Road the burning was not random but was directly correlated with the intersection of a tributary canyon and the main canyon (Weide 1968). Wind eddies and associated fire winds quite common in such situations are normally found on leeward sides of objects that create a barrier to airflow. They can, therefore, be expected on the lee side of ridges, hills, large rocks, and even vegetation. If the prevailing wind is either up or down canyon, the eddies are magnified behind spur ridges, at sharp bends in the canyons, and especially in areas where two or more canyons meet (Countryman 1971). In very steep and narrow canyons the heat may also be a major factor in fire spread and home losses. In the areas considered indefensible from fire, a safety margin can nevertheless be created by reduction of brush and other fuel beyond the legal 100-foot clearance. Terrain permitting, this can be done through wide fuelbreaks surrounding the larger developments.

Understanding Fire Behavior

Understanding the basics of fire behavior will prove helpful to the homeowners. They will be able to judge fuels around their homes in terms of flammability, heat intensity, heat duration, and fire spread. A fire can be visualized as the flame, heat, and light caused by burning (oxidation) after an object has reached ignition temperatures and has been ignited. Ignition temperatures are influenced by the rate of airflow (supply of oxygen), rate of heating, and size and shape of the object. Once ignition has occurred, sustaining combustion requires a continuous supply of oxygen.

The different major wildland fuels, such as grasses, coastal sage scrub, chaparral, and trees, have various ignition requirements. Heat of ignition is greatly influenced by fuel particle size distribution, live-to-dead ratio of these particles and moisture content of live and dead tissues. The physiological condition of the living tissues greatly affects live fuel moisture. A vigorous growing plant has high living tissue moisture and a plant under stress or in poor vigor has relatively lower living tissue moisture. For example, growing grass has a living tissue moisture content greater than 100 to 150 percent of dry weight. Dead tissue moisture content is determined by the ambient air moisture and therefore changes rapidly. Dry grass has the lowest heat requirements for ignition and is therefore easily ignited; it has the longest fire season and also the highest fire frequency. Coastal sage scrub, because of its summer dormancy, its high amount of fine dead fuels, aromatic oils, and the relatively short life cycle of individual species, is next in heat requirements for ignition and in fire frequency. Woody chaparral shrubs in coastal areas have a higher live moisture content than the same vegetation inland and normally do not become dangerously dry until late summer or fall. However, even among these plants, several species, such as chamise, have greater amounts of fine fuel and tend

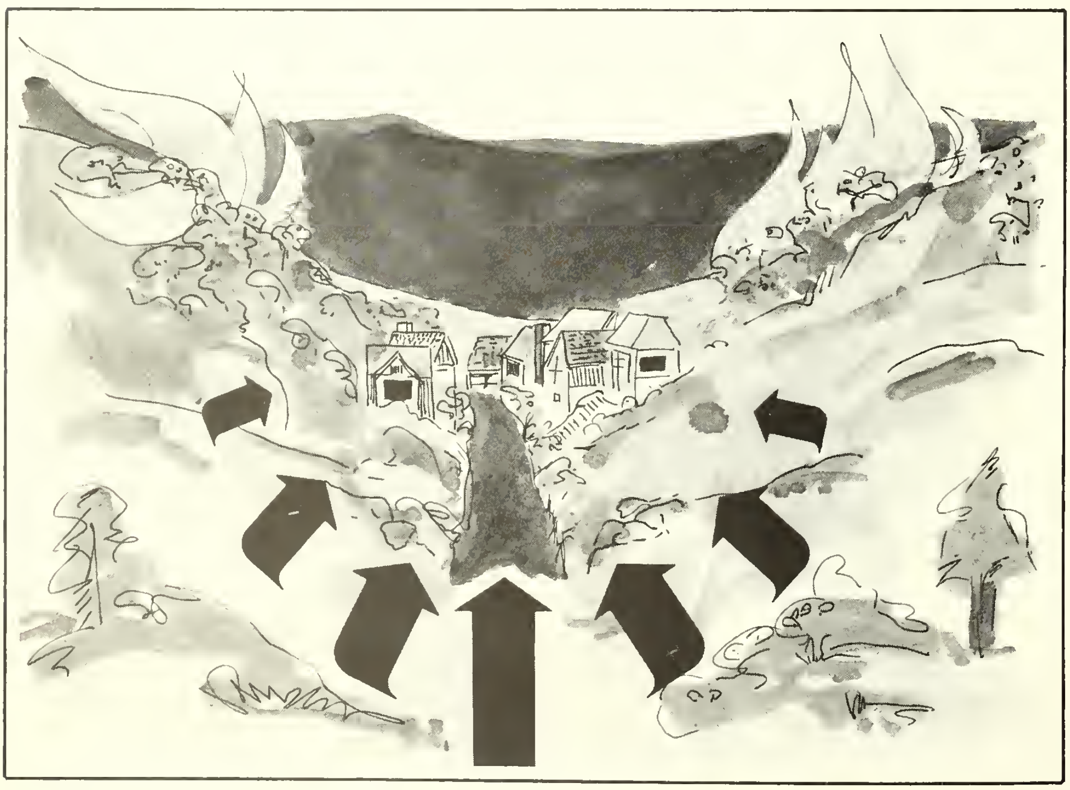


Figure 15—Natural saddles are wide paths for fire winds, and vegetation growing there will normally ignite first.

to have more flammable secondary compounds during the annual dry season.

Heat transfer is by conduction, convection, and radiation. The flame is the visible burning gas produced by the fire and provides (along with airborne sparks) a direct ignition source for fuels that have reached ignition temperatures.

Convection heat is the transfer of heat by atmospheric currents and is most critical under windy conditions and in steep terrain. With light wind and on level terrain, the convection heat column is almost vertical, and radiation heat becomes a critical factor in fire safety. Radiation heat is transfer of heat by electromagnetic waves and can, therefore, travel against the wind. For example, it can preheat to the ignition point the hillside opposite a burning slope in a steep canyon (*fig. 17*). Conduction is the direct transfer of heat by objects touching each other. It is not a critical process during a fast-moving wildfire but can be responsible for igniting a home, as when burning firewood stacked against the side of the garage causes the house to catch fire.

The interaction of the three types of heat transfer with topography can be illustrated by visualizing a burning match (*fig. 18*). When the match is held up, heat transfer is by conduction only, and the match burns slowly. This is comparable to a wildfire burning downhill. If the match is held horizontally, heat transfer is by conduction and radiation, and the match burns a little faster. When the match is held down, it is consumed rapidly because conduction, convection, and radiation heating are occurring together. The situation is comparable to a wildfire burning uphill, and such a fire travels much faster than one on level ground or burning downhill.

The key objective in breaking up the fuel load and fuel continuity around structures is to reduce the amount and duration of thermal radiation the home or the firefighter receives. For a point source of radiation this heat intensity decreases with the square of the distance from the source. The radiation intensity 100 feet (30.5 m) from the burning brush or landscape plants is therefore only one-fourth that at 50 feet (15.2 m). A tree burning within 20 feet (6 m) from a roof or picture window transfers only one-fourth of the heat to the house compared with a tree burning within 10 feet (3 m), and only one-sixteenth the heat compared with a tree within 5 feet (1.5 m) (*fig. 19*). A line source of radiation such as a burning hedge of junipers or cypresses is even more critical than a point source of radiation because the house receives heat from all points along the line (*fig. 19*). In this case, intensity varies with the distance instead of the square of the distance, so that the intensity at the home located within 20 feet from the burning hedge is still one-half that at 10 feet. Increasing the number of flammable landscape plants around the home and increasing the number of trees, or both, will make a house more fire-prone, despite legal brush clearance.

During a wildfire, flames more than 100 feet (30.5 m) long can roar over homes on ridgetops and consume seemingly safe homes a distance away. These flames directly transmit the greater part of the thermal heat of the radiating source (wildland fuel) to the home and thus ignite it. Flame length is controlled by the height and density of the radiating source, by windspeed, steepness of the slope, live and dead fuel moisture, fire spread, and such other specific characteristics of the fuel as ash and oil content and the arrangement and amount of fine fuels present. Reducing

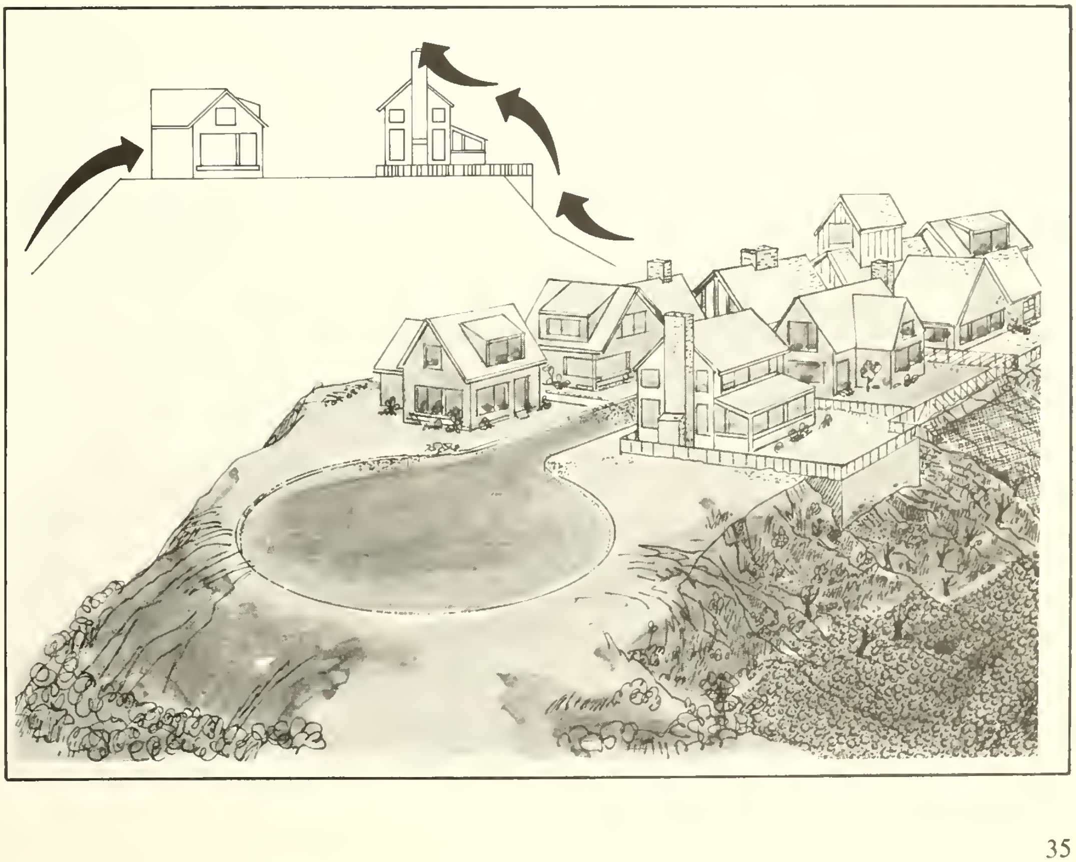


Figure 16—On narrow ridges, homes without adequate setbacks, such as those depicted, are especially vulnerable to fire.

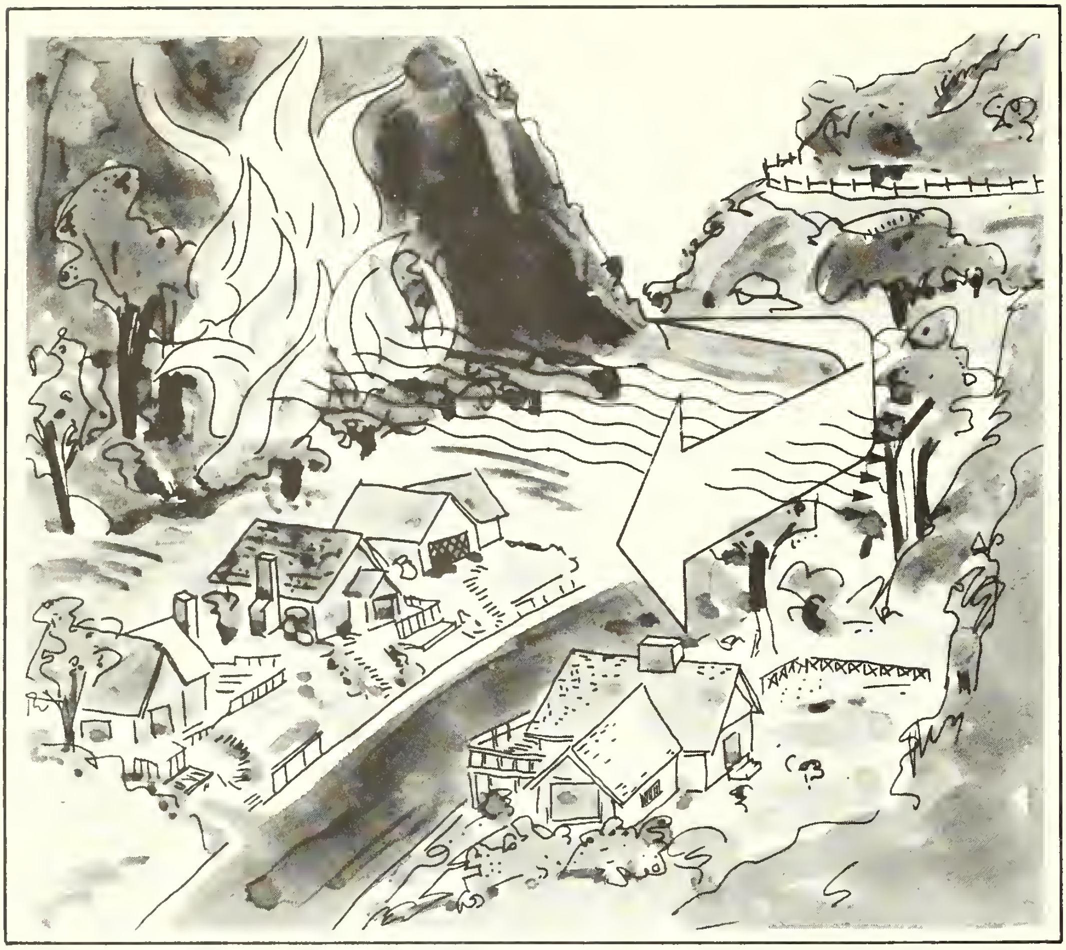


Figure 17—Radiation transfers heat in all directions—even against a wind sweeping through a canyon. In the process, the hillside opposite a burning slope can be ignited.

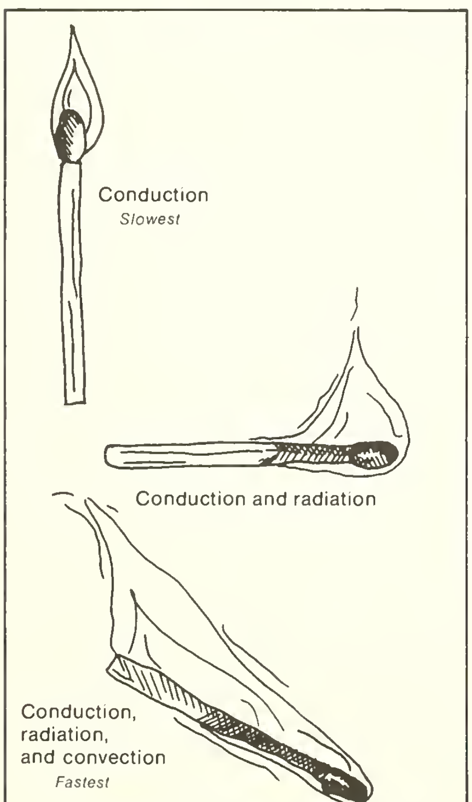


Figure 18—The interaction of three types of heat transfer—conduction, radiation, convection—is illustrated by three burning matches.

6-foot-tall (1.8-m-tall) chaparral to 2-foot-tall (0.6-m-tall) low fuel plants on a 45° slope can reduce flame length by one-third—a powerful incentive for fuel modification (Albini 1976) (*table 9*).

Wildland fires that produce flame length greater than 30 to 35 feet (9.1 to 10.7 m) are considered to be burning out of control. In 6-foot-tall chaparral this critical flame length is already reached at a windspeed of less than 10 mph (16.1 kph), whereas in 2-foot-tall low fuel volume plants the windspeed would have to approach 50 mph (80.5 kph) to produce flames of this length (*table 8*). Low fuel volume plants thus reduce but do not completely eliminate the risk of a wildfire conflagration; they do allow the fire to be contained in a shorter time.

Insurance companies realize that the many factors discussed above have to be taken into consideration for fire safety and therefore affect calculation of brush surcharge on insurance rates. Where there are slopes of more than 30° below the home, twice the 100-foot (30.5 m) legal brush clearance distance may be required to qualify for the same insurance rates (*fig. 20*). This approach, so vital for fire safety, works against maintaining slope stability, as discussed earlier.

The 1983 insurance rates in brush areas in southern California (*table 10*) show that the rates are primarily determined by the protection class of the area and the distance of brush to the building. Roof types are not adequately accounted for; with brush clearance less than 30 feet (9.1 m), costs for unapproved roofs are only 25 percent higher. Surcharges are eliminated with 400-foot (122-m) clearance for both approved and unapproved roofs, even though unapproved roofs can readily ignite from flying embers. This is poor incentive for a homeowner to include a more fire-safe roof in plans for building or remodeling. A homeowner who is concerned with fire safety therefore subsidizes a careless homeowner. Making insurance rates correspond closely to the risk factors is a good way to provide greater fire safety. More direct attempts at regulation tend to fail because building and zoning codes reflect political realities. Insurance incentives have been used to some extent: reductions in rates may be gained by having a swimming pool with an electric, gas, or battery-driven pump or other safety devices. An insurance agent can provide further details.

Promoting Fire Safety

Principles of topography, vegetation, and architectural design can be applied to improve the fire safety of a planned or an existing home (*figs. 21, 22*). Drastic fuel reduction on steeper slopes will result in slope instability (at least temporarily) unless the new vegetation offers the same network of root strength and depth. A basically "fire-safe" home design gives greater flexibility in fuel modification, thereby retaining slope stability to a greater degree.

Table 9—*Effect of windspeed and fuel height on flame length*[1]

Windspeed at midflame height (mph)	2-ft low-fuel plants	6-ft chaparral
	Flame length	*(ft)*
5	9.1	27.7
10	12.9	39.5
15	16.2	49.9
20	19.3	59.5
25	22.1	68.3
30	24.7	76.6
35	27.2	84.4
40	29.6	91.9
45	31.9	99.1
50	34.1	106.0

[1]Source: Albini 1976; adapted by Ronald H. Wakimoto, University of Montana.

Exterior materials used on wildland homes should have a minimum fire-resistive rating of 1 hour. This requirement is especially critical for parts of a home exposed to winds from the north or east, and for homes positioned at the top of a slope, stilted or cantilevered sideslope, or without a slope setback. For further information applicable to residential development see the fire safety guides issued by the California Department of Forestry (1980).

Homes can be designed with specific features to promote fire safety (*fig. 19*). Reduced overhangs or boxed eaves can protect the house from ignition and heat or flame entrapment. Under eaves, vents should be located near the roofline rather than near the wall. Exterior attic and underfloor

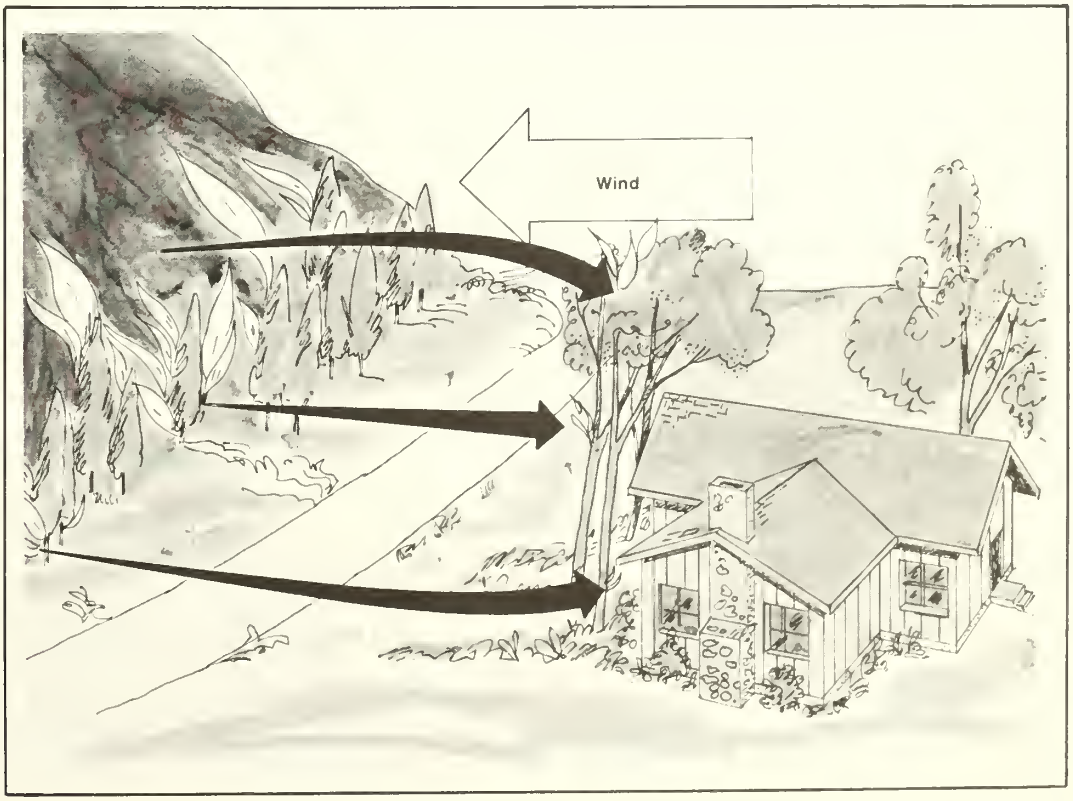


Figure 19—Fire safety is directly affected by the intensity and duration of thermal radiation that a home receives from flammable fuels.

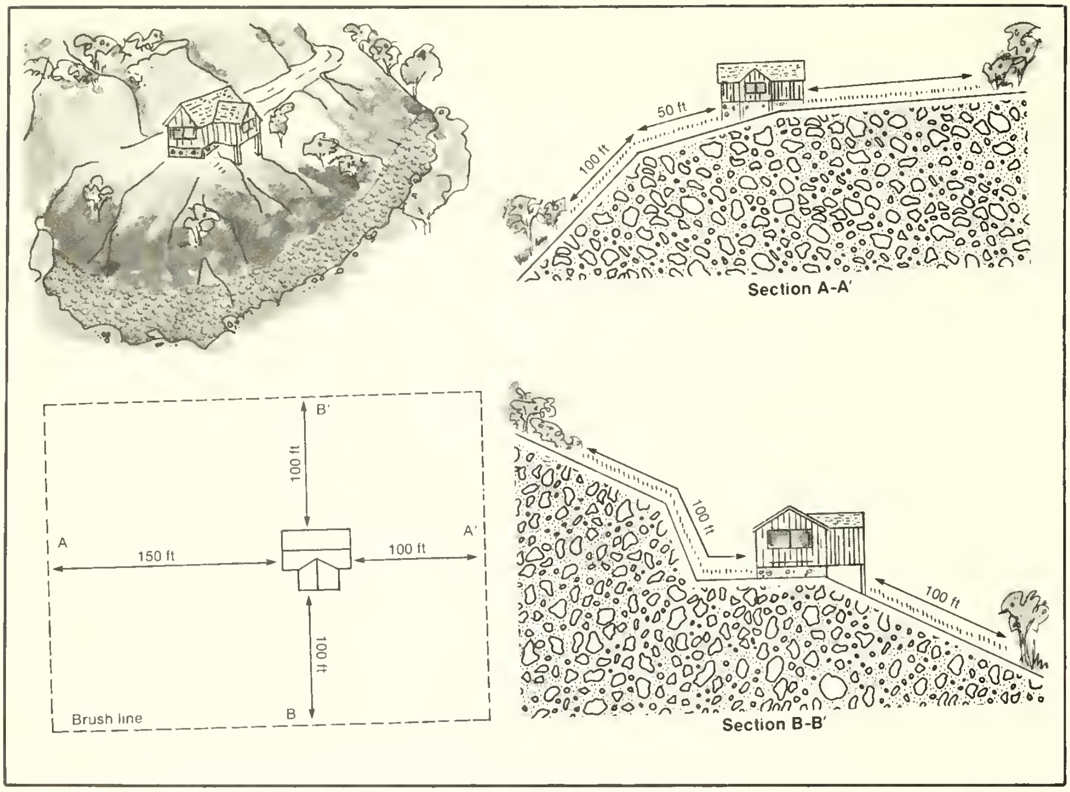


Figure 20—Minimal safety distances from a building to brush recommended by insurance firms will vary by the slope of the land.

Table 10—*Insurance surcharge rates for homes in brush areas with approved roofs (composition, rock, tile, slate, asbestos, or metal) and for nonapproved roofs (wood shingle, wood shake), by exposure distance to brush and protection class, Counties of Los Angeles, Santa Barbara, San Bernardino, and Ventura, in southern California, 1983*

Exposure distance to brush (ft)	Protection class[1]							
	1 to 4		5 and 6		7 and 8		9 and 10	
	A[2]	B[3]	A	B	A	B	A	B
	Annual charge (dollars for $100 property valuation)							
	Approved roofs							
0-29	0.40	0.40	0.48	0.49	0.64	0.64	1.28	1.28
30-59	.28	.36	.36	.48	.56	.64	1.28	1.28
60-99	.20	.28	.24	.32	.32	.48	1.28	1.28
100-199	.08	.16	.12	.24	.24	.32	.96	1.12
200-299	0	0	0	0	.16	.24	.64	.80
300-399	0	0	0	0	0	0	.32	.48
400-over	0	0	0	0	0	0	0	0
	Nonapproved roofs							
0-29	.50	.50	.60	.60	.80	.80	1.60	1.60
30-59	.35	.45	.45	.60	.70	.80	1.60	1.60
60-99	.25	.35	.30	.40	.40	.60	1.60	1.60
100-199	.10	.20	.15	.30	.30	.40	1.20	1.40
200-299	0	0	0	0	.20	.30	.30	1.00
300-399	0	0	0	0	0	0	.40	.60
400-over	0	0	0	0	0	0	0	0

[1] Insurance representatives have listings of the protection class of your area.

[2] Fire station within 5 miles; access road; public water hydrant with 4-inch main with 2½-inch outlet within 1,000 ft.

[3] One or more of the above requirements not met.

vents should not face possible fire corridors and should be covered with wire screen (not to exceed ¼ inch mesh). Picture windows and sliding glass doors should be made only of thick, tempered safety glass and protected with fire-resistive shutters. Stone walls can act as heat shields and deflect the flames. Swimming pools, decks, and patios can be used to create a setback safety zone as well as to provide safety accessories. Pools can provide a convenient auxiliary water source, often of critical importance for firefighters or homeowners before and during a fire, but should not be in lieu of an adequate community water system. Fire engines should be able to get within 10 feet (3 m) of the pool because this is usually the optimum distance for the drafting hose. If this is not possible, the pool should have a bottom drain and pipe system that terminates horizontally or below pool level in a 2 ½-inch valved standpipe equipped with a fire hydrant with national standard thread. This is the thread which most fire equipment in southern California can hook up to without adapters. (The local fire protection agency can specify the thread used and provide other suggestions.) A floating pool pump or portable gasoline pump with a suction hose that can reach the bottom of the pool can assure a usable water source, even when water pressure and electricity fail. A fire hose and nozzle are also needed.

Fabric fire hoses are fine for high pressure equipment such as pool pumps that are designed for firefighting, but should not be used on home faucets because such hoses readily kink as water pressure drops. All outdoor faucets should be equipped with strong ⅝-inch rubber hoses that will not burst when the nozzle is shut off. This system of hoses should be able to reach any part of the house and roof. A ladder should always be available to reach the roof, and should be placed against the part of the house least exposed to fire.

In summary, fire risk can be reduced by installing:

- Fire-resistive roof—preferably Class A, such as tile.
- Stucco or other fire-resistive siding of at least 1 hour fire-resistant rating.
- Reduced overhang (preferably closed eaves with vent covers).
- Roof slanted to accommodate convection heat.
- Safety zone (slope setback of at least 30 feet (9.1 m) for single story home.
- Pool used to create safety zone.
- Shrubs and trees not directly adjacent to home nor overhanging the roof.
- A deck with exterior materials of at least 1 hour fire-resistant rating.

Overhead (roof) sprinklers can increase the fire safety of an existing home. Under favorable conditions, they can provide fire protection by keeping the roof and surrounding landscaping wet (Fairbanks and Marsh 1976), but they can not take the place of a fire-safe building design. The high winds normally associated with wildfires often prevent the water from effectively wetting the roof. Also, the system will break down if there is no water pressure because of power failure or heavy demand on the water supply. Systems that can operate on minimal water pressure, such as full circle, low-pressure impact sprinklers, provide added safety.

The extensive use of water by many neighbors can quickly drain the community water supply, leaving little or no water or pressure for fire suppression use. Fire suppression agencies, therefore, may not recommend the use of roof sprinklers operated by the community water system.

If water is available from an auxiliary source such as a swimming pool, roof sprinklers could be installed in con-

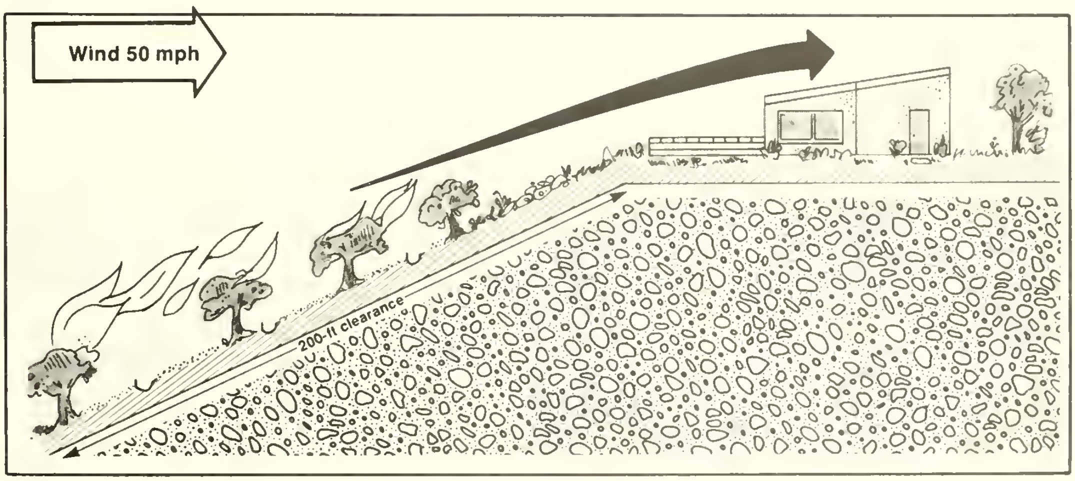


Figure 21—Fire safety can be increased by reducing fuel to twice the legal minimum distance of 100 feet (30.5 meters). To maintain slope stability, retain native plant species within the 18-foot (5.5 m) recommended distance for fuel separation. Flame length is still continuous, but the amount and duration of heat output is less than when brush is cleared to the legal minimum.

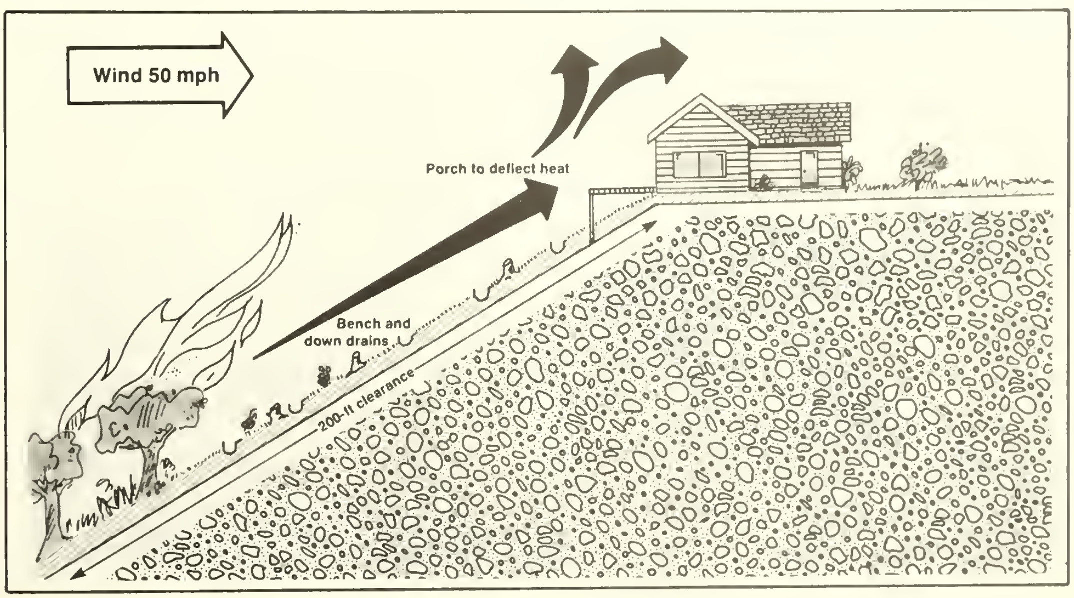


Figure 22—Homeowners can modify their homes to overcome negative characteristics. But they should seek the help of geological, engineering, and erosion control specialists when planning intensive fuel modification on steep slopes. Drastic fuel reduction can lead to slope instability.

junction with a portable pump utilizing the water from the swimming pool only. However, roof sprinklers cannot offer the degree of fire protection obtained by a fire-safe building design.

Modifications to an existing property (*fig. 22*) that could overcome negative characteristics include:

Negative characteristics	*Modifications*
1. Wood shingle roof	Fire-resistive roof
2. Wood siding	Fire-resistive siding (or fire-resistive paint)
3. Large overhand (open eaves)	Reduced overhang (closed eaves); vent covers for fire emergency
4. High gable roof	Redesigning may be too expensive
5. No safety zone (no slope setback)	Create setback with a deck where exterior material has a fire-resistant rating of 1 hour or more
6. Large picture windows	Install fire-resistive shutters
7. Tree crown overhanging the roof	Prune trees

Clearing Brush Around Homes

Some typical fire hazard reduction requirements are set forth below. Local homeowners may receive such information from their jurisdictional fire agency or the California Department of Forestry. Residents of fire-prone areas should be aware of the local ordinances that require such hazard reduction, should understand them and help make them applicable to their particular area. Living more safely in chaparral areas requires a balance of both watershed and fire safety. Clearing brush according to local ordinance will not in itself guarantee fire safety (*fig. 23*). Other measures described in this report should be followed. For additional guidance on fire safety, see reports by the California Department of Forestry (1980), Moore (1981), Perry and others (1979).

You are only required to clear your own property. Clearance on other property is the responsibility of the owner. Contact your local forestry or fire personnel if such clearance is needed.

1. Clear all hazardous flammable vegetation to mineral soil for a distance of 30 feet (9 m) from any structure. Cut flammable vegetation to a height of 18 inches (45 cm) for another 70 feet (21 m). Exception: This requirement does not apply to single specimens of trees, ornamental shrubbery or cultivated ground cover such as green grass, ivy, succulents, or similar plants used as ground cover, provided that they do not form a means of readily transmitting fire from native growth to any structure.
2. Remove limbs within 10 feet (3 m) of the chimney. Cut away dead branches and limbs that overhang the roof.
3. Screen the chimney outlet to prevent sparks from igniting the roof or brush. Use ½-half inch mesh.
4. Clean leaves, needles and twigs from roof gutters and eaves.
5. Clear flammable vegetation within 10 feet (3 m) of liquefied petroleum gas storage tanks.
6. Stack wood piles away from buildings, fences and other combustible materials.

TREATING NEWLY BURNED CHAPARRAL SLOPES

After brush fires, erosion from burned watersheds covered with natural vegetation may be more than 20 times

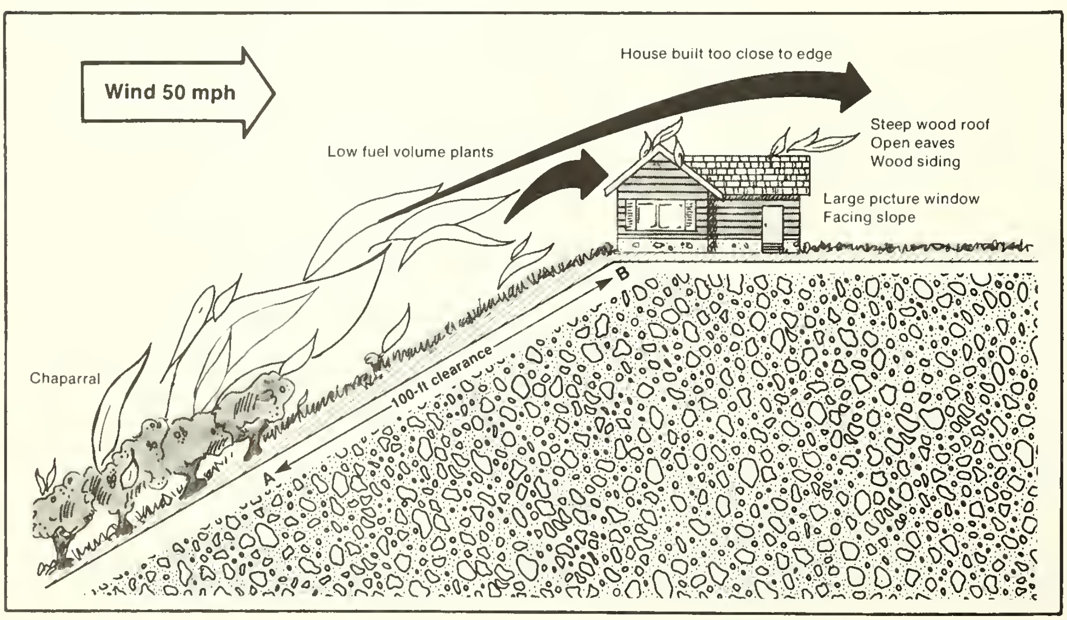


Figure 23—Fire can travel uphill 16 times faster than downhill. At wind speeds of 50 mph (80.5 kph), flames produced by a solid cover of chaparral can exceed the 100-foot (30.5 meter) length of brush clearance. Therefore, a solid flame front will be produced that reaches from the edge of the chaparral (*A*) over the low-fuel plants to the house(*B*).

greater than from unburned watersheds, although it is normally much less. Fire intensity, steepness and length of slope, soil type and parent material, and intensity, duration, and frequency of winter rains all affect the amount of erosion. In any event, immediate action by the homeowner is imperative to reduce property damage from the winter rains. But, what to do? Some suggestions are illustrated in *figure 24*. Additional information can be gathered from other sources (for example, Amimoto 1978, Los Angeles County 1982, Los Angeles Dep. Bldg. and Safety 1978, Maire 1962, Zinke 1962). The appropriate County Flood Control office can provide immediate help when need is urgent.

Direct Seeding

After major fires, Federal, State, and local agencies may immediately start aerial seeding of the hillsides with annual ryegrass (Blanford and Gunter 1971). This is an emergency measure and often seeds exposed on the soil surface will not germinate and start rooting unless encouraged by 4 or 5 days of moist weather. Much of the season's rainfall may be passed before the seeded grasses become well established. Seeds of resident annual grasses, when they are present, germinate more quickly because many of the seeds are buried in the soil layer and therefore have moisture available. This abundant seed source quickly germinates wherever moisture collects. Perennial grasses will resprout soon after the first winter rains.

Annual Ryegrass

Aerially seeded ryegrass is less effective on steep slopes and needs fertile soils (provided by nature after a fire), moisture (rain or sprinklers), and warmth to germinate. When ryegrass is used by the homeowner the best course is to seed the slopes by hand, preferably raking the grass seed in, and then installing a sprinkler irrigation system. If the slope is to be replanted immediately with landscape plants, ryegrass must be seeded in contour rows or it will choke out the newly planted stock. To germinate the seeds before the winter rains, the first few inches of the soil surface must

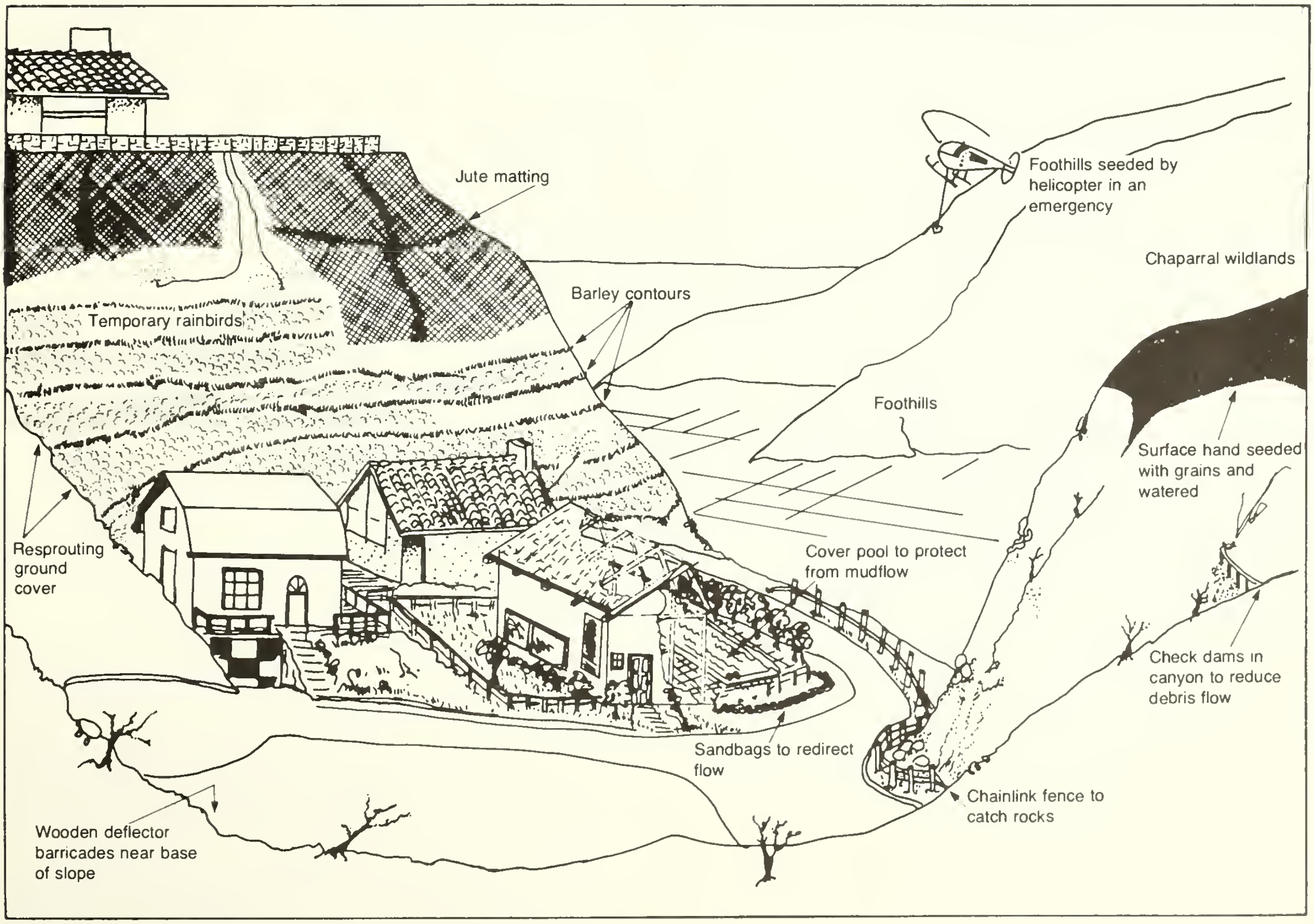


Figure 24—Immediately after a fire, emergency measures should be taken to rehabilitate a chaparral watershed. They include the use of direct seeding, check dams, boards, jute matting, chain link fences, sandbags and deflector barriers, drains, dry walls, plastic sheeting, and guniting on slopes.

be kept moist through frequent light watering. Deep watering should be avoided.

Seeds can be pregerminated to save water, to prevent overwatering of slopes, and to assure a good, quick cover (Esplin and Shackleford 1978, Radtke 1977) (*fig. 25*). This is readily done by putting the seeds into gunnysacks (sandbags) and soaking them thoroughly in large containers, such as trash cans that have small holes or openings for drainage. The excess water, which may contain germination-inhibiting chemicals leached from the seed coat, should be channeled into the street gutter. After the seeds have been kept moist in the sacks for about 1 day, they should be hand seeded on the hillsides or raked in. They will germinate immediately if moisture is continuously supplied.

Ryegrass should be viewed by the homeowner as a management tool for temporary emergency surface erosion control of bare slopes during the immediate rainy season. Eradicating the ryegrass plants on landscape slopes towards the end of the rainy season, before they go to seed, and replanting the areas to deep-rooted low-fuel plants can be an effective method for reducing topsoil erosion. The ryegrass treatment greatly reduces surface erosion but can compete heavily with the deeper-rooted woody plants. Spring and summer annual grasses will become dry, weedy flash fuels. New seeds germinate year after year as long as the soil is disturbed. Perennial ryegrass should not be used, as it can become a weedy pest.

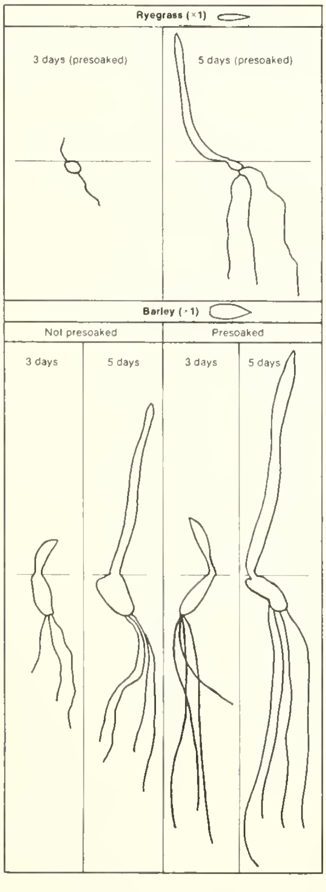


Figure 25—Soaking barley and ryegrass seeds stimulates pregermination, thereby hastening rooting and establishment as ground cover.

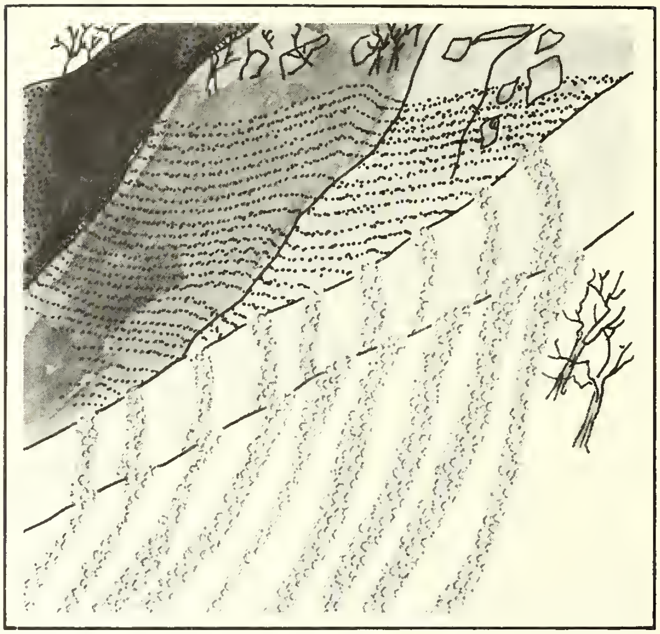


Figure 26—Barley planted on contours is effective in minimizing erosion.

Homeowners should avoid broadcast seeding or contour seeding grasses on recent slippage areas or actively sliding hillsides. The additional infiltration of water into the soil by the shallow-rooted grasses may cause local soil liquefaction and further slippage and mudflow. Plastic sheets should be spread over these areas until a proper slope engineering job can be done.

Barley

Hand planting of barley in contours spaced about 3 feet (0.9 m) apart has proven very effective in minimizing erosion, even on steep slopes (*fig. 26*). The ridges and trenches of the contours form a series of miniature terraces that allow water to infiltrate the soil. This increases plant growth, reduces runoff, conserves soil moisture, and prevents soil loss. On slopes with lower infiltration rates, such as steep, long slopes and hillsides with finer, less coarse soils, contours should be spaced more closely than on watersheds with high infiltration rates. Similarly, contours should be closer in areas where the runoff problems are critical, as near homes at the base of the slopes.

Strip cropping could also be practiced by interplanting the barley rows with rows of low-fuel ground covers in catching and holding water and soil. This method allows for reestablishment of ground covers while at the same time greatly reducing postfire soil erosion. Several years can therefore be saved in relandscaping of fire-prone hillsides. Quick cover and healthy plants are produced through saving the topsoil which is so valuable for plant growth.

For seeding barley, recommended rates are about 150 pounds of barley per acre (167 kg/ha) with about an equal amount of diammonium phosphate fertilizer added to the rows at planting time. Barley is readily available from feed stores and can be ordered immediately after a fire. Care should be taken to order only recleaned barley, as rolled

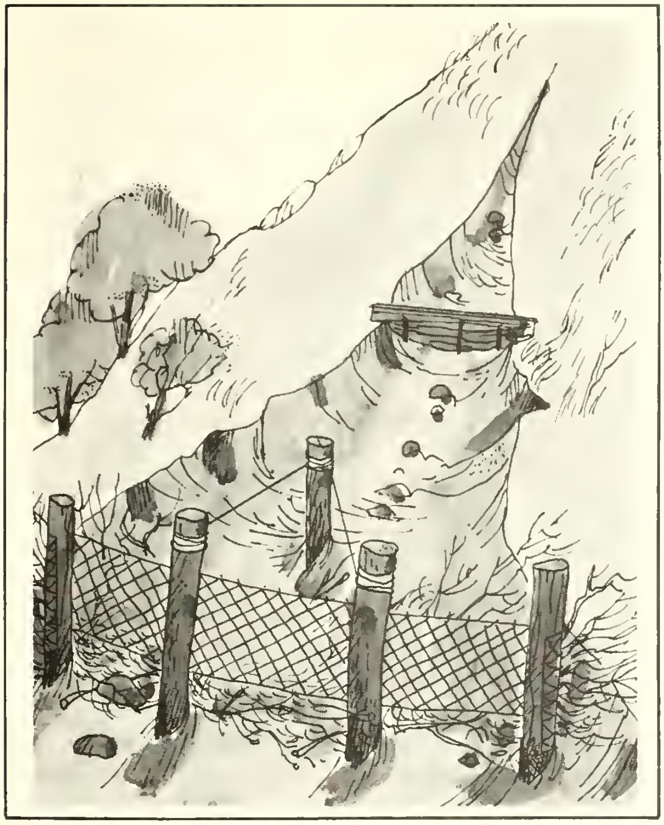


Figure 27—Check dams can reduce gully erosion.

barley (used for feed) will not germinate. Recleaned barley may be cheaper than ryegrass when the demand for it is low.

For quick establishment, barley seeds should be pregerminated no longer than 1 day and should be covered with soil to a depth not exceeding 2 inches (5 cm). Seeds lightly covered with soil germinate with the first winter rains, whereas seed lying on the soil surface need an extended period of moist weather for germination. Compared with ryegrass, barley germinates and grows more vigorously in cooler weather. Broadcast seeding (sowing the seeds on the slope without covering them) is less effective with barley than with ryegrass seeding. Barley seeds are much larger than ryegrass seeds, and very seldom find enough moisture at the soil surface to allow germination. Rodents and birds also tend to eat the seeds before they have a chance to germinate. Even after the barley plant dies, the strong roots can hold the surface soil for another 2 years. When reseeding is not desired, the plants should be cut in the spring before they go to seed. Barley is an annual plant and becomes a flashy fuel after it dies in late spring or early summer.

Check Dams

The object of check dams is to hold back rocks, brush, and other debris, and to slow down the flow of water in canyons or large gullies (*fig. 27*). Reseeding and replanting should go hand in hand with these temporary erosion control measures. Check dams should be repeated about every 50 ft (15 m). Small mesh fencing will act to impede water flow. Additional information regarding liability to downstream residents may be obtained from local flood control officials.

Boards

Redwood boards as thin as 1 inch (2.5 cm) can be used effectively to stabilize steep slopes before planting and to keep existing soil slips from getting worse (*fig. 28*). The boards are the homeowner's emergency soils engineering tools to reduce the effective length and steepness of hillsides by dividing a larger watershed into smaller sections. Boards can be very effective if well engineered and supported by a proper plant cover, but should not be looked upon as a substitute for permanent soils engineering methods. Boards should not be placed closer than 5 feet (1.5 m) vertical distance and should be held by old pipes or rebars at least 4 feet (1.2 m) long and about 1 inch (2.54 cm) or more thick (old pipes may be gathered from a local plumber). Rebars are round, solid construction steel bars that are ridged and anchor themselves in the soil more effectively than smooth pipe, provided the soil is firmly tamped around the rebar after it has been hammered into the ground.

A board 10 feet (3 m) long and 1 foot (30.5 cm) high should be held by a minimum of three rebars. Unless the boards are used as terraces, there should be 1 or 2 feet (30.5 or 61 cm) of clearance between horizontally placed boards.

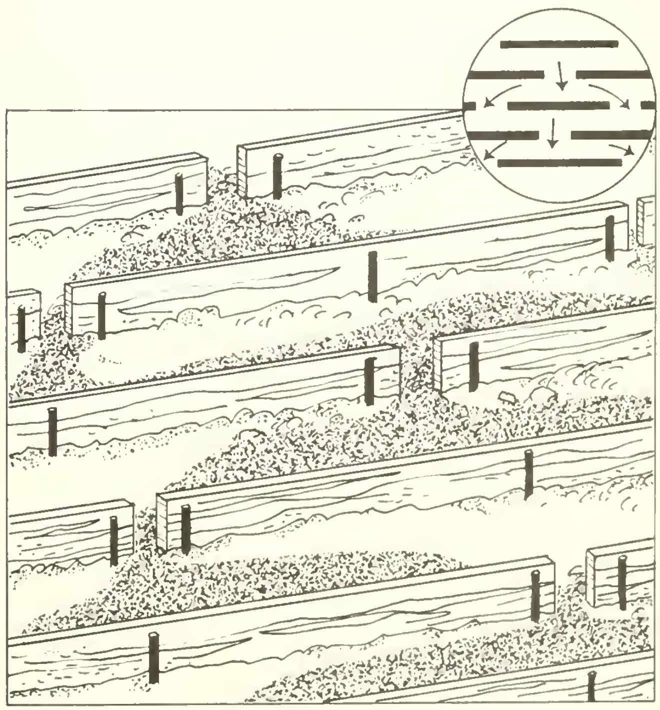


Figure 28—Pretreated or redwood boards help stablilize the face of soil slips.

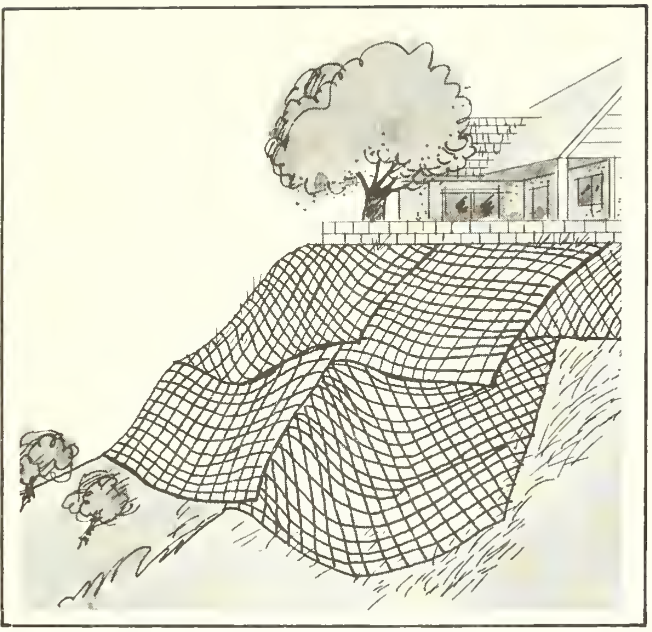


Figure 29—Jute mating reduces surface erosion.

Boards minimize slippage during heavy rains, when both soil and excess water can ooze out between the boards. Remember that a supersaturated slope will slip.

Localized slope instability may result if the pipes that hold the boards are hammered into highly fractured and weak bedrock, especially in areas where such rock layering parallels the slope. Pipes may also fail to hold the boards, especially on steep slopes with thin soils, if much new soil is placed behind the boards to establish a foothold for new plants.

Jute Matting

Matting made from natural fibers can be bought in carpetlike rolls. It is unrolled over the slope and anchored with pins in areas where heavy erosion is expected (*fig. 29*). Every square of the matting acts as a miniature check dam and effectively catches soil particles. The matting eventually decomposes but holds long enough for plantings to become established. Information on how to to use the matting is obtainable from a nursery. Potato sacks (gunny sacks) can be effectively used for both erosion control and weed control of smaller areas.

Chain Link Fence

Where life and property are endangered by falling rocks, chain link fencing can be useful (*fig. 30*). The chain link is flexible enough to catch even large boulders. When these are likely to fall, steel posts or telephone poles should be installed to anchor the fence, but not 4-by-4 wooden posts, because a rock has a better chance of glancing off a round object than a square one without breaking it. Telephone poles should be buried at least 3 feet (0.9 m) deep. Professional help is advisable when designing a chain link fence system to reduce the danger from falling rocks.

Sandbags and Deflector Barriers

Sandbags are used to direct the flow of mud and water to areas where they will do less harm (*fig. 31*). The flow of mud away from one home should not be directed toward another, however. Sandbags can be used effectively to build a berm at the top of slopes to prevent water from running downhill. Channeling water down the slope causes supersaturated soil and slippage.

After major fires, a limited number of sandbags may be supplied by fire protection agencies or the flood control district. The sandbags should be filled half full with sand or soil, and the flaps tied and folded under, pointing toward the direction of water flow. When one layer of bags is in place, bags should be stomped on to eliminate spaces between them. The next layer of bags should be staggered. Sandbags should never be more than three layers high unless they form a pyramid or unless a building is used as backing.

Wood deflector barricades may need to be used in critical areas where emergency revegetation may not be very effective. They serve the same purpose as sandbags but are semipermanent structures. The local flood control district office can provide expert advice regarding these diversion devices.

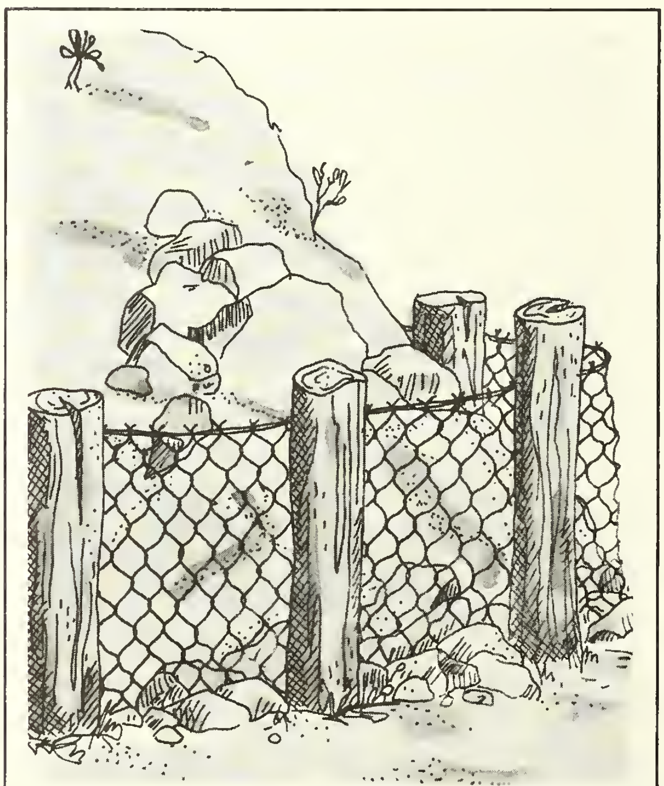


Figure 30—Chain-link fences stop rocks, even large boulders.

Drains

Concrete bench and downhill drains reduce the effect of topography on erosion (*fig. 32*). They reduce runoff and erosion by dividing a portion of a large watershed into smaller watersheds and by removing excess water safely from a slope. Every year before the rains return, all drains in the neighborhood should be inspected and cleared of debris. Clogged drains are a major cause of flood damage and hillside slippage. All drains should be reinspected before sandbags are placed in position and after every heavy rain, especially the first few years after a fire.

Dry Walls

Where slippage has occurred or is imminent, dry walls can be effectively installed, provided they have a firm foundation, as at the base of slopes (*fig. 33*). Dry walls can be made from unwanted concrete pieces from patios or driveways, and the wall can then be put up piece by piece without cement. Such materials are free, except for hauling. No cement is needed and there is no mess. Such a wall may last a lifetime and is more effective than a block wall during an earthquake. If the wall is more than several feet tall, it should be sloped slightly toward the hill as new layers are added. Dry walling against a fill slope leads to slope failure (mudflow) during intense rains unless the fill is well compacted, anchored by plants, and only a few feet high. Lateral drains inserted 20 feet or more horizontally into the slope will lessen the chance of slope slippage by draining the excess water out of the slope.

Plastic Sheeting

Plastic sheeting can keep a slope relatively dry during heavy rains and prevent surface erosion especially after a fire in late fall (*fig. 34*). After a slippage, it will prevent further saturation and movement of the soil. The entire slope or slope area should be covered with the plastic so that water is not channeled from one part of the slope to another. The flow of water at the base of the plastic must be controlled to avoid damage to homes below. Improperly placed sheets that concentrate runoff in selected areas or that cover only portions of a hillside are a leading cause of slope failure. Therefore plastic spread on hillsides must be properly tied down or constantly maintained throughout the rainy season. Broken pieces should be replaced and windblown sections retied. The thicker 6-mil (0.006-inch)

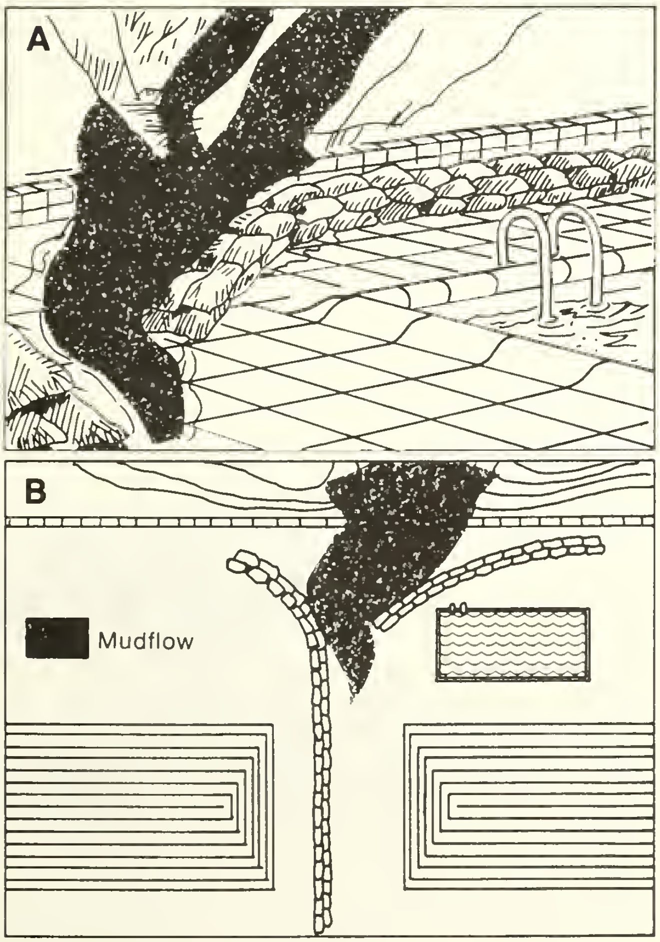


Figure 31—Sandbags divert flow mud.

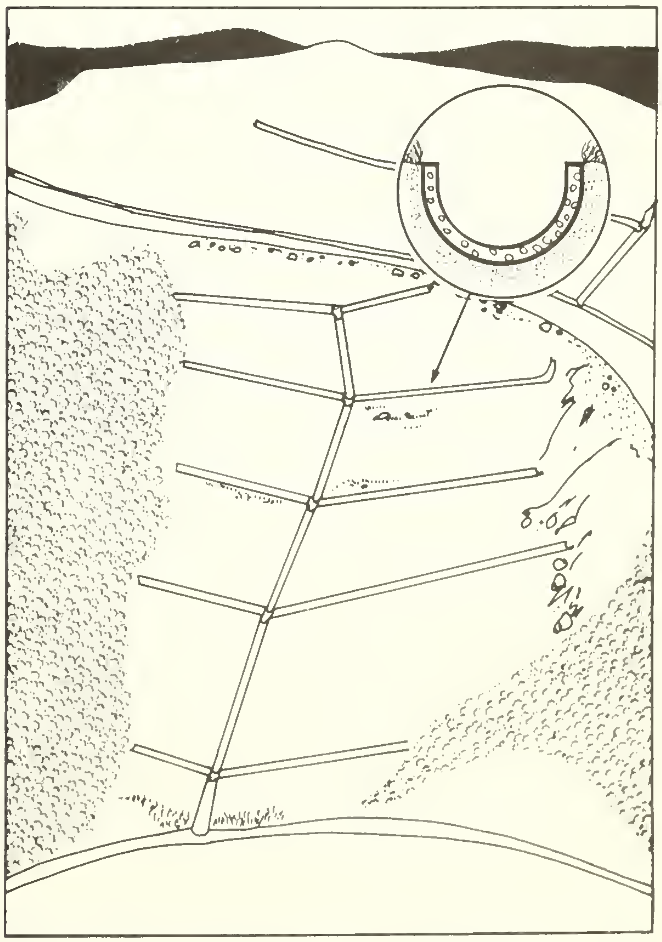


Figure 32—Drains control water flow and reduce excess surface runoff.

plastic is preferred because it rips less easily and covers the slope better, thereby reducing maintenance problems. Sandbags partially filled with soil are used to anchor the plastic. On steeper slopes, sandbags should be tied to ropes that are anchored at the top of the slope. Rocks or stakes should not be used to anchor the plastic because rocks wear through the plastic and stakes are ineffective when winds whip underneath the plastic. Rainstorms bring rain *and* wind. The plastic sheets must therefore be sealed on all edges and on overlaps, to prevent them from becoming sails as the wind whips underneath them.

Guniting

Guniting of slopes above or below homes or on road cuts is the most effective way to eliminate soil erosion in areas where plants are ineffective because slopes are steep and soil erosion is rapid. In effective guniting, a network of construction steel is anchored into bedrock and concrete is poured over this web of steel after drain pipes have been installed at appropriate intervals. The unattractive effect of the gunited hillside can be greatly reduced by coloring the concrete approximately the natural soil color of the area and planting trailing groundcovers at all edges. For safe disposal of the runoff water, the base of gunited slopes must be tied into permanent steel, asphalt, or concrete drains.

Guniting is most effective on slopes not exceeding 25 feet (7.6 m) in vertical distance. It requires a high initial investment but is cost-effective in the long run. It is often the only effective way to stabilize steep roadcuts and slopes already undercut by roads when building is begun. Without treatment, debris from steep or undercut slopes settles at the foot of the slope. Although this process eventually establishes a new, stable slope angle, the debris may also partially block the road and need to be cleared and hauled away periodically. This process continuously undercuts the slope causing further accelerated erosion and larger slides. Building should therefore not be allowed on top of any undercut slope unless the cut is first completely stabilized or unless it consists of a solid rock cliff. Retaining walls and guniting are only a partial solution to hillside problems.

The suggestions made here are quick self-help methods for the homeowner, using materials often readily available. Planting of woody plants, such as shrubs and trees, is not effective as erosion control in the season after a fire. These deep-rooted plants are needed, however, to minimize slippage on steeper slopes, and herbaceous cover such as

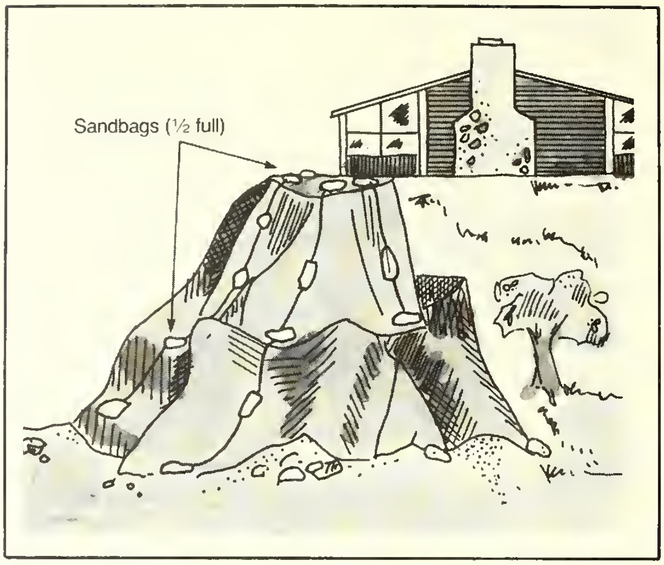


Figure 34—Plastic sheets remove further rainfall from saturated soils.

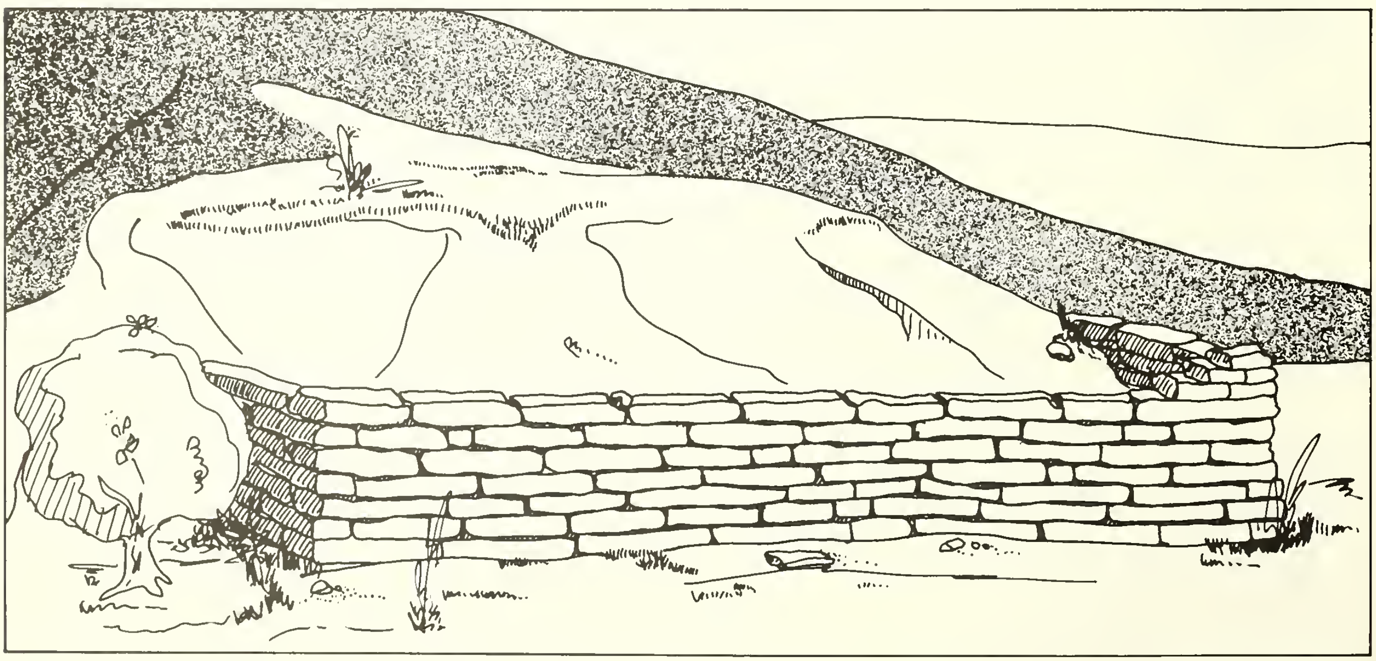


Figure 33—Dry walls can stabilize the toe of slopes.

grasses is needed to reduce surface erosion. Shrubs and trees must be replanted if the burned woody plants do not resprout. Research has shown that converting chaparral to grass covered watersheds after a burn greatly reduces erosion for the first 5 years or more, as compared with the untreated stand where chaparral is resprouting. After this, erosion on the grass-covered site greatly increases because the old chaparral roots that were still holding the hillside have finally rotted away and the grass root zone becomes supersaturated and slips out (Corbett and Rice 1966). Thus, the homeowner must be careful in landscaping a hillside after fire. Steep hillsides converted from chaparral to low-fuel plants often show little subsurface instability in the form of slips and slides for some years. The slips and slides that occur during high intensity rains 5 to 10 years later are therefore seldom attributed to the earlier brush conversion, but they can be prevented.

WHAT TO DO WHEN CAUGHT IN A WILDFIRE

If your home is threatened by wildfire, you may be contacted by a fire or law enforcement official and advised to evacuate. If you are not contacted in time to evacuate, or if you decide to stay with your home, the following suggestions will increase your chances of safely and successfully defending your property.

Before Fire Approaches

1. If you plan to stay, evacuate your pets and all family members who are not essential to protecting the home.
2. Be properly dressed to survive the fire. Cotton and wool fabrics are preferable to synthetics. Wear long pants and boots and carry with you for protection a long-sleeved shirt or jacket, gloves, a handkerchief to shield the face, water to wet it, and goggles.
3. Remove combustible items from around the house. This includes lawn and poolside furniture, umbrellas, and tarp coverings. If they catch fire, the added heat could ignite your house.
4. Close outside attic, eave, and basement vents. This will eliminate the possibility of sparks blowing into hidden areas within the house. Close storm shutters.
5. Place large plastic trash cans or buckets around the outside of the house and fill them with water. Soak burlap sacks, small rugs, large rags. They can be helpful in beating out burning embers or small fires. Inside the house, fill bathtubs, sinks, and other containers with water. Toilet tanks and water heaters are an important water reservoir.
6. Locate garden hoses so they will reach any place on the house. Use the spray-gun type nozzle, adjusted to a spray.
7. If you have portable gasoline-powered pumps to take water from a swimming pool or tank, make sure they are operating and in place.
8. Place a ladder against the roof of the house opposite the side of the approaching fire. If you have a combustible roof, wet it down. Do not waste water. Waste can drain the entire water system quickly.
9. Back your car into the garage and roll up the car windows. Disconnect the automatic garage door opener (in case of power failure you could not remove the car). Close all garage doors.
10. Place valuable papers and mementos inside the car in the garage for quick departure, if necessary. Any pets still with you should also be put in the car.
11. Close windows and doors to the house to prevent sparks from blowing inside. Close all doors inside the house to prevent drafts. Open the damper on your fireplace to help stabilize outside-inside pressure, but close the fireplace screen so sparks will not ignite the room. Turn on a light in each room to make the house more visible in heavy smoke.
12. Turn off all pilot lights.
13. If you have time, take down your drapes and curtains. Close all venetian blinds or fire-resistive window coverings to reduce the amount of heat radiating into your home. This gives added safety in case the windows give way because of heat or wind.

When the Fire Front Arrives and Passes

As the firefront approaches, go inside the house. Stay calm, you are in control of the situation. After the fire passes, check the roof immediately. Extinguish any sparks or embers. Then, check inside the attic for hidden burning sparks. If you have a fire, call the Fire Department and then get your neighbors to help fight it until the fire units arrive. The water in your pool and the water in your garbage cans, sinks, toilet tanks, etc., will come in handy now. For several hours after the fire, recheck for smoke and sparks throughout the house.

In a major conflagration, fire protection agencies will probably not have enough equipment and manpower to be at every home. You cannot depend totally on their help. One of the firefighter's principal responsibilities is to stop the spread of fire from house to house. Therefore, if one home is on fire, firefighters might have to pass it by to save another in the path of the fire. Your careful planning and action during a fire can save your home. Be prepared. Talk with your neighbors to see what resources you have. Ask your fire or forestry personnel for professional advice and assistance.

When Caught in the Open

When you are caught in the open, the best temporary shelter will be found where fuel is sparse. Here are comments on some good and bad places to go:

• Automobile: Move the car to bare ground or sparse fuel areas, close all windows and doors, lie on the floor and cover yourself with a jacket or blanket. The fuel tank of the car will normally not explode until the car is well on fire or may not explode at all. So, keep calm and let the fire pass.

• Road cut: If you are caught without shelter along a road, lie face down along the road cut or the ditch on the uphill side (less fuel and less convection heat). Cover yourself with anything that will shield you from the heat of the fire.

• Canyons: Never be caught by fire in canyons that form natural chimneys. These are narrow, steep canyons that concentrate heat, explosive gases, and updraft. Within chimneys, temperatures may exceed several thousand degrees Fahrenheit during a fire.

• Saddles: When you are hiking out of an area where fire is in progress, avoid topographic saddles if possible. Saddles are wide natural paths for fire winds, and vegetation here will normally ignite first.

• Other areas: Look for areas with sparse fuel (for example, soft chaparral such as black sage or grassland rather than chamise chaparral), if possible, within a depression. Clear as much fuel as you can while the fire is approaching and then lie face down in the depression and cover yourself with anything that will shield you from the heat. Smoke may create as great a survival problem as the flames do. If you are caught on a steep mountaintop or sharp ridge, the back side away from the approaching fire will be safer than the front side. Be aware, however, that fire eddies often curl over sharp or narrow ridges.

Before you hike in fire-prone areas, seek additional advice from wildland firefighting agencies. They may supply pamphlets and can give you specific tips for wildland fire survival.

Evacuation and Road Closure

Fire protection agencies are responsible for determining when the need for evacuation exists, and the jurisdictional law enforcement agency is responsible for carrying out an ordered evacuation. The purpose of evacuation is to protect people from life-threatening situations. Section 409.5 of the California Penal Code provides the legal authority for law enforcement officers to close and restrict access to disaster areas. The news media are legally exempt from this provision.

Owners have the right to stay on their property if they so desire, if in doing so they are *not* hindering the efforts of fire personnel or contributing to the danger of the disaster situation. In fires or floods, able-bodied persons who wish to remain may be able to aid fire personnel in saving their property, and those who are desirous of remaining may be permitted to do so.

In a fire or flood, there may be several different phases of road closure within the disaster area: (a) in an area that forseeably could be involved in the disaster, but presently is not, people without purpose will be restricted from entry to reduce traffic problems or the potential for looting; (b) in an area of imminent danger with limited access or egress, people would be discouraged from entry, though they live in the area, and those who are adamant after being informed of the danger would be permitted entry; (c) in an area presently involved in the emergency where extreme danger to life exists and where traffic must be restricted due to movement of emergency vehicles, people, including residents, will be refused entry.

Road closures around emergency incidents are essential to the expeditious movement of persons leaving the area and mobility of emergency equipment. On major incidents, closures become immediately essential to permit accessibility of firefighting forces, orderly evacuation, and exclusion of unauthorized persons.

In summary, here is what you should do:

• Notify the local fire protection agency.

• Stay calm—you are in control of the situation.

• If you decide to stay with your home during a wildfire, evacuate all family members who are not essential to protecting the home.

• Dress properly to shield yourself from the heat and flames.

• Take steps to prepare your home for the approaching fire.

• If caught in the open, seek shelter where fuel is sparse.

• **Remember—wildfire is erratic, unpredictable, and usually underestimated. Life safety is always the most important consideration.**

APPENDIX

List of Species Mentioned

Flora (native or naturalized)[1]

Common name	Scientific name
Aaron's beard	*Hypericum calycinum*
Acacia ongerup, prostrate	*Acacia rodelens* cultivar *ongerup*
African daisy	*Osteospermum fruticosum*
alfilaria	*Erodium* species
Algerian ivy (freeway ivy)	*Hedera canariensis*
alyssum	*Alyssum* species
annual ryegrass (H)	*Lolium multiflorum*
Australian saltbush	*Atriplex semibaccata*
barley (H)	*Hordeum vulgare*
Bermudagrass	*Cynodon dactylon*
black locust (P)	*Robinia pseudoacacia*
black sage	*Salvia mellifera*
bluegum eucalyptus	*Eucalyptus globulus*
Brazilian pepper	*Schinus terebinthifolius*
buckwheat	*Eriogonum wrightii* ssp. *subscaposum*
bur clover	*Medicago hispida*
bush poppy	*Dendromecon rigida*
California buckwheat	*Eriogonum fasciculatum*
California laurel	*Umbellularia californica*
California pepper	*Schinus molle*
California sagebrush	*Artemisia californica*
California scrub oak	*Quercus dumosa*
California walnut (D)	*Juglans californica*
Canary Island pine	*Pinus canariensis*
capeweed (P)	*Arctotheca calendula*
Carmel creeper	*Ceanothus crisseus*
ceanothus	*Ceanothus* species
chamise	*Adenostoma fasciculatum*
Chilean saltbush	*Atriplex undulata*
chokecherry (P)	*Prunus* species
coast live oak	*Quercus agrifolia*
coyote brush (Twin Peaks)	*Baccharis pilularis* var. *pilularis*
creeping sage	*Salvia sonomensis*
currant, gooseberry	*Ribes* species
cypress	*Cypress* species
deerweed	*Lotus scoparius*
Descanso rockrose	*Cistus crispus*
desert buckbrush	*Ceanothus greggii*
dwarf running myrtle	*Vinca minor*
elderberry	*Sambucus* species
English ivy (P)	*Hedera helix*
english oak	*Quercus robur*
eucalyptus	*Eucalyptus* species
fuchsias	*Fuchsia* species
gooseberries	*Ribes* species
gray santolina	*Santolina chamaecyparis*
green acacia	*Acacia* species
green galenia (P)[1]	*Galenia pubescens*
green lavender cotton	*Santolina virens*
green saltbush	*Atriplex glauca*
gum rockrose	*Cistus ladaniferus*
hoary-leaf ceanothus	*Ceanothus crassifolius*
hollyleaf cherry	*Prunus illicifolia*
honeysuckle	*Lonicera* species
ice plants	*Carpobrotus, Delosperma, Drosanthemum* species
junipers	*Juniperus* species
knotweed	*Polygonum equisitiforme*
laurel sumac (D)	*Rhus laurina*
lawn grass	*Cynodon dactylon*
lemonade berry (D)	*Rhus integrifolia*
lippia	*Phyla nodiflora (Lippia repens)*
mountain lilac	*Ceanothus* species
mountain mahogany	*Cercocarpus* species
Mueller's saltbush	*Atriplex muelleri*
myoporum, prostrate (P)	*Myroporum parvifolium* cultivar *horshum*
navel orange	*Citrus sinensis*
oak	*Quercus* species
old man saltbush	*Atriplex nummularia*
oleander	*Nerium* species
periwinkle	*Vinca major*
pines	*Pinus* species
Point Reyes ceanothus	*Ceanothus gloriosus*
ponderosa pine	*Pinus ponderosa*
prickly pear	*Opuntia* species
prostrate ceanothus	*Ceanothus prostratus*
purple rockrose	*Cistus villosus*
purple sage	*Salvia leucophylla*
reed	*Arundo* species
rockrose	*Cistus* species
rosemary, prostrate	*Rosmarinus officinalis* var. *prostratus*
roses	*Rosa* species
ryegrass, annual (H)	*Lolium multiflorum*
sages	*Salvia* species
saltbush	*Atriplex* species
scrub oak	*Quercus dumosa*
silver saltbush	*Atriplex rhagodioides*
star thistle	*Centaurea* species
sugarbush (D)	*Rhus* species
sugarbush (D)	*Rhus ovata*
sunflowers	*Helianthus* species
sycamore	*Platanus racemosa*
toyon, christmasberry (P)	*Heteromeles arbutifolia*
wavy leaf saltbush	*Atriplex undulata*
white sage	*Salvia apiana*
white trailing iceplant	*Delosperma alba*
wild mustard	*Brassica* species
yucca	*Yucca* species

[1]Tucker and Kimball (1978)
P = plant parts poisonous to ingest
D = may cause dermatitus
H = may readily cause hay fever or other allergic reaction

Fauna

badger	*Taxidea taxus*
California ground squirrel	*Otospermophilus beecheyi*
California quail	*Lophortyx californica*
coyote	*Canis latrans*
golden eagle	*Aquila chrysaetos*
gopher snake	*Pituophis melanoleucus*
mountain kingsnake	*Lampropeltis zonata*
pack rat	*Neotoma fuscipes*
pocket gopher	*Thomomys* species
rabbit	*Sylvilagus* species
rattlesnake	*Crotalus viridis*
red-tailed hawk	*Buteo borealis*
weasel	*Mustela frenata*
western racer snake	*Coluber constrictor*
wildcat	*Felis lynx*

REFERENCES

Agee, J. K.; Wakimoto, R. H.; Darley, E. F.; Biswell, H. H. **Eucalyptus-fuel dynamics and fire hazard in the Oakland Hills.** Calif. Agric. 27(9): 13-15. 1973.

Albini, Frank A. **Estimating wildfire behavior and effects.** Gen. Tech. Rep. INT-30. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1976. 92 p.

Amimoto, P. Y. **Erosion and sediment control handbook.** Sacramento, CA: Calif. Dep. of Conservation; 1978. 198 p.

Anderson, H. W.; Coleman, G. B.; Zinke, P. J. **Summer slides and winter scour.** Tech. Paper 36. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1959. 12 p.

Bailey, Robert G.; Rice, Raymond M. **Soil slippage: an indicator of slope instability on chaparral watersheds of southern California.** Prof. Geographer 21(3): 172-177; 1969.

Bennett, H. H. **Soil conservation.** New York: McGraw-Hill Book Co.; 1939. 993 p.

Blaney, H. F.; Taylor, C. A.; Young, A. A. **Rainfall penetration and consumptive use of water.** Sacramento: California State Printing Office; 1930. 162 p.

Blanford, R. H.; Gunter, L. E. **Emergency revegetation 1956-1970.** Sacramento, CA: Calif. Dep. of Forestry. 1971. 21 p.

California Department of Forestry. **Fire safety guides for residential development in California.** Sacramento: Calif. Dep. of Forestry. 1980; 36 p.

Campbell, R. H. **Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California.** U.S. Geol. Surv. Prof. Paper 851. 1975. 51 p.

Corbett, Edward S.; Rice, Raymond M. **Soil slippage increased by brush conversion.** Res. Note PSW-128. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1966. 8 p.

Countryman, Clive M. **Fire whirls . . . why, when, and where.** Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1971. 11 p.

DeBano, Leonard F. **Water repellent soils: a worldwide concern in management of soil and vegetation.** Agric. Sci. Rev. 7(2): 12-18; 1969.

DeBano, Leonard F.; Rice, Raymond M. **Water-repellent soils: their implication in forestry.** J. For. 71(4): 220-223; 1973.

Esplin, D. L.; Shackleford, J. R. **Cachuma burn reseeding evaluation—coated vs. uncoated seed, first growing season.** Goleta, CA: Los Padres National Forest, Forest Service, U.S. Department of Agriculture; 1978. 24 p.

Fairbanks, William C.; Marsh, Albert W. **Overhead sprinklers and water supplies to protect your home from brush fire.** Leafl. 2403. Berkeley, CA: Div. Agric. Sci., Univ. Calif.; 1976. 2 p.

Franclet, A.; LeHouerou, H. H. **The *Atriplex* in Tunisia and North Africa.** FO: SF/TUN 11-Tech. Rep. 7. Rome: Food and Agric. Organ., United Nations; 1971. 271 p.

Grinnel, Joseph; Dixon, Joseph. **Natural history of the ground squirrel of California.** Sacramento: Calif. State Printing Office; 1918. 116 p.

Howard, Ronald A.; North, D. Warner; Offensend, Fred L.; Smart, Charles N. **Decision analysis of fire protection strategy for the Santa Monica Mountains: an initial assessment.** Menlo Park, CA: Stanford Research Institute; 1973. 150 p.

Ilch, D. M. **Some limitations on the use of succulents for erosion control.** J. Soil and Water Conserv. 7(4): 174-176, 196; 1952.

Kittredge, Joseph. **Forest influences—the effects of woody vegetation on climate, water, and soil.** New York: Dover Publications, Inc.; 1973. 394 p.

Laure, G.; Oieni, S.; Zinke, Paul. **A burning test on *Cistus* chaparral in Sicily.** Lasca Leaves 11(3): 67-72; 1961.

Leopold, Luna B. **The topology of impacts.** In: Proceedings of the Edgebrook conference on cumulative effects of forest management on California watersheds; 1980 June 2-3; Berkeley, CA. Spec. Publ. 3268. Berkeley, CA: Univ. Calif. Div. Agric. Sci.; 1981; 1-21.

Los Angeles County. **Grading guidelines** (excerpts from Los Angeles County building laws). Department of County Engineers, Building and Safety Division. 1975. 8 p.

Los Angeles County. **Homeowner's guide for debris and erosion control.** Los Angeles, CA: Flood Control District; 1982. 34 p.

Los Angeles Department of Building and Safety. **Guide for erosion and debris control in hillside areas.** Los Angeles, CA: Dep. Buildings and Safety. 1978; 26 p.

Maire, G. M. **Landscaping burned areas.** Los Angeles, CA: County Farm Advisor's Office; 1962. 7 p.

Martin, L. B.; Juhren, M. ***Cistus* and its response to fire.** Lasca Leaves 4(3): 65-67; 1954.

McBride, Joe; Jacobs, Dana. **Land use and fire history in the mountains of southern California.** Fire History Workshop; 1980 October 20-24; Tucson, AZ. Tucson, AZ: Univ. Arizona; 1981; 85-88.

Miller, P. C. **Quantitative plant ecology.** In: Horn, D.; Stairs, G. R.; Mitchell, R. D., editors. Analysis of ecosystems. Columbus: Ohio State University Press; 1979: 179-232.

Miller, P. C.; Hajeck, E. **Resources availability and environmental characteristics of Mediterranean-type ecosystems.** In: Miller, P. C., editor. Resource use by chaparral and matorral. New York: Springer Verlag; 1981: 17-41.

Minnich, Richard A. **Fire mosaics in southern California and northern Baja California.** Science 219(4590): 1287-1294; 1983 March 18.

Moore, Howard E. **Protecting residences from wildfires: a guide for homeowners, lawmakers, and planners.** Gen. Tech. Rep. PSW-50. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1981. 44 p.

Muller, C. H. **The role of chemical inhibition (allelopathy) in vegetational composition.** Bull. Torrey Bot. Club 93: 332-351; 1966.

Muller, C. H.; Hanawalt, R. B.; McPherson, J. K. **Allelopathic control of herb growth in the fire cycle of California chaparral.** Bull. Torrey Bot. Club 95: 225-231; 1968.

Olsen, James M. **Cistus, fuel moisture, and flammability.** Res. Note 159. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1960. 2 p.

Osborn, J. F.; Letey, J.; DeBano, L. F., and others. **Seed germination and establishment as affected by nonwettable soils and wetting agents.** Ecology 48(3): 494-497; 1967.

Paysen, Timothy E.; Derby, Jeanine; Black, Hugh, Jr.; Bleich, Vernon C.; Mincks, John W. **A vegetation classification system applied to southern California.** Gen. Tech. Rep. PSW-45. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 34 p.

Perry, Chester A.; Adams, Theodore A., Jr.; McHenry, W. B.; Gilden, L. A. **Protecting your home against wildfire.** Leafl. 21104. Berkeley, CA: Div. Agric. Sci., Univ. Calif.; 1979. 6 p.

Philpot, Charles W. **Vegetative features as determinants of fire frequency and intensity.** In: Mooney, Harold C.; Conrad, C. Eugene, tech. coord. Proceedings of the symposium on the environmental consequences of fire and fuel management in Mediterranean ecosystems; 1977 August 1-5; Palo Alto, CA. Gen. Tech. Rep. WO-3. Washington, DC: Forest Service, U.S. Department of Agriculture; 1977; 12-17.

Radtke, Klaus. **Low-fuel plant research update.** Los Angeles, CA: Forestry Bur., Fire Dep. 1977; 13 p.

Radtke, Klaus. **Wildland plantings and urban forestry: native and exotic 1911-1977.** Los Angeles, CA: Los Angeles County Dep. Forester and Fire Warden, Forestry Div.; 1978. 135 p.

Radtke, Klaus W.H.; Arndt, Arthur M.; Wakimoto, Ronald H. **Fire history of the Santa Monica Mountains.** In: Conrad, C. Eugene; Oechel, Walter C., tech. coord. Proceedings of the symposium on dynamics and management of Mediterranean-type ecosystems; 1981 June 22-26; San Diego, CA. Gen. Tech. Rep. PSW-58. Berkeley, CA:

GPO 791-635/38025

Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982; 438-443.

Rice, Elroy L. **Allelopathy.** New York: Academic Press, Inc.; 1974. 353 p.

Rice, R. M.; Corbett, E. S.; Bailey, R. G. **Soil slips related to vegetation, topography and soil in southern California.** Water Resour. Res. 5 (30): 647-659; 1969.

Rice, R. M.; Foggin G. T., III. **Effect of high intensity storms on soil slippage on mountainous watersheds in southern California.** Water Resour. Res. 7(6): 1485-1496; 1971.

Rice, R. M.; Ziemer, R. R.; Hankin, S. C. **Slope stability effects of fuel management strategies—inferences from Monte Carlo simulations.** In: Conrad, C. Eugene; Oechel, Walter C., tech. coord. Proceedings of the symposium on dynamics and management of Mediterranean-type ecosystems; 1981 June 22-26; San Diego, CA. Gen. Tech. Rep. PSW-58. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982; 365-371.

Rice, Raymond M. **The hydrology of chaparral watersheds.** In: Proceedings, symposium on living with chaparral; 30-31 March 1973; Riverside, CA. San Francisco: Sierra Club; 1974; 27-34.

Rundel, Philip W. **Water balance in Mediterranean sclerophyll ecosystems.** In: Mooney, Harold A.; Conrad, C. Eugene, tech. coord. Proceedings of the symposium on the environmental consequences of fire and fuel management in Mediterranean ecosystems; 1977 August 1-5; Palo Alto, CA. Gen. Tech. Rep. WO-3. Washington, DC: Forest Service, U.S. Department of Agriculture; 1977; 95-106.

Sampson, Arthur W. **Plant succession on burned chaparral lands in northern California.** Bull. 685. Berkeley, CA: Agric. Exp. Sta., Univ. Calif.; 1944. 144 p.

Satterlund, D. R. **Wildland watershed management.** New York: Ronald Press Co. 1972. 370 p.

Stefferund, A., ed. **The Yearbook of Agriculture 1957.** Washington, DC: U.S. Department of Agriculture; 1957. 784 p.

Strahler, A. N.; Strahler, A. H. **Environmental geoscience: interaction between natural systems and man.** Santa Barbara, CA: Hamilton Publ. Co.; 1973. 511 p.

Sweeney, James R. **Responses of vegetation to fire.** Botany 28: 143-250; 1956.

Tucker, John M.; Kimball, M. H. Poisonous **plants in the garden.** Leaflet 2561. Berkeley, CA: Div. Agric. Sci., Univ., Calif.; 1978. 10 p.

Van Burkalow, A. **Angle of repose and angle of sliding friction.** Bull. Geol. Soc. Am. 56: 669-707; 1945.

Weide, D. L. **The geography of fire in the Santa Monica Mountains.** Los Angeles, CA: Calif. State Univ.; 1968. 178 p. Dissertation.

Westman, Walter E. **Coastal sage scrub succession.** In: Conrad, C. Eugene; Oechel, Walter C., tech. coord. Proceedings of the symposium on dynamics and management of Mediterranean-type ecosystems; 1981 June 22-26; San Diego, CA. Gen. Tech. Rep. PSW-58. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1982; 91-97.

Williamson, Joseph F., editor. **Sunset western garden book.** Menlo Park, CA: Lane Mag. and Book Co.; 1976. 448 p.

Zinke, Paul J. **The emergency treatment of burned chaparral watersheds.** Berkeley, CA: Agric. Exp. Stn., Univ. Calif.; 1962. 26 p.

Radtke, Klaus W.H. **Living more safely in the chaparral-urban interface.** Gen. Tech. Rep. PSW-67. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 51 p.

Urban encroachment into chaparral areas has accelerated the fire-flood-erosion cycle. Preventive maintenance measures can help reduce the damage from fire and flood. This report describes the chaparral environment; how to cope with problems in watershed management, how to landscape for fire and soil erosion control, how to plan for home safety from fire, how to treat newly burned chaparral slopes, how to clear brush around homes; and what to do when caught in a wildfire. The information reported is addressed to homeowners, buyers, and developers; and architects, planners, and other officials in municipalities and agencies.

Retrieval Terms: brush clearance, fire control, fire safety, landscaping, erosion, watershed management, wildfire, California

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

General Technical
Report PSW-68

Economic Cost of Initial Attack and Large-Fire Suppression

Armando González-Cabán

The Author:

ARMANDO GONZÁLEZ-CABÁN is an economist working with the fire management planning and economics research unit at Riverside, Calif. He holds two degrees from the University of Puerto Rico: a bachelor of business administration (1969), and a master of planning (1971). He joined the Forest Service and the Station's staff in 1980.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

June 1983

Economic Cost of Initial Attack and Large-Fire Suppression

Armando González-Cabán

CONTENTS

Introduction 1
Fire Management Program Component Costs 1
Fire Management Input Unit Cost 2
Economic Cost 2
Sample Application 5
References 7

Since 1975, the economic efficiency of fire management programs has received increased emphasis in the Forest Service, U.S. Department of Agriculture fire management planning and budgetary allocation process. That year, the U.S. Office of Management and Budget (OMB) asked the Forest Service to estimate the real costs of changes in its fire management program and to indentify the best fire management practices by evaluating appropriate costs and returns. In 1978, during a review of the Forest Service fire management program budget for fiscal year 1979, the U.S. Senate Appropriations Committee noted a dramatic increase in fire presuppression costs without a corresponding increase in apparent benefits. The Committee requested the Forest Service to "conduct a cost-benefit analysis of both presuppression and suppression activities . . . " as a basis for future budget requests (U.S. Senate 1978).

In response to the questions raised by the OMB and the U.S. Senate (1978), the Forest Service made several changes in its fire management policy. By 1978, fire management programs must be not only cost-effective but must be compatible with land management objectives. Now, success probability and economic efficiency, as measured by the minimization of cost plus net value change, are necessary criteria for selecting among fire suppression actions (U.S. Department of Agriculture, Forest Service 1981).

Economic efficiency is also the criterion to be used in judging fire management programs in several states. The California Department of Forestry (CDF), for example, has been asked by the State legislature to reflect more accurately fire damage estimates. The State legislature also asked CDF to evaluate changes in damages resulting from an increase or decrease in fire programs budget. Wisconsin and Alabama also are addressing the question of economic efficiency in fire programs (Mills 1980). A cost estimate of fire management activities is a necessary input into the economic analysis now required.

This report describes a procedure to estimate the economic costs of initial attack and large-fire suppression actions of fire management programs. It explains a measure called fire management input unit cost estimate and how it is used to determine the economic costs of such actions. A sample application illustrates how the procedure works.

FIRE MANAGEMENT PROGRAM COMPONENT COSTS

Fire management program component costs have been categorized in numerous ways. One study, for example, concentrated on direct protection costs, dividing them into two categories (Sparhawk 1925):

- *Primary protection*—Includes the cost of fire management organization for prevention, detection, and suppression. Organizational costs include personnel, equipment, and improvements, and are determined in advance.
- *Actual cost of suppression*—Includes temporary labor, subsistence, transportation, and the time of Forest personnel taken from other work. For a finer resolution, fire management program costs are divided into fire prevention, fire detection, fuel modification, presuppression activities, and fire suppression (Gale 1977). The first four categories combined represent Sparhawk's primary protection costs.

A different breakdown was used to define the costs of protection by Davis (1974). Fire program costs included prevention, presuppression, prescribed fire, mechanical fuel treatment, and fire planning. In addition, general fire system costs, including general administration and planning management information, and public involvement were identified (Davis 1974). Although a different breakdown, all cost elements discussed by Davis (1974) are included in the prevention and presuppression categories developed by Gale (1977).

Other studies have developed cost categories based on the premise that fire program decisions should consider the program's total cost effect over time. With this principle, two major cost categories were defined (Newport 1972)—investment costs and operational costs. Investment costs are one-time expenditures for facilities, equipment, or both, required to initiate the system. Operational costs are the recurring costs of operating, supporting, and manning the fire control system or subsystem.

The main problem with all the approaches to cost the fire management programs discussed previously is that none of them, with the possible exception of Newport (1972), addressed the question of economic costs. All efforts concentrated on categorizing accounting costs. Distribution or overhead costs to the various functions is seldom considered. Also, the concept of opportunity cost is rarely used in evaluating the total cost of the fire management programs. In general terms, the opportunity cost of the current use of some good or of some input is its worth in some alternative use (Mishan 1976). The procedure proposed here corrects these oversights in computing the economic cost of fire management programs.

FIRE MANAGEMENT INPUT UNIT COST

The procedure developed here uses a per-unit cost to estimate the cost of a fire management program on an input-by-input basis (McKetta and others 1981). Fire management inputs (FMIs) are the production units used in initial attack and large-fire suppression organizations to which physical control parameters can be ascribed; for example, a 20-person category-I crew that can produce X chains of fireline in a given period of time.

The unit cost estimates are used initially to determine the fire season fire program standby costs, that is, the total cost of having the fire program available. In the Forest Service these costs are called *presuppression costs*. The budget level for any fire program is converted into a list of FMIs available to fight fires during the season by means of the FMI unit cost. To determine the fire management program standby costs, several steps are taken. One, the total budget is allocated to the various program functions. Two, the allocated money is assigned to different FMIs within the functions. Three, the dollars allocated to the various functions (two above) are translated into an FMI list, for example, number of pumpers available for the season. Because half units cannot be bought, the resulting FMI list is corrected for fractions by rounding to the closer integer. Then the program level is adjusted for the integer solution accordingly. This whole process gives the fire program season standby costs.

The standby or presuppression costs represent only a part of the *cost* figure in the cost plus net value change equation used to evaluate economic efficiency of different fire managemet programs. The second part in the *cost* figure is the cost of using the fire management inputs in actual firefighting or suppression costs. The total cost of the fire program is the standby or presuppression cost plus the use or suppression costs. The FMI unit cost estimates are used to obtain the use cost above and beyond the fire program standby cost through the procedure explained in this report.

The main objectives in developing the FMI unit cost are to . . .

- Identify budgetary costs that should be allocated to a specific FMI.
- Incorporate FMI economic costs that are not typically included in accounting data.
- Convert fixed costs of each FMI to a variable cost element that is relevant for long-term fire management organization planning and optimization process.
- Display the variable costs on a dollar-per-hour basis for each FMI in distinct categories, which represent "standby" and "on-fire" costs during either normal or overtime hours. Standby costs are incurred for a certain period during the year, regardless of whether the FMIs are used.

After these objectives are accomplished, all direct and indirect costs of having available and using the fire management inputs are charged to the FMIs. All applicable overhead costs, such as personnel management costs, are distributed to the FMIs on the basis of their firefighters' use of various overhead support functions. An opportunity cost to the organization for the use of their own capital in facilities is distributed to the FMIs using the facilities. (An equivalent rental rate of similar private facilities in the same area where the agency facilities are located is used to determine the opportunity cost [González-Cabán and others 1982]). The opportunity cost is then allocated over the FMI's availability and is converted into a portion of the variable unit cost. The unit cost reflects the cost of the fire management inputs in a variable cost form, providing a better means for estimating the economic cost of alternative fire management programs to be tested in planning a fire organization.

With the per-unit-cost approach, all cost information relevant to an FMI is integrated as one cost rate, thereby making simulation cost aggregation easier. The unit cost approach also increases flexibility so that the cost procedure can be uniformly applied by all organizations with fire protection responsibilities. A more detailed explanation of the FMI unit cost development can be found in works by McKetta and others (1981) and Gonzalez-Caban and others (unpubl.) As an example, the unit cost for a category-I crew must consider all the components in developing the composite unit cost (*table 1*).

ECONOMIC COST

The economic cost procedure determines only the cost of the initial attack and large-fire actions functional categories to date of the fire management program. The aggregation process described will be used to estimate the total economic cost of a fire management program as cost estimates of the other functional categories become available.

Acquaintance with the overall cost scheme will assist in understanding the cost procedure (*fig. 1*). The cost procedure needs all of the following basic information to compute the suppression costs of any FMI sent to a fire (*fig. 1*):

- Type and number of FMIs sent to a fire;
- Time the FMIs were sent to the fire;
- Time the FMIs spent in firefighting activities;
- Time the FMIs spent in nonfirefighting activities; and,
- Travel time for the FMIs to get to the fire.

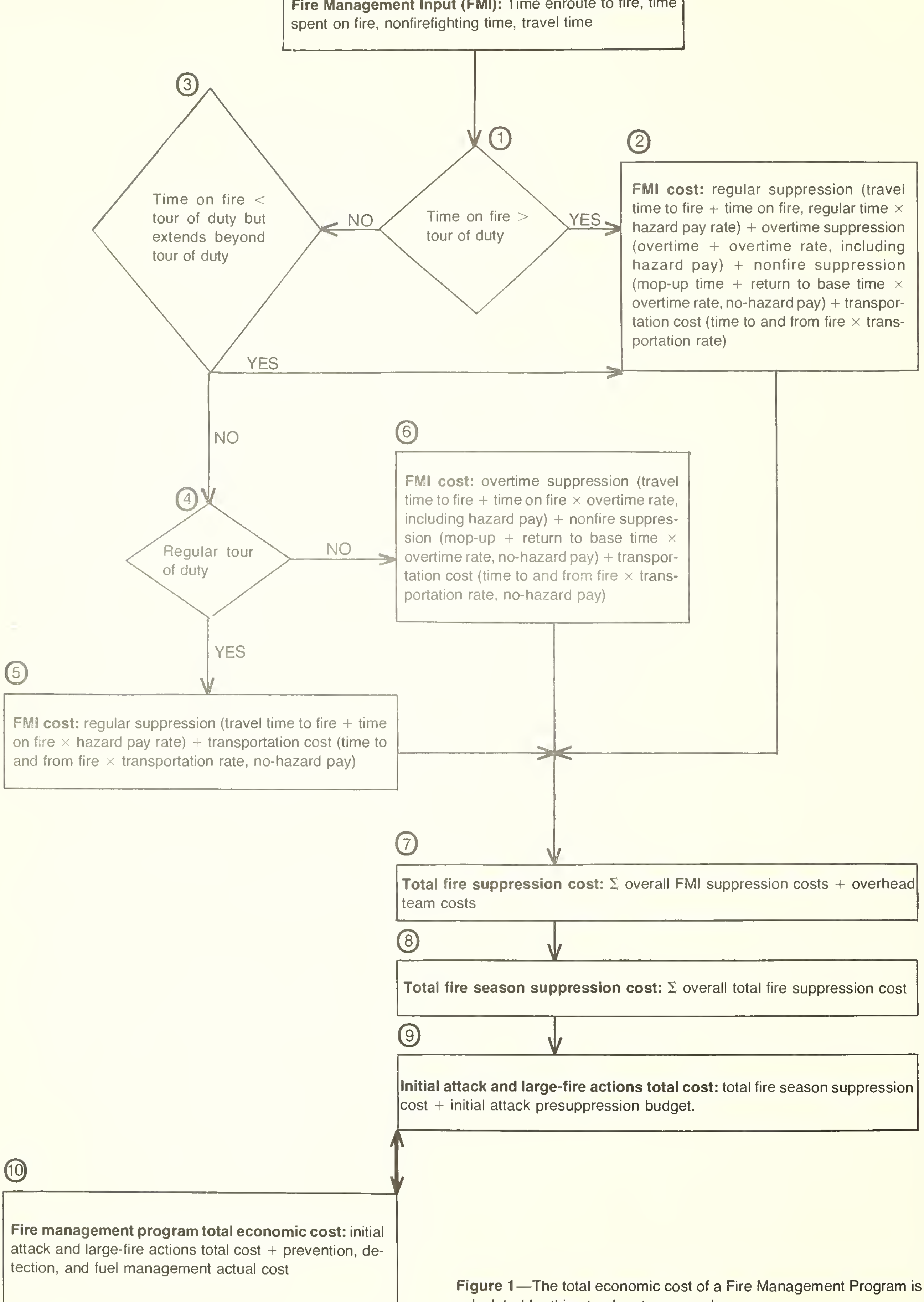


Figure 1—The total economic cost of a Fire Management Program is calculated by this step-by-step procedure.

First, it is determined whether an FMI sent to a fire remained on the fire longer than the regular tour of duty. If this is true, the FMI suppression cost for that fire equals the regular suppression cost plus overtime suppression cost plus nonfirefighting activities cost plus transportation costs. Any activity taking place after the fire has been declared contained (a fireline has been built around the fire perimeter) is considered a nonfirefighting activity. The distinction is that during this time the FMIs do not draw a hazard pay premium. Hazard pay is a compensation above and beyond base pay for dangerous work done. As the fire is contained, it is no longer considered a high risk area so the hazard pay premium stops. The FMI's return trip to base camp is a nonfirefighting activity.

If the FMI time spent on the fire is less than the regular work period but extends beyond the regular tour of duty, the FMI suppression cost is the same as in the previous example. If the FMI stays on the fire during the regular tour of duty, the FMI suppression cost for that fire equals the regular suppression cost plus transportation cost. If, however, the FMI's time spent on the fire is outside the regular tour of duty, the suppression cost for that fire equals the overtime suppression plus nonfirefighting suppression plus transportation cost.

Immediately after dispatch to a fire, all FMI crewmembers start drawing hazard pay premium. As mentioned earlier, however, during the return trip to home base and during that time in which the FMIs are in nonfirefighting activities, the FMI crewmembers do not collect hazard pay premium. The different pay rates for the FMI crewmembers depend on the activity being performed. When the FMIs are waiting to be sent to a fire they get pay at the standby rate. While in transit to a fire they get pay at the standby or overtime basic pay (one and one-half times the standby rate), depending on time of day and tour of duty, plus hazard pay premium. These are called regular suppression pay and overtime suppression pay, respectively. While on the fire the FMI crewmembers get paid the same as when in transit to the fire. Once the fire is declared contained all FMI crewmembers stop drawing a hazard pay premium and their pay reverts to the standby or overtime pay, again depending on time of day and tour of duty. In summary, there are four different pay rates that differ by hazard pay premium and tour of duty.

Once the necessary information for all FMIs used in a particular fire is collected, the sum of all costs equals the total FMI suppression cost for that particular fire. Emergency suppression expenditures are not budgeted at the beginning of the fiscal year, but are covered in supplemental appropriations made by Congress or State legislatures to cover all fire-related expenditures not appropriated in fire presuppression budgets. To determine the total cost of the initial attack and large-fire action of any fire management program, therefore, it is necessary to keep records of suppression funds spent during initial attack and large-fire actions throughout the fire season. The regular tour of firefighting duty of any FMI is always paid out of the presuppression budget. Hazard premium pay, overtime suppression, overtime, and transportation cost while firefighting are charged to emergency fund expenditures.

When the cost procedure presented here is applied over an entire fire season, total costs of the initial attack and large-fire action functions of a fire management program are accounted for. When cost estimates for other functional activity categories are completed, the total cost of a fire management program can be estimated. Although the present procedure deals only with initial attack and large-fire suppression, for reasons of completeness, costs of the other functional activities will be added to estimate the fire management program economic cost. The costing procedure will eventually be extended to include the cost of prevention, detection, and fuels management functional activities.

Because actual firefighting or any other activity while on the fire during the FMI regular tour of duty is covered under the presuppression budget, only the suppression or emergency costs need to be estimated. As explained earlier, standby costs pay for the FMI's availability period, including any action during the regular tour of duty.

Mathematically, the total suppresion cost of any particular fire management input during a fire is given by equation 1:

$$SC_{ik} = [RT_{ik} (PUR_i - PUS_i) + (OT_{ik} \times PUO_i) + (OTNS_{ik} \times PUON_i) + (\sum_{j}^{M} TT_{ijk} \times CH_{ij})] \quad (1)$$

Table 1—*Unit cost for a category-I firefighting crew*

Activity status	Total	Supplies	Pay	Training	Special training	Equipment	Facilities	Overhead	Misc.	Supervisor	Subsist.
Standby	275.66	7.97	165.91	19.55	0.0	0.0	19.01	63.23	0.0	0.0	0.0
suppression											
Small fire	305.26	7.97	195.41	19.55	0.0	0.0	19.01	63.23	0.0	0.0	0.0
Large fire	384.31	7.97	195.41	19.55	0.0	0.0	19.01	63.23	0.0	6.51	72.63
Small fire											
On overtime	364.16	7.97	254.41	19.55	0.0	0.0	19.01	63.23	0.0	0.0	0.0
Large fire											
On overtime	444.41	7.97	254.41	19.55	0.0	0.0	19.01	63.23	0.0	7.62	72.63

in which

SC_{ik} = total suppression cost of input i for fire k.
RT_{ik} = regular time in firefighting activities of input i while on fire k (including travel time to fire).
OT_{ik} = overtime in firefighting activities of input i while on fire k (including travel time to fire).
$OTNS_{ik}$ = overtime in nonfirefighting activities of input i while on fire k (including mop-up and travel back to base).
PUR_i = per unit cost of input i while in regular time firefighting activities.
PUO_i = per unit cost of input i while in overtime firefighting activities.
$PUON_i$ = per unit cost of input i while in overtime nonfirefighting activities.
PUS_i = standby rate of input i.
TT_{ijk} = travel time of input i by method j for fire k.
CH_{ij} = cost per hour traveled of input i by method j.
i = 1, 2, 3 . . . N, input identifier.
j = 1, 2, 3 . . . M, travel method.
k = 1, 2, 3 . . . F, fire identifier.

Equation 1 expresses the total suppression cost of any FMI sent to a fire. The total suppression cost for all inputs used in fighting fire k is derived by summing across all inputs. The cost of any fire overhead teams used in the management of the fire needs to be included as part of the cost of the fire. The overhead teams are not directly related to any specific FMI and their composition depends on fire size. It is easier, therefore, to allocate their cost to any FMI used as a variable cost lump sum on a per-fire basis and always assign their cost to emergency funds. The total suppression cost of any fire is given by:

$$TSC_k = \sum_{i}^{N} SC_{ik} + O_k \qquad (2)$$

in which

TSC_k = total suppression cost of fire k
O_k = overhead team cost.

The fire season total suppression or emergency cost equals the summation over all fires of the suppression cost per fire, as computed by equation 2.

$$FSSC = \sum_{k}^{F} TSC_k \qquad (3)$$

in which

FSSC = total suppression cost for the entire fire season.

To determine the fire season total cost of initial attack and large-fire actions, the fire season total suppression or emergency charges are added to the presuppression budget for initial attack for the planning year.
Therefore,

$$FSC = FSSC + IAB \qquad (4)$$

in which

FSC = fire season initial attack and large-fire suppression action total costs.
FSSC = fire season total suppression or emergency fund charges.
IAB = initial attack presuppression budget.

As mentioned earlier, the procedure explained here determines the economic cost of the initial attack and large-fire actions of a fire management program. As unit cost estimates for prevention, detection, and fuels management activities of a fire management program are developed, the procedure will be used to determine the total economic cost of a fire program.

Equation 5 integrates all fire program functional activity costs into a fire management program total economic cost:

$$ECFP = FSC + PPC + DPC + FPC \qquad (5)$$

in which

ECFP = economic cost of the fire management program
PPC = prevention program cost
DPC = detection program cost
FPC = fuels management program cost.

SAMPLE APPLICATION

In this example, the cost procedure is applied to a simulated fire. All cost computations are done to demonstrate the procedure.

The fire was reported at 1445, and the area burned 175 acres. The fire was declared contained at 1945. Total containment time was 5 hours. There were 2 additional hours of nonfirefighting activities, including mop-up actions. (After the fire is contained all pay reverts to standby or overtime depending on tour of duty; therefore, the nonfirefighting status was assigned to all FMIs during this period.) The fire was declared out by 2145. In addition to the 2 hours of nonfirefighting activities, travel time of some FMIs who remained on the fire until declared out need to be added to the nonfirefighting time. The difference between time of arrival and containment is the FMI's time on firefighting activities on the fire. Air tankers are different; they do not remain on the fire all the time, but return to base for reloading. Air tankers, total firefighting time, and travel time are the same. The per-unit cost estimates developed by McKetta and others (1981) are used in this example.

The fire management inputs sent to the simulated fire are these:

Fire Management Input (FMI)	Unit size	Quantity
Pumper crew	2 persons (250 gal)	3
Air tanker	PV2	1
Air tanker	B26	1
Helitack crew	2 persons	4
Category-I crew	20 persons	3
Smokejumpers	2 persons	5
Pumper crew	3 persons (500 gal)	3

The first step is to determine the total time spent by each FMI sent to the fire (*table 2*). The total time spent by a smokejumper team will be computed here to show how the calculation is done. The smokejumper team arrived at 1500 and remained on the fire until 1945. The total time spent on the fire broken into different time classes, as presented in *table 2*, is as follows: regular suppression (regular tour of duty, assume tour of duty ends at 1700), 2.25 hours (includes travel time to the fire); overtime suppression (after regular tour of duty), 2.75 hours; overtime (nonfirefighting status, travel time back to home base), 0.25 hours.

In total, the smokejumper team remained 5 hours in firefighting status on the fire at different pay rates because of tour of duty and 0.25 hour in nonfirefighting status. It is assumed that all five smokejumper and helitack teams arrived and departed together. All other FMIs, although the same kind, may have arrived at different times. In this example it is also assumed that all dispatches to the fire take place once the fire is reported. This will ease the travel time computation. Differences in arrival times account for FMI base location.

After total time spent on the fire is computed for all FMIs, the suppression cost for each FMI is calculated. This is done by multiplying the unit cost rate by the time each FMI remained on the fire or attended to other activities (equation 1). The cost of the smokejumper teams will be computed here to show the procedure. (The fire and FMI total suppression cost are shown in *table 3*.)

$$SC_{ik} = [RT_{ik}(PUR_i - PUS_i) + (OT_{ik} \times PUO_i) + (OTNS_{ik} \times PUON_i) + \sum_j (M\,TT_{ijk} \times CH_{ij})]$$

$$= [11.25(\$39.96 - \$36.43) + (13.75 \times \$62.21) + (0.50 \times \$54.60) + (0.50 \times \$1000)] = \$1422$$

Once the cost of all FMIs used in the fire is determined, summing yields the total suppression cost of the FMIs. The FMIs total suppression cost is $30,274 (*table 3*). To determine the total suppression cost of the fire, the cost of overhead teams must be added (equation 2). In this example, the overhead team cost was $5000. (This is a hypothetical figure until a procedure to compute the cost of overhead team usage is developed.) The total cost of the fire, therefore, equals the total FMI cost (*table 3*) plus $5000, or $35,274.

The same procedure, as just described, is followed for all fires simulated during a fire season. For each fire, the emergency fund or suppression charges are summed. At the end of the fire season, total cost charged to emergency funds is added to the initial attack presuppression budget to obtain the total cost of initial attack and large-fire actions for the fire season (equation 4).

Table 2—*Total regular suppression time, overtime suppression time, nonfirefighting time, and travel time*

Fire Management Input (FMI)	Regular suppression	Overtime suppression	Nonfire-fighting[1]	Travel time
Pumper crew (250 gal)	2.25	2.75	0.75	1.50
Pumper crew (250 gal)	2.25	2.75	0.75	1.50
Pumper crew (250 gal)	2.25	2.75	3.25	2.50
Air tanker (PV2)	4.66	—	—	4.66
Air tanker (B26)	3.50	—	—	3.50
Helitack crew	[1]19.00	[2]11.00	[2]1.32	[4]0.66
Category-I crew	2.25	2.75	0.42	0.84
Category-I crew	2.25	2.75	0.42	0.84
Category-I crew	2.25	2.75	1.25	2.50
Smokejumper	[3]11.25	[3]13.75	[3]1.25	[4]0.50
Pumper crew	2.25	2.75	0.75	1.50
Pumper crew	2.25	2.75	0.58	1.16
Pumper crew	2.25	2.75	3.00	2.00

[1]Includes mop-up time plus travel time back to base.

[2]Four helitack teams, each remained 2.25 hours in regular suppression, 2.75 hours in overtime suppression, and 0.33 hours in nonfirefighting status.

[3]Five smokejumper teams, each remained 2.25 hours in regular suppression, 2.75 hours in overtime suppression, and 0.25 hours in nonfirefighting status.

[4]All helitack and smokejumper teams are deployed at the same time.

To complete the example, assume an initial program level of $1,162,000. Seventy percent ($813,400) of the program level is assigned to initial attack actions. A fire season of 120 days is also assumed. All figures, including suppression charges for the season, prevention, detection, and fuels management are hypothetical and used for exposition purposes only. A number of *x* fires occurred during the simulated fire season and their costs calculated, as explained previously. The integration pro-

Table 3—*Fire management input (FMI) and total fire suppression cost*

Fire Management Input (FMI)	Quantity	Total suppression cost (SC_{ik}) (dollars)
1. Pumper crew (250 gal)	3	721
2. Air tanker (PV2)	1	[1]11,361
3. Air tanker (B26)	1	[2] 8,529
4. Helitack crew	4	1,249
5. Category-I crew	3	5,615
6. Smokejumpers	5	1,422
7. Pumper crew (500 gal)	3	1,377
FMI total fire suppression cost		30,274

[1]Includes the cost of our loads of retardant at $0.80/gal. Both air tankers have a 1200-gal tank capacity.

[2]Includes the cost of three loads of retardant at $0.80/gal.

cess at the end of the fire season leads to the economic cost of the fire management program. Assuming suppression charges of $1,250,000 for the simulated season, the fire season initial attack and large-fire action total cost equals $2,063,400 (summing the initial attack presuppression budget [$813,400] and suppression charges [$1,250,000]).

Equation 5 is used to compute the economic cost of the fire management program for the season. Assuming $58,100 for prevention, $116,200 for detection, and $174,300 for fuels management, the economic cost of the fire program for the season equals $2,412,000 ($58,100 + $116,200 + $174,300 + $2,063,400).

All costs, regardless of who pays them, must be identified and accounted for. Even if an agency does not actually bear some direct costs of a fire management program, the cost can conceptually be charged to the fire program. Only by assigning all the costs incurred to the beneficiary program can the true cost of the programs be determined. Development of similar procedures for the other functional categories of a fire management program—detection, prevention, and fuels management—will provide the capability to estimate the total economic cost of the fire management program.

The cost procedure described is designed for use by any land management or resource management agency with fire management responsibilities. It is applicable to organizations that use different budgetary systems and allocate costs between agencies. The economic cost information described here will be used in the Fire Economics Evaluation System (FEES) model (Mills and Bratten 1981) being developed by the Pacific Southwest Forest and Range Experiment Station to evaluate the economic efficiency of alternative fire management programs.

REFERENCES

Davis, Lawrence S. **An exploration of the economics of fire management programs in the Rocky Mountains with emphasis on information needs.** 1974. Unpublished draft supplied to author by Lawrence S. Davis.

Gale, Robert. **Evaluation of fire management activities on the National Forests** (Policy Analysis Staff). Washington, DC: U.S. Department of Agriculture, Forest Service; 1977. 127 p.

González-Cabán, Armando; Shinkle, Pat; Mills, Thomas J. **Fire management mix and program level.** 1981. Unpublished draft.

González-Cabán, Armando; McKetta, Charles W.; Mills, Thomas J. **Costs of fire suppression forces**. 1982. Unpublished draft.

McKetta, Charles W.; Ehrenreich, John J.; Clements, Stephen; Overstreet, Joseph. **Fire management cost data collection form and firefighting cost models**. Final report. 1981. Unpublished draft supplied to author by Charles W. McKetta.

Mills, Thomas J. **Problem analysis: fire economics evaluation system (FEES)—basic analysis structure and financial return calculations.** 1980. Unpublished draft supplied to author by Thomas J. Mills.

Mills, Thomas J.; Bratten, Frederick W. **Design of a fire economics evaluation system: FEES**. 1981. Unpublished draft supplied to author by Thomas J. Mills.

Mishan, E.J. **Cost-benefit analysis, new and expanded edition**, Praeger special studies, New York: Praeger Publishers, a division of Holt, Rinehart, and Winston, CBS, Inc.; 1976: 65-74.

Newport, Carl A. **FOCUS: cost model—background, concept forms and user's instruction**. 1972. Unpublished draft supplied to author by Carl A. Newport.

Sparhawk, W.N. **The use of liability rating in planning forest fire protection**. J. Agric. Res. 30(8):693-761; 1925.

U.S. Department of Agriculture, Forest Service. **Forest Service manual, title 5100, fire management, section 5130.3, fire suppression policy**. Washington, DC; 1981.

U.S. Senate. **Report on Department of Interior and related agency appropriations bill.** Rep. 95-1063. Washington, DC; 1978.

González-Cabán, Armando. **Economic cost of initial attack and large-fire suppression**. Gen. Tech. Rep. PSW-68. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 7 p.

A procedure has been developed for estimating the economic cost of initial attack and large-fire suppression. The procedure uses a per-unit approach to estimate total attack and suppression costs on an input-by-input basis. Fire management inputs (FMIs) are the production units used. All direct and indirect costs are charged to the FMIs. With the unit approach, all cost information relevant to an FMI is integrated as one cost rate, thereby making simulation cost aggregation easier. Also, flexibility is increased so that the cost procedure can be uniformly applied by all organizations with fire protection responsibilities. Once the necessary information for all FMIs used in a particular fire is collected, the sum of all costs equals the total FMI suppression cost for that fire. As unit cost estimates for prevention, detection, and fuels management activities are developed, the procedure will be used to determine the total economic cost of a fire management program.

Retrieval Terms: economic cost, fire management program costs, fire suppression cost, fire economics.

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

General Technical
Report PSW-69

Proceedings of a Workshop on

Eucalyptus in California

June 14-16, 1983, Sacramento, California

Cover: A stand of 50-month-old *Eucalyptus camaldulensis* growing in Calistoga, California. Average height of the trees is 6.7 m and average diameter-at-breast-height (d.b.h.) is 7.9 cm.

Publisher

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

October 1983

Proceedings of a Workshop on

Eucalyptus in California

June 14-16, 1983, Sacramento, California

Technical Coordinators:

Richard B. Standiford
Cooperative Extension
University of California

F. Thomas Ledig
Pacific Southwest Forest and
Range Experiment Station

CONTENTS

PART 1. HISTORY OF EUCALYPTS IN CALIFORNIA

Eucalyptus Helped Solve a Timber Problem: 1853-1880
Gayle M. Groenendaal 1

PART 2. SPECIES SELECTION

Adaptability of Some *Eucalyptus* Species in Southwest Oregon
Lee O. Hunt 9

Southern California Trial Plantings of *Eucalyptus*
Paul W. Moore 14

Soil Conservation Service Tests of *Eucalyptus* Species for Windbreaks
Gary L. Young 18

Eucalyptus as a Landscape Tree
W. Douglas Hamilton 22

Creating a Database on *Eucalyptus* for California
Miles L. Merwin 25

PART 3. PRODUCTS, USES, ECONOMICS

Using Eucalypts in Manufacturing
William A. Dost 30

California Wood Energy Program
Gary Brittner 33

Large-Scale *Eucalyptus* Energy Farms and Power Cogeneration
Robert C. Noroña 35

Economic Evaluation of Eucalypt Energy Plantations
Richard B. Standiford and F. Thomas Ledig 42

PART 4. GROWTH AND YIELD

Growth and Yield of Some Eucalypts of Interest to California
Roger G. Skolmen 49

Evaluating Trees as Energy Crops in Napa County
Dean R. Donaldson and Richard B. Standiford 58

Growth and Yield in *Eucalyptus globulus*
James A. Rinehart and Richard B. Standiford 61

Industrial Planting of *E. viminalis* in Mendocino County
Peter C. Passof and John W. Sweeley 69

Yields in High Density, Short Rotation Intensive Culture (SRIC)—Plantations of *Eucalyptus* and Other Hardwood Species
R.M. Sachs and C.B. Low 71

PART 5. CULTURAL REQUIREMENTS

Vegetation Management in *Eucalyptus*
Clyde L. Elmore 76

Spacing Trials Using the Nelder Wheel
Walter B. Mark 81

Establishing a *Eucalyptus* Energy Plantation on the Central Coast of California
Norman H. Pillsbury and Nelson L. Ayers 86

Fertilization and Irrigation of *Eucalyptus* in Southern California
Paul W. Moore 90

Managing a Coastal Bluegum (*Eucalyptus globulus*) Forest
Ralph S. Osterling 93

Harvesting to Get a *Eucalyptus* Coppice Crop
Thomas F. Geary 95

PART 6. PROPAGATION

Propagation and Planting of Containerized *Eucalyptus* Seedlings in Hawaii
Gerald A. Walters 98

Micropropagation of Frost-Resistant *Eucalyptus*
Michel Boulay 102

Clonal Propagation of *Eucalyptus* by Cuttings in France
H. Chaperon 108

PART 7. BREEDING PROGRAMS

Eucalypt Improvement for California: Progress and Plans
F. Thomas Ledig 115

Realized Gain from Breeding *Eucalyptus grandis* in Florida
George Meskimen 121

PREFACE

Although eucalypts (genus *Eucalyptus*) were introduced into California more than 125 years ago, little has been done to provide systematic programs for identifying superior planting stock. Eucalypts have long been considered landscape trees but are now in demand because of their potential for short-rotation fuel biomass production. Growers need a reliable source of rapidly growing planting stock. To provide information for that purpose, species and provenance tests have been and are being conducted.

To bring together researchers working with eucalypts to define the state of our knowledge about the genus, "A Workshop on *Eucalyptus* in California" was held June 14 to 16, 1983, in Sacramento, California. It was sponsored by the Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley, California, and Cooperative Extension, University of California, Berkeley, California.

Speakers from California, Florida, Hawaii, Oregon, and France presented information about advanced breeding programs and discussed how their results and methods could be applied in California. Major topics included species selection, products, uses, and economics, growth and yield, cultural requirements, breeding programs, and propagation

To expedite the publication of the Proceedings, we asked each author to assume full responsibility for submitting manuscripts in photoready format by the time the conference convened. The views expressed in each paper are those of the author and not necessarily those of the sponsoring organizations. Trade names are used solely for necessary information and do not imply endorsement by sponsoring organizations.

These Proceedings will serve as a useful reference for landowners, foresters, nurserymen, and horticulturists who are considering planting species of this versatile and useful genus—the *Eucalyptus*.

Technical Coordinators:
Richard B. Standiford
Cooperative Extension, University of California
F. Thomas Ledig
Pacific Southwest Forest and Range Experiment Station

Eucalyptus Helped Solve a Timber Problem: 1853-1880[1]

Gayle M. Groenendaal[2]

Abstract: Eucalyptus were introduced into California in 1853 as an ornamental by Capt. Robert Waterman. However, due to the destruction of the native woodlands and forests, people became concerned about future supplies of fuel and timber and began to experiment with different types of trees to plant. Eucalyptus became a favorite after 1870, because it was fast growing, was believed to be of great medicinal value, and was supposedly fireproof. By 1880, the eucalyptus were widely planted throughout the state and today many of these early plantings remain to remind Californians of the first energy crisis in California.

California was settled in an era before the full impact of the industrial revolution that was taking place in Great Britain was fully realized, a revolution that was to change the course of western culture more drastically than any previous time in history. Friedrich Engels wrote in 1845 of the industrial revolution as "a revolution which at the same time changed the whole of civil society, and the significance of which for the history of the world is only now beginning to be understood" (Tucker 1972). Society of today tends to forget the needs of the historic peoples before machinery, electricity and advanced technology changed the standards of living. It is only by reading the newspapers, including the advertisements, journals, and books of the previous era do we begin to understand the daily lives and needs of these people. It is through such research that the author has tried to piece together the eucalyptus story in California. In the following article, the impending timber crisis is described, laying the framework for the wholesale planting of eucalyptus in California. Why eucalyptus were chosen will be dealt with in the second part of the article including some of the history of the introduction of the genus to the state.

THE TIMBER PROBLEM--THE BEGINNINGS

Let us consider for a moment the impact of the immigrant population on the environments of California in the early 1850's. Both Sacramento and San Francisco had been small settlements with few inhabitants in 1848. Many of the later boomtowns were located in the foothills in regions that had for centuries been populated with Native Americans with small populations, more or less in harmony with the environment. Within a year, 80,000 gold seekers had passed through or settled in these areas (Bancroft 1890). Tent cities were established to house the new settlers. Urban infrastructures were insufficient or totally lacking--there were no sewage systems, water lines, roads, mail service, transportation facilites, nor fuel supplies (Taylor 1867).

San Francisco was an area of oak woodland and grass, and Sacramento was located in the tules at the confluence of the Sacramento and the American Rivers. Many of the new boomtowns were at first located in the scattered oaks and grasslands of the foothills. None were located in areas of extensive forests, and soon the oaks were gone (Taylor 1867).

As the Bay area and the valley became more and more settled, the need for timber and timber products grew. Lumber was needed for building more permanent structures, including sidewalks, fuel for heating, cooking, and steam production. Everything was built of wood: carriages, wagons, stages, sleds, farm implements, tools for mining timber for weirs and sluices for the gold recovery, and later timber for the mine shafts (Bancroft 1890; Taylor 1867). The list could go on and on.

Timber was abundant in some areas, too much so for the early settlers. Their first thought was of food production and how to clear the land cheaply and easily for crops. Fire was the great land clearer, and in the early 1850's great forests were fired to clear the land rapidly. Soon the timber receded, and the ox teams and skid roads came into being. The very size of the lumber, its location in rugged sites, and its distance from the greatest consuming centers was to bring about a destructiveness that would later motivate the movement by John Muir and others to try to enforce conservation practices (Bancroft 1890; Groenendaal 1983; Sparhawk 1949).

In California Life Illustrated, Reverend (later Bishop) William Taylor writes of the early days in San Francisco in 1849, where firewood was selling for $40.00 a cord. He describes his neighborhood:

> "The sand hills back of where I lived had been thickly covered with evergreen scrub oaks, but they had all been cut off, clean as a newly mown meadow."

The need for fuel was already felt in other parts of California by 1855, as witnessed by a notice to trespassers by John A. Sutter of Sacramento, published in the California Farmer on May 24th, warning that those who cut timber and

---

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Research Associate, Paleobiology Laboratory, University of California, Los Angeles.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

cordwood would be subject to punishment. As settlers spread out over the land, fuel became more precious and harder to obtain.

As early as 1858, Colonel James L. L. Warren was running feature articles in the California Farmer on planting trees for the future needs of the people. He introduces one article as follows:

"The following excellent article we clip from the Germantown (Pa.) Telegraph. It contains many valuable hints worthy of notice, and those who look over our State, can see how many thousands of acres might be improved in the vicinity of farms, that would add to their beauty and value. The day is not far distant when firewood will be wanted, and such labor now 'will pay'".

The article that he was referring to is entitled Planting Trees and gave a description of the silviculture of European countries that were in the habit of setting out forest trees," to supply the places of those which have been consumed to supply material for fires, and artistic and mechanical purposes."

The California Culturist ran an article dated July, 1860 stating:

"Not the least in importance among the many subjects interesting to agriculturists, as also to many others of our population, is that of the question--where are we to obtain our supply of firewood in the future? Taking, for example, that portion of the country known as the Bay district, we find the supply already almost exhausted. The trees which formerly stood on the hills of Contra Costa and Alameda, visible from the bay, are to be seen no more. The magnificent oak groves of Oakland and the Encinal have been so thinned and mutilated to furnish a supply of fuel, that the residents of those vicinities have awakened to the fact that in order to retain a shelter from the strong summer winds, they must abstain from destroying their trees.

Farmers cannot afford to pay the price which is demanded for coal; but as that will before long be as cheap as wood, or, as we should say, wood will be as expensive as coal, it is extremely desirable that we should 'take time by the forelock' and devise some plant for remedying the evil."

On May 4, 1860, Warren published an article in the California Farmer that had been written for the San Andreas Independent entitled, Destruction of the Forest. It read as follows:

"But two or three years ago, all the hills immediately surrounding our mountain towns, were overgrown with magnificent oaks and ornamental manzanitas. Most of the once proud oaks have been wasted: the American with his span of mules, carried away the larger branches in cord-wood; then came the hyena pack-trains of Asia, cutting up the smallest branches, thinning the chaparral, and laying waste all that is ornamental. The huge trunks are generally left to decay where they fell. Our people have been sadly extravagant in this matter; and they may be sure that the day is not far distant, when this immense waste of timber will be unavailingly regretted. Wood is now six dollars a cord. In two years it will be eight dollars."

A paper by the Reverend Frederick Starr, in the report of the Department of Agriculture for 1865, predicted a timber famine within 30 years and advocated the immediate undertaking of carefully planned research on how to manage forest and how to establish plantations, especially of the hardwood trees. This paper was to play an important role in the nation. It became an impetus of the forest movement that would eventually see the founding of the U.S. Forest Service, it was also a prime force behind the development of the Eucalyptus Boom in California (Sparhawk 1949).

C. F. Reed, the President of the State Board of Agriculture in California, wrote in his report to the Board in 1869:

"The subject of a plentiful supply of lumber and wood, for the various purposes of life, is one that we cannot much longer neglect. Whoever takes the trouble to look this subject fully in the face, and reflects upon the future of California, must feel, as we do, that something should be done, and that immediately, looking to the substitution of new forest in the place of the old ones in our State, now so rapidly being consumed and destroyed..."

He continues in a later section, "It is now but about twenty years since the consumption of timber and lumber commenced in California, and yet we have the opinion of good judges, the best lumber dealers in the State, that at least one-third of all our accessible timber of value is already consumed and destroyed! If we were to continue the consumption and destruction at the same rate in the future as in the past, it would require only forty years, therefore, to exhaust our entire present supply..."

He goes on to say, "One of the worst features of the settlement of new countries by Americans is the useless and criminal destruction of timber. In our State this reckless and improvident habit has been indulged in to an unprecedented extent.

Thousands upon thousands of the noblest and most valuable of our forest trees in the Sierra Nevada districts have been destroyed without scarcely an object or a purpose, certainly with no adequate benefit to the destroyer or to any one else. This practice cannot be condemned in too severe terms; it cannot be punished with too severe penalties."

The timber problem was not unique to California, it was a national problem. By 1868, the problem had become so acute as to cause a number of states to enact laws to encourage planting forest trees by offering bounties or by granting tax reductions or exemptions. Arbor Day was first declared and celebrated in Nebraska in 1872, at the instigation of J. Sterling Morton, later Secretary of Agriculture. Several railroad companies planted trees for ties and timber in the Great Plains and in California. But the biggest push towards planting forest trees came about when Congress passed The Timber Culture Act, in 1873. People who received free land for homesteading were required to plant forty acres of each 160-acre claim in trees. The forty acres were later reduced to ten (Sparhawk 1949).

On the Economic Value of Certain Australian Forest Trees and their Cultivation in California was published by the newly established California Academy of Sciences in San Francisco in 1871, and was the first of many papers to urge the planting of the Eucalyptus and Acacias as a solution to the growing timber famine.

Robert E. C. Stearns of the Academy wrote:

"When we consider the fact of the great number of farms in California that are nearly or wholly destitute of wood, and the great and continuous expense entailed by our system of fencing, the importance to the farmer of dedicating a portion of his land to the cultivation of forest trees, from which he can obtain fuel and fencing materials is too palpable to admit of debate..."

He continues,"Of the Eucalypti, E. globulus is very common in California, and easily cultivated: it is the Blue Gum of Victoria and Tasmania. This tree is of extremely rapid growth and attains a height of 400 feet, furnishing a first-class wood; shipbuilders get keels of this timber 120 feet long; besides this they use it extensively for planking and many other parts of the ship, and it is considered to be generally superior to American Rock Elm."

Franklin B. Hough was the first to try to bring about a systematic effort to arouse public interest in the preservation and conservative use of the natural forest areas, distinct from planting of artificial forests, in his address to the American Association for the Advancement of Science in 1873. A memorial written by the Association as a result of Hough's address was sent to Congress (Sparhawk 1949). It said:

"The preservation and growth of timber is a subject of great practical importance to the people of the United States, and is becoming every year of more and more consequence, from the increasing demand for its use; and while this rapid exhaustion is taking place, there is no effectual provision against waste or for the renewal of supply..."

H. H. Bancroft tells the California timber story in his History of California published in 1890. He writes:

"The area covered by forests in California is very small in proportion to its size, 478,000 acres in total acreage of 11,400,000, according to the forestry statistics in U.S. Agriculture Report of 1875, which place it lowest among the 36 states there listed. This gives an average of only 4.0 per cent of forest land, San Diego and Alameda (counties) ranking lowest, with 0.1 and 1.2 per cent, and Nevada, Mariposa, and Santa Cruz (counties) highest, with 55.9, 53.2 and 52.8 per cent, respectively. The valuable timber belts are confined to the humid coast and mountain regions in central and northern parts, from 37° latitude to the Oregon border; and the interior valleys and the south are comparatively bare, relieved by clumps along the streams, and occasionally by a scanty vegetation on the less arid north side of the hills...

Under all the inroads, favored by the small value of land in early days, there has been a great waste of forest resources, and in spots accessible for shipping and near settlements, as in Santa Cruz and San Mateo, and in the mining belt, there is little timber left, large districts being entirely denuded. Before the U.S. occupation, forest fires regularly devastated large sections owing to the custom, among Indians especially, of thus gathering insects and other articles of food. This is one of the evident checks to forests in the valleys. Subsequently shepherds and hunters were in the habit of firing large tracts to promote the growth of pastures. Sheep in particular have kept down the renewal of forest by eating the shoots..."

After this description of waste, Bancroft goes on to contradict this evidence by saying,

"Yet, after all, the inroads upon timber do not affect more than one-fifth of the entire area, and most of this is renewing itself, so that the supply is practically inexhaustible. This is notably the case in the redwoods and partly in the mining belt, and it is believed that the Truckee region will also revive. Laws have been passed for the protection of forests, but with little effect...There is a further compensation in the artificial planting of trees, fostered by the state, and latterly by arbor-day festivals. This is extended not alone to roads and settlements, for shade, screen, and embellishment, but to entire groves of forest dimensions, for fuel and industrial purposes, notably for remedying the lack of hard wood sufficient to supply in due time the demand and to balance destruction elsewhere. The sycamore, willow, and cottonwood grow readily, for fences and fuel, also lombardy poplar, but the black locust and especially the eucalyptus are most widely planted, the latter promising to prove very desirable for elasticity and hardness."

Nelson Courtlandt Brown wrote as late as 1919,

" over one-half of our population live in wooden houses and two-thirds of the population use wood for fuel."

He gives the rates of consumption for 1880 as 18 billion board feet as compared to 40 billion board feet for 1919. He sums up the timber problem that was plaguing the nation in the following sentence.

"We are using our forests three times as fast as they grow."

After 1868, tree planting the United States had become a patriotic duty. Articles appeared urging the planting of trees to stave off the impending timber famine. California began to heed the call with the rest of the nation and commenced planting trees. the California State Agricultural Society offered a premium of $50.00 to be awarded to the best timber plantings in the winter of 1870. The California Horticulturist commented on the situation in the following article in August of 1876.

"In California everything is done on a large scale if at all. Grape vines are planted by the hundreds of thousands, and wheat fields extend to thousands of acres, and the groves of forest trees are what in the East would be called extensive forests.

Of late Californians have commenced the planting of forest trees, and this, too, upon the same extended scale which marks all their operations. The Blue Gum tree at present being a general favorite..."

Why were bluegums the present favorite? Why were they chosen over better timber trees and thousands planted over the countryside to such an extent that even today the horizon of California is dotted with the remnants of the 19th century plantings? The answer lies in the needs of the populace of the 1800's.

EUCALYPTUS--INTRODUCTION AND USAGE

Californians were not the only people who had become enchanted with the eucalyptus trees. A Frenchman, Prosper Ramel, traveled to Australia as a trader in 1854, where he visited the Botanical Gardens in Melbourne. He saw his first Tasmanian bluegum in the gardens and was so taken by the phenomenal vigour of this species of tree that he became determined to promote this tree in the old world. He saw it covering the mountains of Algeria, making marshes salubrious and chasing away fever. He was aided to this end by Ferdinand von Mueller, the most famous of all the early Australian botanists (the first to classify and systematize the genus *Eucalyptus*). Between 1855 and 1857, they pushed enthusiastically and perseveringly for culture of the bluegum on a forestral scale overseas (Zacharin 1978).

France was to play a very important role in the eucalyptus transfer story. (Although, they do not grow well there except along the Mediterranean coast from Cannes to Monaco and on the island of Corsica.) French botanists and gardeners were pioneers in studying the eucalyptus and it was through their efforts that France was to become the key distributing point for the secondary transfer of seeds and knowledge of the eucalyptus to southern Europe, Africa, and the United States (McClatchie 1902; Zacharin 1978).

It was due to the research done on the eucalyptus in France and the Mediterranean countries that gave rise to the fable that eucalyptus, especially *Eucalyptus globulus* (Labill.), could purify the air and eliminate malaria. Medicinal properties of all kinds were attributed to the oil, leaves and bark of the tree. *Eucalyptus globulus* became known as the fever or miracle tree (McClatchie 1902; Pacific Rural Press 1870-1880; Zacharin 1978).

Eucalyptus globulus is a fast growing hardwood tree, obtaining a growth of twenty feet per year.

The wood is dense and burns well. A plantation of globulus can be harvested every seven years for firewood without harm to the tree, as it coppices from the roots and can be harvested continuously without replanting. Globulus grows well in a variety of soils, including many poor soils, and can survive with a minimum of rainfall. One limiting factor is freezing weather, which it cannot tolerant for any length of time without killing the tree. These facts, taken together with the supposed medicinal uses, made the tree a very valuable tree. It is little wonder that the people, not only in California, but also in China, India, Portugal, Spain, South Africa and South America began to plant the tree by the thousands (Penfold and Willis 1969).

Eucalyptus were introduced into California as an ornamental by clipper ship Captain Robert H. Waterman in 1853. In a biography of Waterman, David A. Weir (1957) reports that Waterman had a dream when he retired from the sea and that dream was to plant a "heap o' trees." On retirement, Waterman set forth to accomplish that dream.

Waterman bought an undivided half interest in a twelve-mile square tract of land in Suisun Valley in 1850 with another sea captain, A. A. Ritchie, as his partner. The Captain laid out the cities of Fairfield and Cordelia, which he named for his wife, in Solano County. He hired Josiah Allison, a horticultural expert, to help him landscape his towns and his own ranch home. Waterman, accompanied by Allison and Ritchie traveled the immense Suisun Valley and surveyed the boundaries, staked out roads, and marked future tree locations (Weir 1957).

Waterman commissioned his ex-first mate, Jim Douglass, to bring him some eucalyptus seeds on his next voyage to Australia. In 1853, records Weir, Douglas brought the Captain a bag of bluegum seed, and from these seeds came the stands of eucalypts that are still growing around the Captain's home and along many of the roads of the Suisun Valley. Waterman reportedly gave seeds of the eucalyptus to the new settlers of Fairfield and to his friends in other areas (Weir 1957). This is the first record identifying the genus Eucalyptus with sailing vessels and tied them to the trade that must have brought them from the Australian continent to the California coast.

Two turn-of-the-century writers, Alfred J. McClatchie and C. H. Sellers, identified William C. Walker as introducing 14 species of eucalyptus in 1856. Abbott Kinney, another writer on eucalyptus credits C. L. Reimer as introducing 14 species in January of 1856. Other writers have claimed Bishop William Taylor introduced the genus. Based on the surviving records, Waterman introduced eucalyptus, while R. W. Washburn, owner of the Shell Mound Nursery of Alameda, was the first tradesman to list the genus for sale in his one page catalog for 1856 (Brown 1982). The late Charles Shinn, whose father, James Shinn, owned the Shinn Nursery in Niles, California, and whose uncle, Charles Shinn, was the editor of The California Horticulturist, wrote to the Oakland Tribune in 1936 that Colonel James L. L. Warren, editor and owner of the California Farmer," widely advertised and distributed seeds, especially E. globulus as early as 1856."

Very little is known of Washburn, and what is known has been gleaned from the California Farmer between the years 1858-1860. According to the Farmer, "R. W. Washburn of the Shell Mound, made a handsome display of fruit," at the State Horticultural Society meeting in 1858. Washburn's ad of March 23, 1860 stated that Shell Mound had been awarded the First Premium for the best nursery by the Alameda County Agricultural Society; that twelve Premiums were awarded by the California Horticultural Society in 1859; and that two diplomas by the Sonoma and Contra Costa Agricultural Societies had been awarded them. However, in the February 8, 1861 advertisement for Shell Mound, Mr. L. A. Gould, was listed as the proprietor. Neither the nursery nor Washburn is mentioned in later years in the California Horticulturist nor in the Pacific Rural Press (Groenendaal 1983).

William C. Walker, owner of the Golden Gate Nursery in San Francisco from 1849-1865, has been given the credit for the introduction of eucalyptus by most authorities. While he may not have introduced the genus, he wass the first to list the different species that he had in stock in his nursery catalog dated 1858-59 (Brown 1982; Butterfield 1938; Butterfield and Eastwood Letters). Col. Warren of the California Farmer considered the Golden Gate Nursery in 1856 to have, "the largest and most choice collection of plants in the state...[and was] very liberal in introducing in the country many new and rare plants of great value." He first introduced the term Eucalyptus into his advertisements June 26, 1857, but no species were listed, only the genus name. He continued to advertise the nursery in the Farmer until the early 1860s.

Stephen Nolan, owner of the Bellevue Nursery established in 1860 in Oakland, was an active promoter of eucalyptus and had the most extensive offerings of different species. Nolan had imported seed from Australia in 1860 and planted them in 1861. By 1871, his nursery catalog listed 34 different species (Brown 1982; Butterfield 1935). His nursery was described in the January 23, 1875 issue of the Pacific Rural Press. The article describes many of the trees that were found in the nursery at that time, but of particular interest was the following passage:

> "We were especially pleased with the great variety and fine specimens of Australian gums, and with one among them just suited for the crests of those apparently barren hills away in the distance. The eyes of our friend

> "lighted with enthusiasm of Nature's poet as he pictured the day when that landscape would be relieved and the whole country fertilized by these magnificent trees..."

Southward, near Alameda, another importer was busy. This was Annie Taylor, wife of Bishop William Taylor. Bishop Taylor left San Francisco in May of 1862 to do missionary work in Australia. In his autobiography, The Story of My Life, Taylor wrote:

> "There were no Eucalyptus in California in 1849. I sent seed from Australia to my wife in California in 1863. Her seed sowing made such a marvelous growth that a horticulturist neighbor of ours wrote me to send him a pound of seed--the smallest of all seeds, and the nurseries, thus seeded, dotted the whole country with great forests of evergreens, the most prominent land marks [sic] of the Pacific Coast."

Many people have taken Bishop Taylor's statement in his autobiography to mean that he introduced the eucalyptus to California, but this was explained in a brochure that was written by his son, William, and distributed at the Bishop's funeral. According to the brochure, the eucalyptus trees were widespread in California when Bishop Taylor left for Australia, and it was their popularity that led him to send the seed to his wife (Oakland Tribune 1936).

Annie Taylor gave many of the seeds to James T. Stratton, the Surveyor-General of California. Stratton planted and propagated the bluegums to such an extent that by 1870, he had the largest commercial eucalyptus planting in the state (Transactions of the California State Agricultural Society 1870-71).

Up until this date the eucalyptus had been used mainly as ornamentals and, as such, many of the early pioneers of California had planted them to a limited extent. Only a few of these early plantings will be noted here. Captain Joseph A. Aram planted good sized groves of Eucalyptus globulus and Eucalyptus camaldulensis in the early 1860s. The first supply of seed to reach southern California was sent in 1863 by "an Australian missionary" (Reverend Taylor?), the seeds were divided among the large land holders of the area: Verdugo, Workman, Banning, Sanchez, and Wolfskill (Padilla 1961). General Henry M. Naglee planted about sixty acres of mixed eucalyptus trees in 1866, that were reported to be eighty feet tall with diameters of eighteen inches in 1876. There are records of more plantings during this period that are covered more extensively by Groenendaal (1983).

To promote commercial planting of forest trees, the California State Agricultural Society in 1870 offered a premium of $50.00 for the largest quantity of useful trees to be planted during the year. James T. Stratton won the premium by demonstrating that he had planted fifty-three and one-half acres of Eucalyptus globulus and three thousand Eucalyptus camaldulensis (Dehnh.) trees (Transactions of the California State Agricultural Society 1870-71). This was the birth of a new era for the eucalyptus trees in California, from this date forward the trees would be planted mainly as a commercial venture instead of as an ornamental.

Throughout the pages of The California Horticulturist and The Pacific Rural Press, Stratton's premium winning forest can be followed over the years. The California Horticulturist carries this article in 1874.

> "...When Gen. Stratton was setting out the trees, the neighboring farmers laughed at him and advised him to desist and attend to his surveying, as he would be dead long before the timber would amount to anything; but the laugh is now on the other side. Five years hence the available timber will be immensely valuable for manufacturing and for firewood...No doubt General Stratton's foresight in planting these extensive and beautiful groves will produce not only cords of wood but cords of money; for, if cut down and sold now, at the age of only four years, the young forest would bring many thousands of dollars."

In the first volume of the California Horticulturist (1870), Professor Henry Nicholas Bolander of the California Academy of Sciences published a lengthy article on the eucalyptus, explaining that such a paper has become a necessity because eucalyptus are so extensively planted in California. He quoted Ferdinand von Mueller's work in which von Mueller envisions,

> "Even the rugged escarpments of the desolate ranges of Tunis, Algiers and Morocco, might become wooded; even the Sahara itself, if it could not be conquered and rendered habitable, might have the extent of its oases vastly augmented. Fertility might be secured again to the Holy Land, and rain to the Asiatic plateau or the desert of Atacama, or timber and fuel be furnished to Natal and La Plata. An experiment instituted on a bare ridge near Melbourne demonstrates what may be done."

In 1870, a man settled in Santa Barbara who would do more to publicize the eucalyptus than any man of this era. This was the Honorable Ellwood Cooper, a wealthy gentleman who was retiring from diplomatic service. In 1872, he purchased a pocket ranch (2,000 acres) twelve miles west of Santa Barbara and named it Dos Pueblos Ranch, where he began to experiment with eucalyptus. Cooper wrote to James McClatchie in 1900 about his interest in eucalyptus:

> "There were Blue Gum trees growing in the state during my first visit in 1868. I saw a few specimens in private gardens from ten to twenty feet high; was attracted to their beauty; so that when I located in Santa Barbara in 1870, I at once conceived the idea of forest planting (McClatchie 1902)."

The ranch was a desolate spot when he bought it, covered with scrub and a few oaks, but within a few years, it became a show place, featuring many species of eucalyptus. Taking advantage of a previous acquaintance with Thomas Adamson, Jr., the United States Consul General at Melbourne, Australia, Cooper wrote to him asking for seeds of different species and asked for books or information on the eucalyptus. Adamson sent him seeds and informed Cooper that Ferdinand von Mueller, the government botanist, had delivered some lectures on the subject. The lectures had been printed, but all had been sent to London. However, von Mueller would send one of his originals, provided Cooper would have it printed in America and return to him fifty copies. Cooper, using von Mueller's propagation and culture notes, planted the seeds that Adamson had sent him (Warren 1962).

In 1876, Cooper was asked to give a lecture to the college of Santa Barbara, of which he was the president. He combined his interest in eucalyptus and the need to promote forestry in his lecture. The lecture was so well received that he was asked to publish it. This led to his book on the subject, Forest Culture and Eucalyptus Trees. Cooper's book makes an emotional appeal to forest the slopes of California with eucalyptus trees to counterbalance the destruction of the hardwood forests on the eastern seaboard. His speech was published along with Ferdinand von Mueller's lectures, keeping his promise to have the material published in America. In the book, Cooper writes of his own plantation:

> "At my home I have growing about 50,000 trees. The oldest were transplanted three years ago. A tree three years and two months from the seed, transplanted two years and ten months ago is nine and one-half inches in diameter and forty feet and six inches high (Cooper 1876)."

The rapid growth of the eucalyptus trees began to excite farmers. It seemed practical after all to plant forest trees, that would mature in one's lifetime, and could be harvested in only seven years for firewood. Soon the Rural Press, The California Horticulturist and The California Culturist ran articles in nearly every edition describing the new plantings. One such article published in the Pacific Rural Press in 1874 describes the growth:

> "The rapid growth of the eucalyptus is wonderful. Anson Goodspeed has on his lot in north Healdsburg some trees which have grown 40 feet in two years, and others 22 feet in 18 months..."

However, it was not just the rapid growth of the trees that convinced the farmers to plant eucalyptus trees. Reports of the medicinal uses of eucalyptus trees were also reported in the press. Claims were made for the eucalyptus as an anti-malarial antidote; bronchial and pulmonary complaints could be cured by smoking the leaves; drinking eucalyptus tea would clean the system; and cholera epidemics were stemmed by planting eucalyptus around living quarters. The Pacific Rural Press ran several articles over the years on the subject, the most extensive one published on April 5, 1879.

The eucalyptus were also reported to be fireproof. On October 20, 1877, an article was published in the Pacific Rural Press called attention to a tree standing on the grounds of the old German hospital on Brannan street that had passed through the fire of August 1876 seemingly unharmed. This was reported at a meeting held at the Academy of Sciences. In that same meeting, Dr. Gibbon proposed that the planting of eucalyptus trees along public streets would be an important means of checking a conflagration, while Dr. Albert Kellogg stated that eucalyptus shingles were used on houses in Australia and added that it was impossible to fire a roof made of this material; he further suggested that Californians would be wise in following the Australian's example.

The attributes of the eucalyptus filled the pages of the early press reaching its zenith when the Central and Southern Pacific Railroads made public its intentions in January of 1877 to plant eucalyptus along the entire line of both roads. The railroad companies saw great advantages in these plantings: they would have a constant supply of timber suitable for repairing the roads; the fall of rain would be increased by the trees and the climate modified; and they would absorb malarial poisons along the lines (Pacific Rural Press 1877).

By the mid-1870s the planting of eucalyptus was so evident in California that visitors to the state remarked on their prominence. Mary Cone mentions in her book, Two Years in California, published in 1876 that the eucalyptus were a great favorite and were "much" cultivated. Ludwig Salvatore wrote in his book, Los Angeles in the Sunny Seventies: A Flower from the Golden Land,

> "The largest forest is on the Anaheim branch of the Southern Pacific at a point where it crosses the San Gabriel

River, about twelve miles from Los Angeles, where 190,000 trees have been set out. This forest belongs to the Forest Grove Association of which Judge [R. M.] Widney is president. In December [1874] ten pounds of seed were brought down from San Francisco, and the seeds planted in a nursery. When two months old, the shoots were transplanted into a lot box and set two inches apart. By April [1875], the young plants had a height of 9 or 10 inches, and at that time they were set out in the ground ten feet apart. Within a year they were from 9 to 12 feet high (Padilla 1961)."

By 1880 over fifty groves had been planted in eucalyptus (mainly E. globulus) amounting to several thousand acres (Groenendaal 1983). The first Eucalyptus Boom was beginning to take place (the second boom would occur in the early 1900s). Farmers heeding the cry to plant fuelwood and timber could see the advantages (the disadvantages not being known at this time) in planting eucalyptus trees. Eucalyptus would give them fuel and timber, cure their ills, prevent conflagrations, and turn a profit in a very short time. It truly was considered the miracle tree.

REFERENCES

Bancroft, Hubert H. History of California. Vol. VII. San Francisco: The History Company Publishers; 1890:75-78.
Bolander, Professor. Austalian Gum Trees. California Horticulturist I:50-54; 1870.
Brown, Nelson C. Forest products their manufacture and use. New York: John Wiley and Sons, Inc.; 1919:340.
Brown, Thomas. A list of California nurseries and their catalogues 1850-1900. Berkeley: Univ. of Calif.; 1982. 56 p.
Butterfield, H. M. The introduction of Eucalyptus into California. Madrono 3:149-154; 1935.
Butterfield, H. M.; Alice Eastwood Letters. Unpublished. San Francisco: California Academy of Sciences. 1935, 1941, 1943, 1946.
California Culturist. Los Angeles. 19-20, 31; 1859-1860.
California Farmer. Warren, James L. L., owner and editor. Sacramento and San Francisco; 1858-1870.
California Horticulturist and Floral Magazine. Shinn, Charles, H., ed. San Francisco: John H. Carmany and Company; 1870-1880.
Cone, Mary. Two years in California. Chicago: S. C. Griggs and Company; 1876:82.
Cooper, Ellwood. Forest culture and eucalyptus trees. San Francisco: Cubver and Company; 1876:18.
Groenendaal, Gayle M. History of eucalyptus in California, 1853-1880. Northridge: California State University; 1983. 150 p. Thesis in progress.
Hall, Norman. Botanists of the eucalypts. Australia: Commonwealth Scientific and Industrial Research; 1978. 160 p.
Kinney, Abbott. Eucalyptus. Los Angeles: B. R. Baumgardt and Company; 1895. 306 p.
McClatchie, Alfred James. Eucalyptus cultivated in the United States. Bulletin No. 35 Washington, DC: Government Printing Office; 1902:18.
Our first eucalyptus, Bishop Taylor's gift, and Oakland had a part. Oakland Tribune. 1936 May 31:1. Oakland.
Pacific Rural Press. San Francisco: Dewey and Company Publishers; 1870-1880.
Padilla, Victoria. Southern California gardens. Berkeley and Los Angeles: University of California Press; 1961:43-57.
Penfold, A. R.; Willis, J. L. The eucalypts, botany, cultivation, chemistry, and utilization. New York: Interscience Publishers, Inc.; 1969. 559 p.
Sparhawk, W. N. The history of forestry in America. Trees, Yearbook of Agriculture. Washington, DC: U.S. Government Printing Office; 1949:701-714.
Sellers, C. H. Eucalyptus, its history, growth, and utilization. Sacramento: A. J. Johnston Company, Printer; 1910. 93 p.
Taylor, William. California life illustrated. London: Jackson, Walford, and Hodder; 1867. 393 p.
Transactions of the California State Agricultural Society. Sacramento: O. M. Clayes, State Printer; 1868-73:28-35.
Tucker, Albert. A history of English civilization. London: Harper and Row; 1972:535.
Warren, Viola L. The eucalyptus crusade. The Historical Society of southern California, Quarterly Volume. 44:31-42; 1962.
Weir, David Andrew. That fabulous Captain Waterman. New York: Comet Press Books; 1957. 111 p.
Zacharin, Robert F. Emigrant eucalypts. Australia: Melbourne University Press; 1978. 129 p.

Part 2. Species Selection

Adaptability of Some *Eucalyptus* Species in Southwest Oregon[1]

Lee O. Hunt[2]

Abstract: Professional and official attitudes and reports discourage the use of exotics in the Northwest. Not only will the small woodland owner fail to make a reasonable return on his investment in growing native trees, he may not live long enough to harvest a crop. Short rotation alternatives are sought by using certain species of Eucalypts. Adaptability of such species is sought by outplanting plots in Douglas County. Considerable data has been accumulated on cold tolerance, survival, juvenile growth and deer damage to the species planted. Certain species appear to be adapted in southwest Oregon.

One of my forestry professors in the late twenties expressed the view that by midcentury all the commercial timber in western Oregon would be cut. His definition of commercial timber was strictly old-growth Douglas-fir within easy reach of the major waterways. He was substantially correct since logging trucks, cats, mobile skidders, and loaders, etc., had yet to appear on the scene.

As late as the early seventies no less an authority than Dr. Roy Silen, Principal Geneticist of the Pacific Northwest Forest and Range Experiment Station expressed the view that there was no place in the Northwest for exotic forest tree species. On the basis of his studies at the Wind River Experimental Forest in central Washington, he indicated that no exotic species of forest trees could successfully compete or produce the volume and quality of timber that Douglas-fir and associated conifers can.

Only about a year ago the Oregon State Department of Forestry agreed to recognize any hardwood species as acceptable to meet the reforestation requirements of the State's Forest Practices Act. Further, in their standards for qualifying under the Western Oregon Small Tract (Forest) Optional Tax program they set a rotation of 60 years for Site Classes I and II, Douglas-fir, and 90 years for Site Classes III through V. Forest land taxes in Oregon are substantially higher than those for Washington. Over 93 percent of forest land in southwest Oregon is Site III or below; over two-thirds of this is in the two lower Site Classes, IV and V.

Several cost and return workshops on growing Douglas-fir forest crops have shown that using a discount rate of 8 to 10 percent and a 60-year rotation will inevitably fail to yield the grower a reasonable return on his investment.

With that background of professional and official policies and attitudes, there were virtually no incentives for the non-industrial forest land owners to grow crops of trees which they would have little likelihood of harvesting in their lifetimes. The screening of trials of Eucalyptus species were a part of a personal program to try to find some alternatives to the 60- to 90-year rotations considered necessary to grow a crop of merchantable trees.

One can wonder why anyone in their right mind would consider spending money to grow Eucalyptus in southwestern Oregon with the professional and official attitudes plus the lack of specific knowledge on the silviculture of growing Eucalypts and an unknown market. Other disincentives include the lack of a nearby pulp market, lack of nursery stock sources, and the general antipathy toward trying untested and largely unknown species. There is a common attitude that there are no cold tolerant Eucalypts and thus they won't grow in Oregon. Even if they would survive, the wood is thought to be useful only for a low grade of firewood. This attitude is the more surprising when one sees, as I did last fall, vast areas of native Maritime pine, (Pinus pinaster Ait.) in Spain being converted to Eucalyptus and Monterey pine (Pinus radiata D. Don). Some 60 percent of the output of rayon, paper pulp and hardboard in Spain is from Eucalyptus. The expansion of Eucalyptus plantations is exploding throughout the world's milder climatic areas.

Several timber supply surveys and programs, such as Beuter, McClean, and Forestry Program for Oregon, predict as much as a 22 percent decline in timber supplies in Oregon by the end of this century. Can Eucalyptus and other short rotation tree crops fill the hiatus between the end of the old-growth native forests and the second crop? Just two years ago only about 1,000 cords of firewood were shipped from Douglas County, Oregon to California. This past season some 20,000 cords were shipped south, mostly to the San Francisco Bay Area, and almost entirely consisting of oak and madrone.

There has been a phenomenal increase in the harvesting of hardwoods, chiefly oak and madrone, in southwest Oregon in the past couple of years. Government agencies have sharply increased charges for firewood cutting permits from federal and state lands. The high cost of fossil fuels and electricity has brought on a wave of interest in wood as a fuel source. Thirty-two small woodland owners have purchased Eucalyptus seedlings this

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Private Consulting Forester and Tree Farmer

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

past season from my small backyard nursery for the express purpose of growing firewood. As I make each sale and suggest some site and cultural requirements I shudder a bit because of the lack of specific data on species requirements, growth, yield, wood properties, and, of course, their cold and drought tolerances. However, I can take some consolation in the fact that at my age I probably won't be around to face the consequences of those recommendations.

Please forgive the lengthy introduction. I do believe we must recognize that we are entering a new field, one in which few professional foresters are interested or will accept. Now let us take a look at the chain of events that has brought us the limited amount of information on the adaptability of Eucalypts in southwest Oregon. Correspondence with CSIRO (Commonwealth Scientific and Industrial Research Organization), the research group in Australia, brought 14 packets of Eucalyptus seed to us in 1971. These species are included in table 1.

Table 1--List of Eucalyptus Species in Original Field Trials

E. amygdalina	E. grandis
E. dalrympleana	E. nitens
E. delagatensis	E. obliqua
E. fastigata	E. ovata
E. fraxinoides	E. regnans
E. flaucenscens	E. subcrenulata
E. globulus	E. viminalis

These species were recommended as being the better timber species with some cold tolerance. They were grown in Spencer-LeMaire Tinus Root-trainer containers for one growing season. They were out-planted in the early winter of 1972-73 in replicated plots at elevations of about 500 to 2,500 feet. Perhaps fortunately, the midwinter following these out-planting recorded the lowest temperatures in about two decades. Lows at 0°F and below occurred in all plot locations. All species were killed outright or frozen back to the ground. Only a few specimen of Eucalyptus dalrympleana, delagatensis, glaucescens and nitens survived at all. These four species were replanted in new plots during the 1974 through 1977 seasons. Temperatures during these four years were moderate with minimums of 12° to 15°F. Only minor frost damage was noted and growth was generally good.

Early season rains occurred in late August and early September of 1978. This was followed by warm sunny weather for the next six weeks. The trees continued to grow vigorously during this early fall period. During the second week in November temperatures dropped 40° to 50°F over night to lows of 5° to 10°F. Almost all trees of all species were wiped out. Some few larger trees from earlier plots were killed, others badly damaged. All of these plots were in the interior valleys and foothills of Douglas County. One plot located near Bridge, along Highway 42 on the west slope of the Coast Range, showed only minor frost damage to a few trees of any of the species at a minimum temperature of about 140°F. These trees have shown remarkable growth even with considerable native hardwood competition. Insofar as the interior valleys and foothills of southwest Oregon were concerned we were again back at square one.

Another plot was established in the spring of 1978 on the Schofield Creek drainage near Reedsport, Oregon, some 10 miles from the coast. This was Site Class II land owned by Douglas County and had been previously planted to Douglas-fir nursery stock. Table 2 indicates the survival and average growth of the species at the age of 5 years, along with the seed source elevations in feet.

Table 2--Survival and Average Growth of Species, Age 5 years

Tree Species Tree Species Name	Seed Source Elev.	Averages for Trees Survival Percent	Ht. Ft.	DBH Inch
E. dalrympleana	3800	79	27.6	5.4
E. delegatensis	4500	67	35.6	6.0
E. gunnii	3200	71	22.6	2.9
E. johnstoni	1800	67	29.5	3.3
E. nitens	4000	75	30.8	5.8
E. urnigera	3000	71	24.3	2.9

In the coastal areas of southwest Oregon, these three Eucalyptus species appear to be out-growing Red Alder by almost 2 to 1, as shown in figure 1. The widespread use of Eucalyptus species throughout the world would make one suspect that they are superior to red alder for chip production, both in volume and quality.

Additional plots were established in late summer and early fall of 1979 on our tree farm near Winston, Oregon. Species planted again included E. dalrympleana, delagatensis, gunnii, and nitens. New species were added, including archeri, pauciflora, and urnigera. The following winter saw temperatures drop to 2°F at the planting sites. Table 3 shows an evaluation of the frost damage that was sustained by these species.

The winters of 1981 and 82 were very mild and no additional frost damage was observed at minimums above 15°F. These results would indicate that only E. archeri, gunnii, glaucescens, and urnigera can be considered suitable at this time for the interior valleys of southwest Oregon.

Several other species have been out-planted for cold tolerant screening the past two years, but

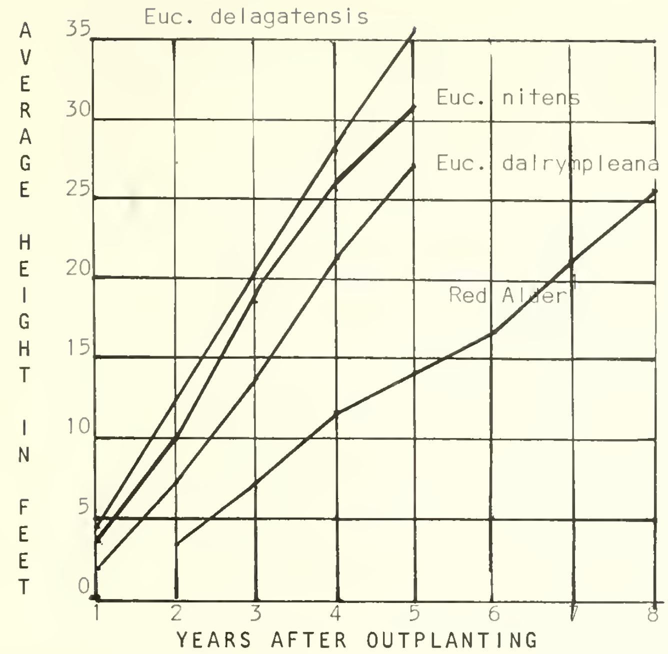


Figure 1--Comparison of early growth for three of the Eucalyptus species and that of Red Alder (Alnus rubra Bong).[1]

[1]Data from: DeBell, Dean S. and Wilson, Boyd C. Natural Variation in Red Alder. Utilization and Management of Alder (Symposium Proceedings) 1978. Published by PNW Forest and Range Experiment Station, Portland, Oregon.

they have not gone through even a moderately severe winter. Thus, they have not had a sufficient test to evaluate them. Included in these last out-plantings are Eucalyptus camphora, cinerea, divaricata, globulus (Barnback seed source), irbyl,

Table 3--Evaluation of Frost Damage

Species Name	Damage in Percent by Class[1]				
	0	1	2	3	X
E. archeri	81	16	3	0	0
E. dalrympleana	6	22	19	12	41
E. delagatensis	5	19	21	31	24
E. glaucescens	23	10	7	19	31
E. gunnii	96	4	0	0	0
E. nitens	2	14	34	34	16
E. pauciflora	0	0	8	79	13
E. urnigera	98	2	0	0	0

[1]Damage classes are: 0 - no damage observed; 1 - slight damage shown by tender tips frosted; 2 - tender tips frosted and up to 50 percent of the leaves frozen; 3 - severe, total tree frozen and killed back to the ground, but subsequently re-sprouted; X - tree killed and failed to resprout.

nova-anglica, stellulata, subcrenulata, and viminalis. Only Eucalyptus globulus sustained frost damage at the 16°F temperature of two years ago and the 21°F of this past winter.

R.L. Tichnor of the North Willamette Experiment Station, Oregon State University, has recorded more specific data on a greater number of Eucalyptus species than any other worker with whom I'm familiar. Even most of the hardier species he tested, such as Eucalyptus gunnii, pauciflora, and urnigera he found were killed by temperatures of 5° to 8°F.

Another serious problem is deer damage, both from browsing and horning of the stems of young trees. There is a wide variation to susceptibility from deer damage as indicated by table 4, compiled from a survey made in May of this year.

Table 4--Deer Damage to Certain Eucalyptus Species

Species Name	Age Yrs.	Surv Pct.	Damage Class			
			0	1	2	3
E. archeri	5	45	0.0	12.8	41.0	46.2
E. archeri	3	55	0.0	0.0	0.0	100.0
E. dalrympleana	3	50	66.7	13.3	13.4	6.6
E. divaricata	2	65	0.0	0.0	0.0	100.0
E. glaucescens	3	43	68.8	13.7	11.7	5.8
E. globulus	2	45	100.0	0.0	0.0	0.0
E. gunnii	3	33	0.0	0.0	15.4	84.6
E. irbyi	2	93	0.0	23.0	20.5	56.5
E. nitens	3	69	95.0	0.0	5.0	0.0
E. nova-anglica	2	74	100.0	0.0	0.0	0.0
E. subcrenulata	2	70	100.0	0.0	0.0	0.0
E. urnigera	3	33	7.8	23.0	30.7	38.5

Deer Damage classes are: 0 - no damage observed; 1 - light damage showing less than 40 percent of side branch tips browsed with no visible reduction in height growth, 2 - 41 to 75 percent of twigs including the leader browsed, some stunting of growth visible; 3 - severe damage with virtually all twigs including leader and most of leaves eaten, almost no height growth since planting, occasionally horned trees were girdled and killed.

A few additional species were grown this past year (1982) from seed furnished by Dr. Stanley Gessel of the University of Washington on his return from a visit to CSIRO in Australia. Dr. Gessel is carrying on some testing of Eucalypts in the Seattle area. The species included Eucalyptus cinerea, coccifera, camphora, dalrympleana, delagatensis, stellulata, and viminalis. All but two were out-planted in three separate areas in central Douglas County this late winter of 1983. They have been subjected to no less than 28°F to date and have had no substantial deer pressure.

Dr. Nicholas Malajscuk, Mycologist with CSIRO at Perth, Australia, spent a year working with Dr. James Trappe, Principal Mycologist with the Pacific Northwest Forest and Range Experiment

Station at the Forest Science Laboratory in Corvallis, Oregon, on mycorrhizae of Eucalyptus. Eucalyptus archeri, glaucescens, gunnii, and urnigera were innoculated with three species of mycorrhiza, Hynangium carneum, Scleroderma albidum and Hymenogaster albellus. Besides laboratory tests, innoculated seedlings were out-planted on our Willis Creek Tree Farm. Preliminary findings indicate that in the laboratory only Hydnangium carneum produced abundant mycorrhiza and it did so on all four of the Eucalyptus species. Field surveys will be made this year and findings will be published probably next year.

So where are we in this scramble for information on growing Eucalyptus in southwest Oregon? From observations to date, our screening tests indicate that in the interior valleys and foothills only Eucalyptus archeri, glaucescens, gunnii and urnigera have consistently shown sufficient cold tolerance to withstand our more severe winter temperatures. Of the four, Eucalyptus urnigera appears to be the fastest growing and is adapted to a wider range of sites. In four years of growth Eucalyptus dalrympleana, delagatensis and nitens show greater diameter growth than does Eucalyptus urnigera but not as much height growth. At this point my major production, if you can call some 5000 to 7000 seedlings per year a major production, is concentrated on Eucalyptus urnigera and to a lesser extent on glaucescens. Both are inherently larger trees than the other two, are about equally cold tolerant and much less susceptible to deer damage. I do find considerable frost tolerance variation among trees in the same species and even within the same seed lot.

Along the coastal strip there are greater opportunities for using other species that may yield higher volumes and perhaps better wood quality. If chips for paper pulp or hardboard is the objective of the plantations, then it would appear that Eucalyptus dalrympleana and johnstoni would be preferable since Eucalyptus nitens and delagatensis are non-sprouters. If a truly cold tolerant provenance of Eucalyptus globulus could be found it would, no doubt, produce greater volume than almost any other species. There appears to be little chance that the highly prized species, Eucalyptus grandis or regnans can be grown in the Northwest, although I still have three of the latter alive after four years. The one surviving Eucalyptus grandis has frozen back to the ground every year but this past winter. With the number of species in the genus there may be others that will prove to be valuable and adapted to this area.

I have avoided being specific about site conditions at our out-planting sites. This is due to a lack of detailed soil surveys and rainfall records in the immediate vicinity of the plantations. Generally, rainfall in the interior valleys and foothills varies from about 28 to 40 inches per year at elevations under 2000 feet. Snow is usually light and remains on the ground only a few days during the few times that snow does occur.

At the Bridge site the rainfall approaches 70 inches and in the Reedsport area from 80 to 90 inches; both areas rarely receive any snowfall.

Coastal soils tend to be deeper, more fertile and better drained than those in the interior. Soils in the interior valleys and foothills vary widely, but largely are moderate to heavy clays and clay loams, often shallow on the hills. Of special interest is the apparent ability of Eucalyptus urnigera to tolerate dense clay soils with impeded drainage. In low areas water may stand around the trees, even when young, for several days at a time without ill effects.

So far as I have been able to learn, only one timber company has initialized trials of Eucalyptus, along with cottonwood, for biomass fiber production. International Paper Company is investigating the possibility of growing Eucalyptus species on its coastal lands near their pulp mill at Gardiner. There is no firewood market for Eucalyptus in the Northwest since there are no established stands of a size to harvest. While it is premature to draw specific conclusions from the limited research I have carried on, there is a developing interest and demand, and people can be expected to plant Eucalyptus trees.

REFERENCES

Beuter, John H.; Johnson, Norman K.; Scheurman, H. Lynn. Timber for Oregon's tomorrow, an analysis of reasonably possible occurrences. Research Bulletin 19. Corvallis, OR: Forest Research Laboratory, Oregon State University; January 1976. 111 p.

Hall, Norman; Johnson, R. D.; Ghippendale, G. M. Forest trees of Australia. Canberra, Australia: Australian Government Publishing Service; 1975.

Hunt, Lee O.; Cate, Rufus. A survey of private non-industrial woodland owners of Douglas County, Oregon. Roseburg, OR: Douglas County Board of Commissioners; 1977.

Jacobs, Maxwell R. The genus eucalyptus in world forestry. Seattle, WA: College of Forest Resources, University of Washington; October 1970.

MacLean, Colin D. Timber resources of Douglas County, Oregon. Resource Bulletin PNW-66. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1976. 42 p.

Metcalf, Woodbridge. Eucalyptus species for California. Berkeley, CA: University of California Extension Service; 1967. 23 p.

Oregon State Department of Forestry. Forestry program for Oregon, timber supply today and tomorrow. Phase 1. Salem, OR: State Department of Forestry. Prepared for the people of Oregon, submitted to the Board of Forestry by State of Oregon Department of Forestry; 1977. 161 (80) p.

Oregon Department of Energy. The Oregon woodheat handbook. Salem, Oregon; 1980.

Standiford, Richard; Donaldson, Dean R.; Breece, James R. Planting eucalyptus for firewood.

(Leaflet 21297). Berkeley, CA: Univ. of California, Div. of Agric. Sci.; 1982. 4 p.
Ticknor, R. L. Landscape tree performance. Circular of Information 622. Revised. Corvallis, OR: Agricultural Experiment Station, Oregon State University; May 1974.
Turnbull, J. W. (Letter). 1975. Forestry and Timber Bureau, Department of National Development, Yarra lumla, ACT, Australia.
Vall, Charles W.; Fraser, Malcom D.; Henry, Jean-Francois. Higher productivity through energy plantations. Chicago, IL: American Society of Agricultural Engineers; 1975.
Walduck, Tom. The potential for growing eucalyptus pulpwood on the U.S. west coast. July 1976. Unpublished paper. Kingston, Tasmania.

Southern California Trial Plantings of *Eucalyptus*[1]

Paul W. Moore[2]

Abstract: A trial planting to compare the biomass production of 9 tree species was established in May 1979. Species compared were Acacia melanoxylon, Casuarina cunninghamiana, Casuarina equisitifolia, Eucalyptus camaldulensis, E. dalrympleana, E. regnans, Populus hybrid, and Taxodium distichum. E. globulus was substituted for E. regnans when the latter failed to survive.

E. camaldulensis and E. dalrympleana were superior to all other species.

Other commercial plantings have been established in the intermediate and interior valleys of Riverside and San Diego Counties. Eucalyptus species included in such plantings are E. bicostata, E. camaldulensis, E. camphora, E. deanei, E. globulus, E. grandis, E. rudis, E. saligna, E. tereticornis, E. trabuti, and E. viminalis.

Observations are being made on the comparative performance of the different species and their response to varying stocking rates and cultural practices.

Following the Arab oil embargo of the 1970's, new interest was generated in renewable energy resources. Among the forest species that had potential for rapid production of biomass was Eucalyptus.

Three species had shown wide adaptation to California soils and microclimates. Eucalyptus globulus was widely planted as windbreaks and woodlots in the milder coastal and intermediate valleys from the Mexican border on the south to the Oregon border on the north. E. camaldulensis and its closely allied species E. teretecornis dominated the interior and desert valley plantings.

Observations and comparisons of these Eucalyptus species with other genera such as Acacia, Grevillea, Pinus, Platanus, Populus, Prosopis, and Taxodium strongly supported the assumption that certain Eucalyptus species would be the best selections for biomass production in climatically suited sites in California.

In order to obtain better data on the comparative performance of Eucalyptus in an interior valley of southern California, a trial planting was made in the spring of 1979 at the Moreno Ranch field station of the University of California near Sunnymead, California (117°11' W longitude, 33° 54' N latitude).

Eight species were planted on May 22, 1979. These were:

Casuarina cunninghamiana, Casuarina equisitifolia, Eucalyptus camaldulensis, Eucalyptus dalrympleana, Eucalyptus globulus, Eucalyptus regnans, Populus hybrid, Taxodium distichum.

The eucalyptus species were obtained from the California State Department of Forestry nursery at Davis, California.

The Casuarina, Populus hybrid, and Taxodium seedlings were obtained from the Florida State Dept. of Forestry nursery. The Populus hybrid was planted as unrooted hardwood cuttings. All other trees were small seedlings. Acacia melanoxylon were grown from seed purchased from Carter Seed Co., Vista, California.

Each species was replicated 10 times with 9 trees planted 3 X 3. Spacing was 10' X 10'.

Soil

San Emigdio Loam. One percent slope.

Temperature

Extreme annual range between -12.8°C to 43.3°C. In most years the lowest minimum is close to -7°C. The highest maximum is in the range of 40°C to 42°C.

Wind

Prevailing daily winds during the growing season are from the west and southwest with velocities of 9 to 12.9 km per hour. During the

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Paul W. Moore, Specialist, Superintendent of Agricultural Operations Department, University of California, Riverside.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

winter months strong easterly Santa Ana winds with velocities of 30 mph and gusts as high as 60 mph occur annually.

Rainfall

The 100-year annual average rainfall is 10.85". Total annual precipitation ranged from 2.95" to 22.45". Rainfall patterns show several occurrences of 2 to 6 consecutive dry years with monthly rainfall patterns that would be unfavorable for establishing and maintaining non-irrigated plantings. Seventy-one percent of the total annual rainfall occurs during the 4 months December through February. Monthly rainfall during April to October is insignificant and would not contribute enough soil moisture to sustain growth.

Irrigation Water

Irrigation water is supplied from wells. Total dissolved solids fluctuated around 550 ppm. Boron content is 0.77 ppm. During the first year irrigation was given weekly for the first month then extended to 3-week intervals during the summer months. Three-week intervals have been maintained during the second, third, and fourth growing seasons.

Fertilizer

No fertilizer has been applied throughout the life of the planting.

Weed Control

Weed control has been practiced to maintain a weed free condition. The worst weed on the site is bind weed (Convolvus arvensis). Mechanical cultivation by disk plus Roundup spray as required is the program.

Survival

Survival rates were taken on July 24, 1979 -- 9 weeks after planting.

Eucalyptus regnans had very poor survival rate: 58 percent were dead by July 24, 1979; 25 percent were weak and only 17 percent were considered normal. Because of the poor survival all plots of E. regnans were eliminated and planted with Acacia melanoxylon. The Acacias were grown on the site in 1-gallon cans from seed purchased from Carter Seed Co., Vista, California. Transplanting was done during the 1st week in August 1979.

Survival counts were made on July 24, 1979. Eucalyptus globulus had a survival rate of 66 percent; E. camaldulensis 99 percent; E. dalrympleana 78 percent; Populus hybrid 92 percent; Casuarina cunninghamiana 78 percent; C. equisitifolia 67 percent; Taxodium distichum 99 percent.

Cold Tolerance

Minimum temperatures of -7.2°C occurred on the night of November 14, 1979 and -7.8°C on the night of November 21, 1979. Freeze injury was evaluated on December 10, 1979.

Severe injury was sustained by E. globulus, C. cunninghamiana and Acacia melanoxylon. Most trees of these species were killed to the ground. A few resprouted from the basal buds in the spring of 1980.

Moderate injury occurred on C. equisitifolia.

Slight to moderate injury occurred on E. camaldulensis.

Slight tip burn was sustained by E. dalrympleana.

No injury was experienced by the Populus hybrid or Taxodium distichum.

Insect Damage

The only insect damage observed was an invasion of Poplar borers. The trunks were so weakened by borer activities that several trees broke near ground level. The infestation occurred on all of the Popular trees in the planting. This was considered to be a serious drawback for the species and it was eliminated from further studies and all trees were removed at the end of the 1981 growing season.

Eliminations and Selections

At the end of the 1981 growing season an evaluation was made to select the species with the best potential for wood fuel production.

The following species were eliminated from further study due to their poor performance as indicated below:

Acacia melanoxylon due to susceptibility to cold damage and slow growth compared to the 2 remaining Eucalyptus species.

The 2 Casuarina species due to cold tenderness and comparatively slow growth.

The Populus hybrid because of susceptibility to severe damage by the Poplar borer.

Taxodium distichum due to extremely slow growth and injury by boron in the irrigation water.

The 2 Eucalyptus species, E. camaldulensis and E. dalrympleana performed so much better than the other species that they were saved for further observation and future selections for seed trees.

E. camaldulensis is superior to E. dalrympleana for total biomass produced to date. However, in cold locations E. dalrympleana would be more likely to survive sub-freezing temperatures during the early life of a planting. E. dalrympleana is cited as being resistant to temperatures as low as -12°C whereas E. camaldulensis is cited to resist minimum temperatures of -6°C.

Observations of established E. camaldulensis in the interior valleys around Perris, Hemet and Winchester verify that this species is resistant to -10° in these locations.

Variability

Great variability exists in the population of E. camaldulensis in this trial. Volume calculations on a tree-to-tree basis made on December 8, 1982 showed a range in volume of 0.12 cubic feet to 5.30 cubic feet per tree. Fifty percent had a calculated volume of 2.00 cubic feet or larger.

It has been decided that the best 25 percent of the trees should be saved as a seed source block for future plantings and all others will be removed. This decision is based on the possibilities of genetic improvement demonstrated by Franklin and Meskimen in Florida.

E. dalrympleana produced less wood than E. camaldulensis. The calculated volume of the smallest tree was 0.19 cubic feet and the largest 3.17 cubic feet ; 10.5 percent was larger than 2.00 cubic feet and 18.4 percent was larger than 1.5 cubic feet. The largest 50 percent averaged 1.2 cubic feet per tree.

One is tempted to speculate from data collected to date and estimate yields under another set of conditions.

The spacing on this trial is wide, 10' X 10', and the planting density is low, 435 trees per acre.

Increasing stocking density to 680 trees per acre (8' X 8') would be expected to increase yield in a short-term harvest cycle. Observations of the present planting suggest that an 8' X 8' spacing would increase the number of stems by 56 percent without decreasing stem sizes during the first 4 growing seasons.

In addition, genetic improvement could improve yield. In this trial planting there is a great variability between trees.

If we could improve our seed sources to eliminate genetically weak seedlings from the population it appears reasonable to increase yield per acre by 50 percent. In fact, Franklin and Meskimen, working in Florida, achieved a 68 percent increase in volume after one generation of selection in Eucalyptus robusta. Comparisons were made at 4-1/2 years of age.

Using two concepts of a denser planting and genetically improved seed sources, it appears that we could have achieved a theoretical increase in yield of approximately 55 percent.

The yield per acre of E. camaldulensis for all trees at the 10' x 10' spacing was 8.99 cords per acre at the end of the third growing season (90 cubic feet of solid wood equal 1 cord). A closer spacing of 8' x 8' would have resulted in a yield of 13.6 cords per acre.

If a genetically improved strain could have been used which would have performed as well as the largest 50 percent of the trees in the existing planting, production would have been 14.4 cords per acre at the 10' X 10' spacing and 22.5 cords per acre for the 8' X 8' spacing.

The dalrympleana yield at the 10' X 10' spacing was 6.42 cords per acre at the end of the third growing season. An 8' X 8' spacing would have yielded 10.0 cords per acre.

A genetically improved strain yielding the equivalent of the largest 50 percent of the existing trees would have produced a theoretical yield of 8.7 cords per acre in the 10' X 10' spacing and 13.6 cords per acre at the 8' X 8' planting.

Measurements on an irrigated 34-month-old commercial planting of E. x trabutii with a very close spacing of 3' X 5' (2904 trees per acre) gave an estimated yield of 3.24 cords per acre. The high density of this planting contributed to extremely light competition and small stem diameters averaging 1.9" DBH. Mortality, or weak trees which would most likely be unharvestable, was estimated at 25 to 30 percent of the stand. At this point in time it appears that very dense plantings will not develop good marketable cord wood sizes during a short harvest cycle of 4 to 5 years. Marketing of such plantings may be in the form of chips or densified pellets.

Other Plantings

A number of plantings have been made in San Diego, Riverside, and Imperial Counties. Those that I have observed were planted in 1980 and 1981 and 1982. Among Eucalyptus the species that have been included in commercial plantings are: biocostata, camaldulensis, camphora, dalrympleana, deanei, globulus, grandis, gunni, nova-anglica, rudis, saligna, tereticornis, trabutii, urnigera, and viminalis. Clonal lines from E. grandis, E. camaldulensis, and E. x trabutii selections are being compared to seedling populations for uniformity.

It is too early to make recommendations based on the limited time that such plantings have been growing. However, some interesting observations might be cited.

E. grandis has been the most rapid grower but is also frost sensitive; 7-month-old trees exposed to -7.7°C sustained the most damage compared to 13 other species in the same planting. Saligna was the next most sensitive.

Three selections of E. globulus from cold provenances of Tasmania were only slightly injured whereas E. globulus from a California seed source were killed to the ground by the same temperature in 1979. These provenances may be cold tolerant candidates for future plantings in the interior valleys of southern California. E. globulus appears to be equivalent to E. grandis in growth rate.

E. x trabutii, alleged to be a hybrid of E. botryoides X E. camaldulensis, is growing more rapidly than E. camaldulensis. Cold tolerance is equivalent to camaldulensis.

E. dalrympleana may be a satisfactory selection for cold sites. It appears to be growing more rapidly than E. gunnii.

E. camaldulensis and E. tereticornis occur on old non-irrigated stands throughout the interior valleys of Riverside County. They have survived drought, high temperatures, and sub-freezing temperatures. E. camaldulensis appears to be the most universally adapted species for the interior valleys and Imperial Valley of southern California. When in doubt regarding species selection in these localities, E. camaldulensis would be the safest choice.

The best seed source is the Lake Albacutya provenance of Australia and is available from Australian seed companies.

It is doubtful if any planting can be established without irrigation at least during the first two years of life.

Availability of low-cost water is an important consideration in site selection.

Although Eucalyptus has grown in California for well over a century, it has been only since the Arab oil embargo that interest in its culture as a renewable energy source has been renewed. Until recently, no research has been conducted in California on species performance, cultural requirements under intensive care, and the economics of production and marketing wood for fuel.

Some research is now under way to find answers to these questions. Significant information should be available since 1979. The first harvest of these plantings may be made as early as 1984 assuming a 50-year harvest cycle for the better plantings.

Following the first harvest the California industry will have better recommendations for future management of wood energy farms.

REFERENCES

Franklin, E. C.; Meskimen, G. F. Genetic improvement of Eucalyptus robusta SM in southern Florida. In: Proceedings, Tropical Provenance and Progeny Res. and Int. Cooperative Joint Meeting, Nairobi, Kenya October 22-26, 1973; 421-424.

Soil Conservation Service Tests of *Eucalyptus* Species for Windbreaks[1]

Gary L. Young[2]

Abstract: The Soil Conservation Service is in the early stages of testing many species of Eucalyptus for windbreaks. Over 260 different species have been collected. The pre-planting selection criteria and process is described as well as the test conditions and procedures. Some sources of information on the use of the Eucalypts may be misleading through overgeneralization. Early results support the need for greater communication and testing of a wide variety of species and provenances in California.

The Soil Conservation Service (SCS) is an agency of the U. S. Department of Agriculture. Our national plant testing program includes many grass and tree species and its goal is selecting adapted cultivars for soil erosion control. The SCS operates 23 Plant Materials Centers (PMC) nationwide, and 2 of the Centers located at Tucson, Arizona and Lockeford, California are involved in testing trees for windbreaks in the southwest. We are looking for widely adapted cultivars of several Eucalyptus species for use as windbreaks throughout the Mediterranean climate area of California and the adjoining warm winter area of Arizona. Our program will consist of initial testing, evaluation, and advanced testing. We expect to be involved with growing and evaluating Eucalypts for the next 20 years.

TEST CONDITIONS

Climate

The climatic means and extremes at Lockeford and Tucson are similar. The minimum temperature reached on an average of once each year is -8° to -7°C (18° to 20°F) and lasts less than 6 hours. The highest temperatures expected in the summer are 42° to 44°C (108° to 112°F), slightly lower in Tucson. For Lockeford, the long term average annual rainfall is about 430mm (17 inches), nearly all falling in the 6 months of winter.[3] Tucson is dryer, with an average of 280mm (11 inches), but the rain is more evenly distributed over the year (Briggs 1982).

Soils

The soils at Tucson are Grabe loam and Comoro fine sandy loam more than 1.5m (60 inches) deep. They are moderately alkaline and somewhat calcareous (Richardson 1979). The soils at Lockeford are deep Honcut loam and Columbia fine sandy loam. They are neither alkaline nor calcareous.[4]

Management Practices

The management practices at Tucson and Lockeford are also similar. Because we are testing these trees for use as part of a 2 or 3 species windbreak, we will manage them as we would expect the landowner to manage them. The Eucalyptus are planted in the spring and given deep irrigations as needed during the first summer. Supplemental irrigations in following years will be applied as necessary. We feel the increased survival and vigor of the trees justifies the investment of water and time to provide irrigation for many years.

Weed control is essential and is performed chemically and mechanically as long as needed. The trees are usually able to shade out weeds and/or withstand the competition from them after 2 years.

The management program for the nursery also includes removing broken limbs and downed or severely damaged trees. Any pattern that may be found in the breakage of limbs and trees is valuable data to record and can eliminate from further testing any species that are excessively prone to windthrow and damage.

Design and Evaluation

At Lockeford, the plantings (nurseries) are made in blocks, not oriented or designed as windbreaks. This is primarily to save space and to facilitate management within our normal field divisions. The nurseries contain 36 accessions of Eucalypts (in addition to many accessions of other genera) planted in 1979, 1980, and 1981.

At Tucson, in order to include the largest possible number of different species in the tests,

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Agronomist, Lockeford Plant Materials Center, Soil Conservation Service, U. S. Dept. Agric., Lockeford, Calif.

[3]Weather records on file, Lockeford Plant Materials Center, Lockeford, Calif.

[4]Soil survey records on file, Lockeford Plant Materials Center, Lockeford, Calif.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

a decision was made to include those accessions where there were only 1, 2, or 3 specimens available after propagation. This causes problems in measuring the significance of observations based on so few individuals. The normal full complement at Tucson is 4 and at Lockeford is 6. At Lockeford, no accessions were included which had fewer than 6 specimens at planting time.

The trees are planted in rows of 5 accessions, each represented by 6 specimens. The spacing between the trees is 3m (10 feet); the spacing between rows is 6m (20 feet). This spacing represents a compromise between proper spacing for windbreaks and wider spacing to allow the natural shape and size to be expressed. The different accessions are evaluated throughout the year. The trees are measured for height and width (canopy cover) at the end of each growing season. The accessions are also rated for stem abundance and distribution and foliage abundance and distribution in comparison to a known standard. The standard we are using for our Eucalypts is Dwarf blue gum, (Eucalyptus globulus var. compacta Labill.), which has been in the California landscape trade for many years. As a common landscape tree, it has been planted widely, and its performance is well known. The trees are also rated for their resistance to disease, insects, cold, heat, and drought. A rating is made twice a year of the accession's vigor and of its suitability. Both of these ratings are somewhat subjective, but both are closely related to the standard of comparison. As a measure of vigor, Tucson has used the height of each year's growth expressed as a percentage of the mature height expected. All of these measurements and ratings (and many more facts) are done on standard forms. The data is then entered into the nationwide data bank SCS maintains for plant material evaluations.

SPECIES SELECTION

When we assemble a collection, it is for a particular need; in this case, windbreaks. The selection process used by the SCS is to explore existing information sources to select the 2 or 3 most promising species. We then conduct ecotype testing within that species. Unfortunately, there are many species of Eucalyptus and a small number of references and information sources for their adaptations. Because of this, we decided to test a large number of Eucalyptus species for general characteristics. From these, we would select a few species on which to conduct provenance or ecotype testing.

Collection

The group of species from which we can make our selection has been strongly affected by our source of seed. We requested packets of seed from Australia through our National Plant Materials Center at Beltsville, Maryland. The Australians sent us many small packets from the National Botanic Garden in Canberra. Most of the packets are marked with some collection location data. The amount of seed in a packet (usually less than 1 gram) is seldom enough for more than a single test. The Australians have compensated for this by sending a large number of species. We have received over 300 accessions from Australia and about 50 from domestic sources. Many of these 50 were probably also collected in Australia. These 350 accessions represent 263 species. We will select from these to compile the list of species and accessions for our future plantings. The next nursery will be propagated soon and will be planted in the early spring of 1984. It will consist of approximately 200 accessions.

To guide us in our selection, we are using information from the first small nurseries we planted in 1979, 1980 and 1981 combined with information from the Tucson PMC. Several reference books we have located contain information on adaptations, requirements, and physical properties for a large number of species (Jacobs 1981). These books also cover a wide range of conditions. Some data are on important or restrictive conditions tha we cannot test at Lockeford, such as shallow soils and saline or calcareous soil.

Selection Criteria

Species that are adapted to a wide range of soils and climatic conditions are most appropriate to our needs. More importantly, when we make a selection, it is primarily based on those character istics that we feel are most relevant to windbreaks in California: growth habit, mature size, drought tolerance and frost tolerance.

Growth Habit

The preferred growth habit is a tree with a columnar form and one to several trunks. The foliage and small limbs should be persistent and relatively dense near the ground for several years. These two basic requirements can cause conflicts with other management systems. The multiple trunks and the persistent foliage near the ground would be negative factors in a woodlot management system. The low foliage would also contribute to the fire hazard that is a concern with the Eucalypts.

Deciduous bark, leaves and branches can create a problem when Eucalyptus are planted near row crops. Selection of a species for agricultural windbreaks is limited by these characters not because they affect windbreak efficiency, but because they affect the acceptance of a species by users.

Mature Size

For our needs and our tests, the mature size should be between 15m (50 feet) and 40m (130 feet). This large size is preferred for two reasons.

First, the large trees have a very rapid growth rate when young, (expressed as a percent of mature height achieved each year) and will thus achieve a suitable height for windbreaks (8-12m [26-40 feet]) feet) in a relatively few years. Second, the major application for these trees is the protection of agricultural land and operations. The economics of farm management dictate that windbreak rows be tall and widely separated to minimize the land consumed and maximize the size of the fields between windbreaks.

Drought and Frost

Drought tolerance and frost tolerance are the two most important factors used by Eucalyptus growers in species selection.[5] Both are somewhat subjective and are affected by local conditions. The data the growers are relying on could be misleading.

Their information may be based on a vigorous local planting. A species' sensitivity may be masked by an unknown irrigation source or a more sheltered position during frost periods. To obtain accurate frost sensitivity or tolerance data, we maintain a recording weather station approximately 300m (1000 feet) from our plantings.

We are trying to select species that are drought tolerant, but we are not subjecting our plants to drought at this time for two reasons. First, we propose and presume that windbreaks will generally be irrigated. Second, we are unable to subject the plants to a true drought due to a fairly shallow moisture level from the nearby Mokelumne river.

In the future, advanced testing will involve several different sites in the various climatic areas of California where more extreme conditions will be encountered.

Selection Complications

Another source of errors in suitability information is the misidentification of species that survive or fail. Only training, care, and good reference authorities can solve this problem.

It is also very difficult to interpret the existing climatic data from foreign sources. There are always questions of which data most accurately describe the critical factors. Are they mean maximums and minimums of temperature or are they the extremes?; is it the amount or the distribution of rainfall for the year?

[5]Personal communication with Sherman Finch, State Forester, Soil Conservation Service, Davis, Calif.

Other questions remain if the information is incomplete or misleading through generalization. Does the dry season coincide with the hot season? Are the frost periods of long duration or of only a few hours? One example of such misleading data comes from a European publication. In describing the climate of California relative to the needs of (E. globulus Labill.), San Francisco is used as the reference climatic station for the state (Jacobs 1981).

RESULTS

One result of our test to date is the observation of two conditions or patterns that exist in some of the Eucalypts.

The first is a variation in the limb attachment morphology between species. The process of shedding small branches in the Eucalypts has been praised by timber and landscape users for producing clear trunks. The process we observed affects the major limbs or secondary trunks in some species, e.g. (E. grandis W. Hill ex Maiden). As a limb puts on its second years' growth, a crescent-shaped area of bark is formed just above where the limb meets the trunk. This crescent extends into the joint area, filling it and forming a plane of weakness directly across the area where tension forces supporting the limb are greatest. The wood in this area also seems to be weak, separating along a conical surface, with very little shattering or breaking. In those species not showing this limb characteristic, e.g. (E. globulus Labill.), the joint area is filled by trunk and limb wood instead of bark.

The second pattern is similar. In some species, e.g. (E. smithii R. T. Bak.; E. macarthurii H. Deane & Maiden), the trunk will separate from the roots. After a tree falls during a strong wind, we see it has broken cleanly near or slightly below ground level. The broken end of the trunk is a convex surface. This surface consists of several planar areas each representing the attachment point for a root. The wood in these areas is not shattered and broken. It appears to be compressed and fiberous. The plane the fibers are in is perpendicular to the centerline of the trunk and roots. A similar surface is on the ends of the roots. There is very little broken wood and virtually no disturbance of the ground where roots have started to pull loose. The area involved appears to be at or near the point where "root" tissue meets "stem" tissue. This physiological point may be a contributing factor in the location of the failure point.

Further observation of these and other species is needed to see if a predictable pattern exists.

Some other preliminary results are variations and correlations between our test plants and the literature.

Manna gum, (E. viminalis Labill.), has exhibited enough differences between our two accessions that a provenance trial should be conducted under California conditions. There are many provenances recognized in Australia (Jacobs 1981). Both accessions have reached 10m (32 ft.) in 4 years.

Maiden's gum, (E. maidenii F. J. Muell.), is now called (E. globulus Labill. ssp. maidenii Kirkp.). This is our outstanding performer. Starting from seed, it has reached a height of 12m (40 ft.) in 4 years. In Australia, the crown widens as the tree matures (Forestry Commission 1980). This may require a rotation management system to maintain the proper shape.

Sugar gum, (E. cladocalyx F. J. Muell.), shows good vigor and growth rate, but it has a bare trunk and an open crown. Sugar gum has been widely used for windbreaks in Australia (Jacobs 1981). Multiple row windbreaks are planted, and every few years one row is cut for wood or poles. The coppice shoots from the stumps fill in the openings between the remaining trunks.

Karri gum, (E. diversicolor F. J. Muell.), is described as a tall, single trunk tree that is excellent for timber (Jacobs 1981). Our accession has suffered very minor visible frost damage, but as a result, has become a very irregular shrub.

Camden wollybutt, (E. macarthurii H. Deane & Maiden), is considered a good shelterbelt tree because of its form and lack of windthrow. In our accession, 5 of the 6 specimens have broken at the base in moderate winds.

Dwarf blue gum, (E. globulus var. compacta Labill.), has demonstrated excellent potential for windbreaks. Ours have grown to 5 m (16 ft.) tall in 4 years and are very dense. It may be too dense for the first 3 years, letting very little air filter through. Approximately 5 percent of the plants revert spontaneously to the tall form. This leaves gaps in the row. This variety may make an excellent 2-row windbreak with one of the taller, more open species.

CONCLUSIONS

It is too early in our testing program for us to have a recommended variety or even a species of Eucalyptus for growers and researchers. There are some things we do have. We have seed samples of a large number of species for our future work. As a government agency, we can work through foreign research groups to get more seeds and test results. We also have the facilities of the Plant Materials Center, our testing and evaluation system, and our nationwide data base, to help us develop and distribute information on Eucalyptus.

REFERENCES

Briggs, James A. Tucson Plant Materials Center, 1981 Annual Technical Report. Tucson, AZ: Soil Conservation Service, U.S. Department of Agriculture; 1982. 195 p.

Forestry Commission of New South Wales. Trees and Shrubs for Eastern Australia. Kensington, NSW, Australia: New South Wales University Press; 1980. 165 p.

Jacobs, M. R. Eucalypts for Planting. Rome, Italy: Food and Agriculture Organization; FAO Forestry Series No. 11, 1981. 677 p.

Richardson, M. L. Soil Survey of Santa Cruz and parts of Cochise and Pima Counties, Arizona. Washington, DC: Soil Conservation Service, U.S. Department of Agriculture; 1979. 105 p.

Eucalyptus as a Landscape Tree[1]

W. Douglas Hamilton[2]

Abstract: Ninety-two species of Eucalyptus were evaluated at the University of California research station in San Jose. The purpose: to find acceptable new street and park trees. Growth rates and horticultural characteristics were noted. Forty-three species were studied in locations statewide to evaluate site adaptation and landscape usefulness; flooded, cold, dry, saline. Susceptibility-to and recovery-from the prolonged freeze of December 1972 was studied and published. Species response was wide. Prevention of unwanted resprouts was studied. Four alternatives for success were offered.

There have been 5 distinctly different studies by Cooperative Extension from the Hayward Office in the last 15 years involving the genus eucalyptus and are briefly discussed.

1. Landscape Tree Evaluations: two studies

a) Known as the LTE project, this study, initiated in 1971, involved Extension advisors in 15 counties under the leadership of Extension Specialist, W. B. Davis. We evaluated a range of Eucalyptus, most of which were not in the trade. We also evaluated problems related to the site. Forty-three species were selected which were known to have a broad range of adaptability. Seed was obtained from a commercial company in New Zealand and container-grown at University of California, Davis. While growth measurements were made yearly and problems noted, a final rating was made as to the acceptability of the species for the site, from outstanding to unacceptable. In order for a candidate species to be considered outstanding statewide, the species had to be planted at 11 or more project sites which had a wide range of climates and soil conditions and the majority of ratings had to be 4 or 5. Of the 43 candidates, three ranked as outstanding: E. botryoides, E. camaldulensis rostata and E. aggregata. Three species were given a special ranking for salinity tolerance: E. platypus, E. spathulata and E. sargentii. Much more information is included in the Report on Evaluations of Several Eucalyptus Species, edited by W. B. Davis.

b) The Landscape Eucalyptus Tree - An Evaluation Study 1971-78, is the title of a study conducted at the University of California Deciduous Fruit Station in San Jose by W. Douglas Hamilton, Cooperative Extension. Seed sources were botanical gardens in Australia. The plants were grown under the direction of Andrew Leiser, Department of Environmental Horticulture, UC Davis. Ninety-two species were planted; about half in April, 1971, the others in October, 1971. Several observations were recorded.

The April planting quickly became established. The October planting was stunted by the winter temperatures and recovered slowly the following spring, although no difference could be noted after the first year.

All species were measured for height and trunk circumference annually and growth habit, whether mallee or single trunk was noted. Notes were also taken on relating strength of branch angle attachment and flowering. Also, all species were evaluated regarding injury-and-recovery to the 1972 freeze.

Leaf, twig, fruit litter accumulation was measured each month for one year in an effort to evaluate fire hazard and trashiness.

Thirteen species were rated as "most promising" by the author and by industry groups: landscape architects, principal park people, etc. Growth habits, adaptation to the site and possible usefulness were considered among the "winners": E. accendens (street tree), E. archeri (small, cold tolerant, florist trade), E. blakelyi (street tree for cismontaine California), E. bosistoana (attractive in nursery, "clean" skyline tree), E. burdettiana (small, boxy, exudes character for non-frosty locations), E. grandis (50 feet in 5 years, self pruning to single trunk and thus "dirty," fast growing windbreak in mild climate), E. gunii (narrow upright, "clean" on droughty soils), E. intertexta (a weeping "mayten," excellent patio tree, variable), E. scoparia (a more open and "weeping" E. viminalis). The report is available from the Hayward Extension office.

2. Damage and Recovery to Eucalyptus Resulting from the December 1972 Freeze.

From December 8 through December 15, minimum temperatures at the San Jose research station and

---

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, Calif.

[2]W. Douglas Hamilton, Horticulture Advisor, University of California, Cooperative Extension, Hayward, California.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

generally in the San Francisco Bay Area were below freezing; 23°F to 28°F, maximum temperatures ranged from 36°F to 48°F, but mostly near 40°F. This provided an opportunity to evaluate injury and recovery to all the Eucalyptus and note effect of spring and fall planting dates to 1.5 years before. The injury rating scale was: 1 - no visible damage; 6 - above-ground plant dead. An early recovery rating was made on January 4, 1973. A late recovery rating was made on July 26, 1973: 1 - complete recovery or no damage; 6 - dead or no recovery.

Regarding freeze injury, planting date did not appear to affect freeze injury although no one species was planted on both dates. Cold tolerance and recovery of promising species mentioned earlier is as follows:

	Ratings (average)	
Species	January 4	July 26
E. accendens	3	3
E. archeri	planted after freeze	
E. blakelyi	1	1
E. bosistoana	4	2
E. burdettiana	4	5
E. grandis	2	1
E. gunii	1	1
E. intertexta	2	1
E. scoparia	1	1
E. microtheca	1	1
E. spathulata	3	3
E. maculosa	2	2
E. populnea	1	1

3. The top-kill of between 2 and 3 million bluegum and river redgum Eucalyptus in the Oakland-Berkeley hills raised many questions: how to avoid a fire danger from the litter and resprouts, how to open fire lanes and biking trails, protect views and how to generally prevent Eucalyptus from resprouting where they were unwanted. Methods used in Australian forests were untenable in the urban areas. In view of this, field research was initiated in 1973 and numerous trials were conducted through 1978. Two methods were successful (+97 to 100 percent control). One was to cut the stump to 4 to 6 inches below the ground surface. A survey of the points of attachment for bluegums indicated that all sprouts originated between ground level and 4 inches below. The second method was to make a fresh cut near the ground level, into the wood. It is essential that the cut be continuous. Into this cut, whether it be the whole cross-section or just the ax frill, is poured a solution (50 or 100 percent); 2,4-D water soluble amine (Weedar-64), glyphosate (Roundup), or the granular material ammonium sulfamate (Ammate-x). Other materials were tested on an experimental basis, but are not available or not registered for this use.

4. Control of trunk sprouts with growth regulators on the landscape tree was successfully tested more than 10 years ago by R. W. Harris, R. M. Sachs and R. E. Fissell at UC Davis. Sprouts on *E. camaldulensis* and *E. viminalis* were prevented from developing by the application of 1 percent napthalene acetic acid (NAA). Results were significant at the 1 percent level. Translocations of materials stayed at the sprout attachment, so no injury to the trees was observed.

5. The storms of late 1982 and early 1983 in the San Francisco Bay Area resulted in considerable limb breakage and tree blow-over. A survey of November-December storms damage involving 35 communities indicated that Eucalyptus species in general and several Eucalyptus species in particular (bluegum, ironbark, silver dollar, peppermint and sugargum) had severe blow-over problems. Limb breakage was noted to be the highest for any one problem species. Twenty-five surveys mentioned Eucalyptus and acacia as problem trees. The genetic habit of the species plus splitting crotches, dense tops, closely-spaced limbs and large limbs of equal size were most often cited as causes of problems. In fairness, however, much of the problems observed were termed catastrophic failures; unpreventable.

Somewhat akin to folks devoted to native plants, the species Eucalyptus has its devotees and detractors. Generally, detractors are people familiar only with the bluegum. While it is true that few people are planting bluegums, others have found that in general, Eucalyptus have an aggressive root system which tends to be shallow and fast-growing; thus there are root-pavement problems and problems of sufficient irrigations of companion plantings. Many of the Eucalyptus grow too large for the small properties where they are planted and the litter produced by many becomes an unwanted nuisance. Some nurseries indicate a slowing demand for Eucalyptus. For Eucalyptus to maintain or serve their useful place in the landscape, it will be necessary to recognize certain species and extoll their usefulness.

REFERENCES

Beatty, R. Freeze damage survey, a report of plants damaged at U. C. Berkeley. U.C. Cooperative Extension, Hayward, CA; October 1973. 25 p.

Davis, W. C. Report on evaluation of several eucalyptus species. Miscellaneous environmental horticulture report. Cooperative Extension, University of California, Davis, CA; 1981. 35 p.

Hamilton, W. D. Eucalyptus at the deciduous fruit station, 1971-73. Miscellaneous publication. U.C. Cooperative Extension, Hayward, CA; August 1973. 3 p.

Hamilton, W. D. Eucalyptus test trees, San Jose, freeze injury evaluation from December 1972 freeze. Miscellaneous publication. U.C. Cooperative Extension, Hayward, CA; January 1983. 4 p.

Hamilton, W. D. The landscape eucalyptus tree: an evaluation study 1971-78. Miscellaneous publication. U.C. Cooperative Extension, Hayward, CA; 1978. 8 p.

Hamilton, W. D. November-December 1982 storms,

California central coast tree damage survey. Miscellaneous publication. U.C. Cooperative Extension, Hayward, CA; January 1983. 2 p.
Hamilton, W. D. Prevention of eucalyptus re-sprouts, progress report. Miscellaneous publication. U.C. Cooperative Extension, Hayward, CA; July 1982. 2 p.
Hamilton, W. D.; McHenry, W. B. Stump sprout control. Miscellaneous publication. U.C. Cooperative Extension, Hayward, CA; November 1973. 3 p.
Hamilton, W. D. Stump sprout control cost study. Miscellaneous publication. U.C. Cooperative Extension, Hayward, CA; November 1973. 1 p.
Harris, R. W.; Fissell, R.; Sachs, R. Control of trunk sprouts with growth regulators. University of California, Davis, CA: California Agriculture; November 1971. 5 p.

Creating a Database on *Eucalyptus* for California[1]

Miles L. Merwin[2]

Abstract: While public agencies, nurserymen and landscapers are receiving more inquiries about individual eucalyptus species for California plantings, little information is readily available to them on the potential usefulness or adaptability of these species. A survey of eucalyptus species was undertaken to collect information on their performance both in California trials, their native range and other overseas countries. It is proposed that this survey form the basis of a printed handbook and computer database on eucalyptus in California as an ongoing interagency project.

Increasing interest in rural woodlots for fuelwood and low-maintenance ornamental plants has sparked a resurgence in eucalyptus plantings in California. Those concerned with planting, propagating and maintaining trees are turning to public and private land use advisors, e.g. University of California Cooperative Extension, Calif. Department of Forestry and U.S. Soil Conservation Service, for detailed information on the many eucalyptus species that have been introduced into the state. Despite the fact that eucalyptus have been planted in California for over a century, up-to-date, reliable information on the growth, yield and suitability for different uses of individual species is not readily available. While a number of past and present species trials have been performed, the results of this work have not been collected systematically into a form readily useable by those called upon to provide information to the public.

Interest in eucalyptus planting as well as organized field trials are likely to continue in future. Therefore, a coordinated effort to collect and disseminate information about eucalyptus species in California would benefit a wide variety of people concerned with the genus. This information would be useful to public and private agencies that advise landowners on land use decisions, nurserymen that propagate the trees, landscapers that incorporate eucalyptus into the urban landscape for amenity and shade, and ultimately the individual citizen interested in planting the trees.

INITIAL SPECIES SURVEY

In 1982, a compilation of information was begun on a number of eucalyptus species that have been planted or proposed for trial in California. The purpose was to collect the following information: (1) results of past and present planting trials in the state; (2) data on the typical growth, climate and soils of the native range in Australia; and (3) other relevant information on the performance of individual eucalyptus species when planted as exotics (introduced species). This species survey was intended primarily as a useful reference for public land use advisory agencies, foresters, farm managers, nurserymen, landscapers and researchers. It was not intended as a popular guide for the average landowner, except those cooperating in research trials.

The species survey was initiated under the direction of Dr. Andrew Leiser, Dept. of Environmental Horticulture, University of California, Davis. Species chosen for study were taken in part from earlier unpublished work by Dr. Leiser on drought resisting plants (Leiser, 1983) and in part from a review of the literature on other species exhibiting some degree of frost and/or drought tolerance. Over 100 species were initially chosen for study.

Using standardized data collection sheets, information was first compiled on the growth, climate, soils, wood and uses of each species in its native range in Australia, and the comparative success and productivity of those species when planted commercially overseas. After this initial review, several species not adaptable to cultivation as exotics or suitable only as ornamentals were eliminated from further consideration.

Information on the remaining 79 species was summarized in a standard format. This first draft was then sent to a number of reviewers in California with requests for information on past and present planting trials, uses and other practical experience with their cultivation in the state. The literature was also searched for published reports on past trial and commercial plantings of eucalyptus species. Only those species for which well documented information on trial plantings is available are included in the final selection. The particular selection of species covered in the published report (Merwin, 1983) does not mean to imply that other species have not been tested or would not also be potentially successful if introduced into California.

FORMAT AND CONTENT OF SPECIES SURVEY

A standardized format was used for the compi-

---

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Director, International Tree Crops Institute U.S.A., Inc., Winters, California

Eucalyptus camaldulensis Dehnh.

GROWTH IN NATIVE RANGE: Tree usually 80-120 ft. (to 150 ft.) tall with an often crooked trunk 3-7 ft. in diameter and a thin crown. Vigorous coppicer. Fairly fire resistant. Fast growing.

NATIVE RANGE: All states except TAS, along year-round and seasonal watercourses, esp. the Murray-Darling River system, at 100-750 (to 1800) ft. elevation. Latitudinal range 15.5°-38°S.

CLIMATE OF NATIVE RANGE: Annual rainfall mainly 10-25 in. (to 40 in.). Relies on seasonal flooding or high water table in areas of 10-15 in. rainfall. Hot dry summers with temps. to 115°F. Lowest temp. 23°F. (-5°C). Frosts 5-20.

CLIMATIC TOLERANCES: Drought. Reportedly tolerates 20-26°F as exotic.

SOILS OF NATIVE RANGE: Best on deep silty soils, clay soils and podsols. Ecotypes grow on poor soils, e.g. poorly drained flats wet for several months that don't completely dry out, acid sands, alkaline swampy clays. Becomes chlorotic on calcareous soils.

SOIL-RELATED TOLERANCES: Flooding. Heavy clay soils. Salinity (selected provenances). Coastal salt spray.

WOOD: Red, interlocked or wavy grain, gum veins or pockets common, hard, durable, termite resistant, density 980 kg/m3. May be difficult to split.

USES: Fuelwood, post/poles, shelter, amenity, honey, particle board, sleepers.

PROVENANCE: At least 8 distinct groups of provenances identified, each with significant differences in drought or frost resistance, growth rate and wood properties. 6845 Lake Albacutya, VIC proven consistently superior in tests throughout Mediterranean-type climates (FAO).

SUCCESS OUTSIDE AUSTRALIA: Important commercial species in Spain, Morocco, Israel, Turkey and other Mediterranean countries.

PRODUCTIVITY IN PLANTATIONS: Good sites: aver. 2.2-3.3 cords/ac/yr. Poor sites: aver. 0.2-1.1 cords/ac/yr (FAO).

GROWTH IN CALIFORNIA:

Chapman, 1982: "Spanish" selection from Florida Div. of Forestry gave best growth rate and survival of all species tested over a wide variety of Calif. sites.

Davis, 1978: Outstanding results. Species most tolerant of wide range of unfavorable soil and climatic conditions, e.g. salinity, flooding, poor drainage and drought. Survived 1972 freeze (15-25°F). Upright narrow growth form observed.

Ledig, 1983: In test of 23 provenances at Concord N.W.S. and other sites, Lake Albacutya, VIC was approximately 161 percent better than average for all provenances. This and other superior provenances all came from Murray-Darling River darinage in VIC and NSW.

Heavilin, 1978: Killed by frost at Redwood Exp. For.

King and Krugman, 1980: One of the best surviving, fastest growing spp. at Concord N.W.S.

McClatchie, 1902: Grows well on coast and in foothills, interior valleys and deserts. Fast growing. Open grown trees often very forked.

Metcalf, 1924: MAI of 26 plantations, average age 9 years, was 1.2 cords/ac/yr (range 0.4-2.8). Grows better in interior valleys and So. Calif. than along the coast.

Metcalf, 1967: Survives annual flooding along Sacramento River. Grows well in Imperial VAlley with irrigation. Has survived temps. lower than 23°F in Sacramento Valley but tops killed back by 1932 freeze. Tree at Watson Arb. grew 14 ft. with 1.6 in. dbh in 2 yrs.

Sachs and Low, 1983: Two year old coppice growth at Davis from 5000 trees/ac with flood irrigation (fertilizer at planting only) yielded 16.81 ODT/ac/yr (aver. 2.0 ODT/cord). Yield for hybrid with E. rudis in same trial was 16.94 ODT/ac/yr.

PLANTING PROSPECTS: Excellent with careful provenance selection.

PROPAGATION: Adaptable to containerized nursery production but liable to be quickly overgrown. Light essential for full germination.

OTHER: Hybridizes with E. botryoides to form E. X trabutii, and also with E. rudis.

REFERENCES: Boland, et. al., 1980; Coate; FAO, p. 369; Hall, p. 100; Hemstreet.

Figure 1--Example of standardized format for compilation of species information.

lation of species information, an example of which appears in Figure 1. Species nomenclature conforms to the most recent classification of the genus (Blakely, 1965). The "Blakely Number" assigned to each species or subspecies is listed after the Latin binomial.

Native Range

The first few headings describe the common growth form, geographic and topographic locations, average climatic conditions, soil factors, wood characteristics, main farm and/or commercial uses, latitudinal range and provenances (if any) for each species in its native habitat in Australia.

Under the heading "Growth in Native Range," the range of observed heights for each species, as a tree or mallee, are given along with crown characteristics and the diameter, form and length relative to total tree height of the trunk. Observations from the native range are also included on relative growth rate, coppicing ability, fire sensitivity and other details.

Australian states included in the native range of each species appear under "Native Range." Topographical distribution, elevations, and latitudinal range are also listed here. The more widespread the geographic and topographic distribution of a species, the more diverse the local ecotypes are likely to be. Thus careful selection of provenance for seed collection becomes more important (F.A.O., 1979).

Average climatic data for the native habitat is listed under "Climate of Native Range." Annual amount and seasonal distribution of precipitation is listed along with the relative length and severity of the dry season. Rainfall and dry season length are indicative of the relative tolerance of low moisture and high summer temperature conditions that the species may exhibit as an exotic. Lowest recorded temperatures in the native range and the frequency of frost are also given. While this information may indicate the relative cold hardiness of a species, widely distributed species will exhibit high variability in this trait. In some cases, species may tolerate lower temperatures when planted as exotics than in the native range (F.A.O., 1979).

Edaphic factors for each species are listed under "Soils of Native Range." Listed first are the preferred types of soils on which best growth occurs, then those soil types on which the species also occurs but where its development is not optimum. Among the characteristics noted of these soils are texture, structure, relative depth and drainage, pH, presence of salts or limestone and overall quality.

Environmental Tolerances

Data on growth form, climate and soils recorded under the headings described above is representative for each species in their native range and is intended as a benchmark for each species. Their growth and environmental tolerances when planted as exotics, e.g. in California, may be different than that found in the native range. Thus information listed under the headings "Climatic- and Soil-Related Tolerances" summarizes observations from both the native habitat and plantings outside Australia. Comparative tolerance to the most important limiting factors, e.g. drought, cold, flooding, salinity, etc., are listed under these headings.

For the introduction of these species into California, cold tolerance is generally a more important limiting factor than drought (since plantings are usually at least established with irrigation), thus determining their adaptability to different geographic regions of the state (Hemstreet, 1983). However, drought tolerance is also an important factor since many eucalyptus species are used in low-water, low maintenance situations specifically because of their resistance to drought. Soil factors may be less important in determining the suitability of individual species to exotic plantings, except in extreme situations such as heavy clays, infertile sands, shallow or poorly drained soils, and highly alkaline or saline soils.

Characteristics described of the wood of each species as harvested under native range conditions include color, grain, hardness, structural strength, durability (in contact with soil as a fencepost), ease of splitting, and density. Traditional or commercial uses for each species and its products in Australia are recorded under "Uses." Feasible uses for the trees when planted as introduced species in California may be different from those listed.

Provenance

Seed provenances that have been identified, collected and tested are listed under "Provenance." In some cases where the geographic and topographic distribution of a species is wide, recommendations for provenance testing or careful selections are noted. Due to the inherent seedling variability of these wide ranging species, proper selection of seed provenance can be crucial to the success of a trial or commercial planting (F.A.O., 1979). In prior evaluations of overseas trials of these species, the possibility should be considered that the provenance of the seedlings tested was mismatched to the test site or was atypical of the species. Current provenance trials in Cafiornia and other countries are also noted under this heading.

Overseas Plantings

Then follow several sections related to species performance as exotics, i.e. successful plantings outside Australia, yield in intensive plantations, and growth in different areas of California. Growth rates and wood yields from intensively-managed, overseas industrial plantations, under "Productivity in Plantations," are reported with a word of caution that the yield that can reasonably be expected from stands of any species is strongly dependent on site quality and level of management (Standiford, 1983). Mention of successful commercial overseas plantings under the heading "Success Outside Australia" is restricted to only other American states (e.g. Florida, Hawaii) and those countries that contain areas climatically similar to California (i.e. Mediterranean type), even though there may be other nations where a particular species has been planted.

Under the heading "Growth in California," published reports on field trials and commercial plantings in the state are summarized. Personal communications with individual researchers, foresters, nurserymen, etc. are also included here. When comparing the performance of a species in the various test plantings reported, consideration should be given to the existence of factors that affect seedling performance, e.g. differences in planting method, irrigation, spacing, provenance, etc. While efforts were made to report on as many plantings of eucalyptus in California as possible, there are obviously many others that are either not well documented or were unavailable to the author.

Propagation

The section entitled "Planting Prospects" is a consensus of opinion from the references cited on the relative usefulness of a particular species and its adaptability to different regions of the state. Species are rated under "Propagation" for their relative adaptability to containerized production in commercial nurseries based on information supplied by two experienced California nurserymen (Coate, 1983; Solomone, 1983). While most eucalyptus species are adaptable to containerized propagation, fast growth during the early seedling stages makes them susceptible to quickly becoming overgrown and rootbound, thus timing is more critical than with slower-growing species (Coate, 1983). Finally, additional information on hybrids, varieties, cultivars, seedling variability, disease and pest resistance, storm damage, pruning needs, etc. are listed when available under "Other."

PROPOSED HANDBOOK AND DATABASE

The information contained in the written survey of eucalyptus species described above lends itself to adaptation for an electronic database accessible by microcomputer. This database would be designed for use in conjunction with a printed, looseleaf handbook on eucalyptus, published as an on-going interagency project. It is proposed that this initial survey form the basis for the creation of such a handbook and database.

Most of the inquiries about eucalyptus received by land use advisors, nurserymen and landscapers will likely be to identify those species adaptable to a particular set of climatic and edaphic conditions, and useful for particular purposes. With a computerized database, this information can be retrieved with relative speed and ease compared to manual searching of printed documents. Several database managment programs are commercially available that could be used to cross-index succinct categories of information, or "fields," for individual species, such as growth rate, drought tolerance and uses. Thus, for example, one could use several "keywords" each relating to a different field to ask for a list of species adaptable to moderately cold winters and summer drought on heavy clay soils that are useful for windbreaks or firewood. Once such a list was retrieved, users could than refer to the printed handbook for a current, detailed description of each species, listing such information as seed provenances, commercial availability of seedlings and research contacts.

Creating the Database and Handbook

The primary task of creating the database will be to define the individual characteristics of each species that will be cross-referenced by computer, either in relative or absolute terms. Once the necessary software is modified and the original database is completed, periodic updating of species information could be done simply by issuing supplemental pages for the handbook. Researchers and others involved in field evaluations could report their results as available to one agency whose responsibility would be to update the handbook with this new information. Such updates would probably only be necessary one or two times per year. The handbook could also be expanded to include narratives on topics such as propagation, establishment and management.

Online access to the database could be arranged through local offices of the public agencies involved using any compatible terminal or microcomputer. This is facilitated by the fact that more of the public agencies receiving requests for eucalyptus information will soon have microcomputer systems in their local offices, e.g. University of California Cooperative Extension and U.S. Soil Conservation Service (Finch, 1983; Standiford, 1983). Those offices without such equipment could request searches to be done at a central office and the results printed out and mailed to them. Alternatively, the database could be accessed from remote terminals to a central computer via appropriate telecommunications equipment.

Funding

The bulk of the funding for this project would be needed in the first year, since the major tasks will be to create the initial database and printed handbook. The database can then be reporduced on inexpensive "floppy diskettes" and copies distributed to local offices. From then on, the relatively low cost of periodic updates and distribution could be covered by sales of the handbook and database or fees charged to the cooperating agencies or the individual end users. It has been suggested that the University of California, through the U.C. Davis Dept. of Environmental Horticulture and/or U.C. Berkeley Extension Forester's office, be the lead agency for the database if foundation funding can be secured for the project. Since its purpose will be to benefit public land use advisory agencies, nurserymen, landscapers, etc. in California, these groups must necessarily be involved in determining the format and content of the handbook and database that best serves their needs.

REFERENCES

Blakely, W.F., A key to the eucalypts. 3d ed. Canberra: Forestry and Timber Bureau; 1965.

Coate, Barrie, Director, Saratoga Horticultural Foundation, Saratoga, CA. Personal Communication, April 1983.

Finch, Sherman, State Woodland Conservationist, U.S. Soil Conservation Service, Davis, CA. Personal communication, May 1983.

Food and Agriculture Organization of the United Nations. Eucalypts for planting. Rome: F.A.O.; 1979. Forestry Series No. 11.677p.

Hemstreet, Chester L., Farm Advisor, University of California Cooperative Extension, Lakeport, CA. Personal communication, March 1983.

Leiser, Andrew T., Professor, Department of Environmental Horticulture, University of California, Davis, CA. Unpublished data on file.

Merwin, Miles L. Selected Eucalyptus species for rural plantings in California. Winters, CA: International Tree Crops Institute U.S.A., Inc.; 1983. 71 p.

Solomone, Joseph, S and S Nursery Growers Inc., Watsonville, CA. Personal communication, April 1983.

Part 3. Products, Uses, Economics

Using Eucalypts in Manufacturing[1]

William A. Dost[2]

Abstract: Eucalypts have a number of characteristics affecting processing and utilization that distinguish them from other woods. The major current interest in the eucalypts is as a fuel. Possible demand as a chemical feedstock, for pulpwood, panel products, lumber or round timbers should be be considered in initial planning and management as a hedge against changes resulting from economic, political or environmental pressures. In general, returns to the grower will be maximized by concentration on maximum yield (cubic volume x specific gravity) for energy, chemical feedstock and pulpwood uses. Specific gravity, as an indicator of strength, is also important for sawn products, round products and some panel products although processing considerations such as internal stresses and drying characteristics are important. Permeability of the wood for penetration by pulping chemicals or preservative solutions is important to pulpwood, and to sawn and round products. Characteristics such as specific gravity and fiber length can be manipulated to a considerable degree by species and seed source selection as well as by silvicultural manipulation.

The implications of these and other characteristics for utilization will be reviewed.

The eucalypts as a group are attractive because of their rapid growth. This results in very high yields on a volume basis and in combination with the comparatively high specific gravities, the yields of dry fiber can be truly impressive. Maximum yield of dry fiber is the logical goal when the anticipated use is for fuel, or as a chemical feedstock for processes such as destructive distillation. However, for solid wood products such as lumber and veneer, high specific gravity and the more complex anatomical structure may be quite disadvantageous when compared with softwoods.

The softwoods as a group are more efficient as a structural material, with a quite high strength to weight ratio. This superior rating relative to the hardwoods is not a consequence of any differences in chemical composition or relative amounts of cellulose and lignin present. The softwoods are composed almost entirely of a single cell type, the tracheid, with a length roughly 100 times the diameter. Hardwoods on the other hand have a more diverse anatomy (for oaks, 20 percent vessels, 40 percent fibers, 25 percent rays and 15 percent parenchyma). The fibers are the longest but length is generally one-third to one-eighth that of the softwood tracheids and with a poorer length to diameter ratio (only 40:1). In addition, other properties of the hardwoods make them more difficult to process.

The eucalypts, in addition to these general hardwood characteristics, typically contain high internal stresses and are prone to excessive shrinkage and distortion on drying. The net effect of these is to severely reduce the yield of usable material. Nonetheless, there are opportunities for the use of these woods for other products than energy or chemicals. They should be considered in planning any eucalyptus plantation since choices made then can substantially affect alternate use potential. Pulpwood is already in established use in California, as well as elsewhere. However, use in solid products such as sawn lumber and plywood and in round form for poles and piling, is not.

Use for Energy

The fuel value of woody cell wall substance is relatively independent of species, with a potential yield of between 8000 and 8500 BTU per dry basis. The differences between species result largely from the character of the extractives; those with a cyclic molecular structure are higher in value than straight chain structures such as sugars and starches. Burning characteristics generally improve with specific gravity although any hardwood above about 0.5 seems to burn very well when dry. Industrial fuel is sold on a dry weight basis and income will be maximized by concentrating on the yield of dry fiber. Cordwood for home heating is sold on a volume basis so income will be maximized by concen-

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Cooperative Extension Wood Products Specialist and Forest Products Laboratory Applied Problems Group Leader, University of California, Richmond, California.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

trating on yield on that basis, as long as the specific gravity is high enough so it is perceived to be a "quality" fuel.

The eucalypts characteristically exhibit interlocked grain, in which the stem alternates between left hand and right hand spiral grain. While this has no significance for heat content, it does increase the effort required in splitting cordwood and also will result in rough look pieces that are somewhat more difficult to handle. Wetwood occurs in the heartwood of mature trees and drying is made more difficult. This may not be a problem in plantations where the young stems will be substantially sapwood.

Chemical Feedstocks and Charcoal

Although neither of these are at present a particularly viable primary product the possibility exists that either economics or process technology may change so that these could become attractive. The best strategy for maximum raw material value is the same as for industrial fuel, maximum yield on a dry weight basis. However, if the process eventually adopted requires penetration of the wood by a solution, the species should be one that does not develop tyloses in the sapwood cells after felling in order that the process liquor may penetrate the wood.

Pulpwood

It is well established that young eucalypts are well suited for pulping by a full range of processes to yield pulps suitable for a wide range of end uses. Pulps from high density species are often blended with those from low density species or softwood to yield high quality pulps. In short, the potential for young eucalypts to provide good quality pulpwood appears to be very attractive.

Panel Products

The different panel products that are manufactured of wood are usually classified as plywood, hardboard, particleboard and insulation board, although the distinctions between these classes have become blurred as technology has advanced.

High quality hardboard is produced in volume from the mature wood of a large number of eucalypt species. This indicates that, at least for wet process production, the eucalypts in general are well suited. Eucalypts can also be used for insulation board manufacture without excessive problems, but species of lower specific gravity are generally preferred.

Panels of intermediate density in the range of 40-60 pcf are usually classed as particleboards although they may also be described as medium density fiberboards and hardboards. E. saligna is used commercially for production of particleboard at one plant in Brazil. In general, the eucalypts are not as well suited for particleboard production as lower density species, especially softwoods.

However, it should be noted that technology is advancing rapidly in this area and, at the 1982 annual meeting of the Forest Products Research Society, the keynote speaker observed that "It is now possible to manufacture panels whose properties are more dependent upon the process used than upon the species." Under this circumstance, the potential of the eucalypts should not be underestimated.

A small but significant portion of Australian plywood production is based on veneer from mature trees of several eucalypt species. Specific gravities below about 0.65 are required as is careful control of cutting parameters. Collapse and other forms of abnormal shrinkage are a problem and recovery of usable veneer is relatively low. Specific adhesive formulations and careful control are necessary to achieve good glue bond quality. "Excessive" end splitting of veneer logs, along with high shrinkage losses and kino defects, has contributed to the low veneer recovery from fast-grown young eucalypts. The wood makes a strong panel for structural use but appearance quality panels are not generally produced. Veneer for use green in wire-bound produce crating was successfully produced in Santa Cruz, California from E. globulus for a number of years.

Lumber

Eucalyptus lumber is widely used by the Australians for the equivalent of our structural light framing. However, there is some preference for radiata pine because it is less prone to warp. Some of the characteristics of the eucalypts that affect lumber manufacturing have been noted earlier. Internal stresses lead to splitting, brittleheart and shake in the log, change in shape of the log during sawing and to warp of the sawn lumber. Kino, in pockets or veins, is a defect that is peculiar to the eucalypts and the wood of many species characteristically exhibits excessive cracking, shrinkage and collapse on drying.

Quite a bit of information has been developed on drying techniques to minimize degrade in timber from both mature and fast-grown young stands. However, checking, warp, shrinkage and collapse are all reported to be more severe in material cut from young trees.

Round Timber

Utility and construction poles, marine and foundation piles, posts and rails are all produced from eucalypts in other countries and these applications certainly represent potential markets in California. The characteristics of young, fast-grown timber of each species need to be examined carefully for suitability. The splitting of log ends and development of circular checks or shake, both due to growth stresses, are a serious defect that is commonly reported. Maximum sapwood thickness is a desirable goal and thin sapwood species are unsuited. Ease of preservative treatment is critical and so, while sapwood is generally presumed to be treatable, this needs to be verified. Soft rot attack of eucalypt poles well treated with arsenical salts is a problem of widespread concern and investigation. Heartwood of high durability is a plus and the higher strength of the eucalypts in comparison to the currently used softwoods is also very attractive.

Management to Improve Utilization Opportunities

A number of basic properties have been noted as being important for their effect on utilization potential and are to some degee under the control of the forest manager. These include wood density, cell dimensions, sapwood thickness and permeability, and growth stresses. Seed source is often but not always related to density and does not appear to be an important factor in fiber length. Seed source seems very important to growth stress intensity. Increased growth rate achieved by fertilization results in decreased fiber length and vessel diameter, a decrease or no change in density, no change in growth stresses, and an increase in sapwood thickness. When increased growth rate is achieved by thinning, fiber length and growth stresses are increased. Higher environmental temperatures improve fiber dimensions (longer and more slender) and frost may increase the occurrence of kino. Longer rotations decrease the percentage of product lost in conversion due to growth stresses. High soil moisture during harvest can result in higher residual stresses and techniques to reduce tree vigor in advance of harvest will reduce them.

These generalizations are based on observations of a large number of workers on a range of species in diverse areas of the world and should not be considered as certainties for any given species and cultural practice.

SUMMARY

The eucalypts are very attractive for their potential to augment wood supplies. There is little or no problem in their use for fuel or pulpwood and they have been shown to make excellent hardboard. There are impressive difficulties in conversion to solid wood products such as lumber and plywood but generally these problems can be managed at some cost. For those species with a wide and permeable sapwood, use as roundwood products represents an excellent opportunity provided that end splitting can be controlled.

The potential of the eucalypts for utilization in California has been clouded by the choice of *E. globulus* as the principal species for planting, since it is one of the more difficult species to process. Establishment of other, more readily processed, species will lead to a change in attitudes and in use. However, none of the species can be considered to be easily converted to solid wood products.

REFERENCE

Hillis, W. E.; Brown, A. G., eds. Eucalypts for wood production, Part G. East Melbourne, Australia: Commonwealth Scientific and Industrial Research Organization; 1978. 434 p.

California Wood Energy Program[1]

Gary Brittner[2]

Abstract: Many varieties of eucalyptus adapt well to growing conditions in the coastal and central valley regions of California. The California Department of Forestry is conducting growth research on a variety of sites throughout the state with many species. Eucalyptus is an excellent fuelwood and has potential for other uses, including chemical feedstocks. Plantations established on marginal sites may be an alternative to grazing or agricultural crops.

The California Department of Forestry Wood Energy Program was established in 1978 and has been actively participating in many research and demonstration projects to increase utilization of wood for energy. The Wood Energy Program came about partly in response to the energy crisis of the 1970s, but a more important reason was a need to improve the management of the wood resource. The Department of Forestry recognized that an extensive resource was being undermanaged; there were uncoordinated research efforts and many unanswered questions about wood energy. California is rich in wood energy; forests and brushlands have been producing this natural and renewable energy resource for centuries. The timber industry in California has for many years been using captive waste from mills for energy, pulp, and composite products. One purpose of the Wood Energy Program is to expand utilization of the wood resource from more than just sawlogs and captive waste. Only about 40 percent of a tree's fiber is actually removed from the forest. The remaining portions are usually left because they cannot produce lumber and are uneconomical to harvest for pulp or fuel. The Wood Energy Program has worked on pilot projects to expand the utilization of unmerchantable wood, including: gasification, densification, chemical extraction, and charcoal production.

The California Legislature has authorized the Department to conduct research concerning the economic and environmental cost, benefits, and feasibility of utilizing wood for energy production. We are also able to provide technical and other assistance with respect to forest management and species selection to encourage energy production. The projects with which we are involved cover a broad range of fields including equipment design, chemical extraction, nutrient cycling, consumer information, and fuelwood plantations.

It is fuelwood plantations that I would like to dicuss today. Our experience with plantations comes from both contract and in-house fuelwood projects. California has a long history of eucalyptus plantations dating back to the turn of the century when there was a strong push to plant groves of eucalyptus for sawlogs and railroad ties. Unfortunately, the species planted did not lend themselves well for manufacturing into lumber. We are again experiencing rising interest in the use of eucalyptus, primarily for fuelwood. The renewed interest in eucalyptus has been brought about by a variety of factors such as: rising heating costs for conventional fuels, favorable return on fuelwood sales, and for many individuals, energy independence for winter heating.

The California Department of Forestry has two major projects investigating the use of eucalyptus and other fast-growing species for use as fuelwood. The projects are the Biomass Tree Farms and an in-house program growing fuelwood plantations on lands adjacent to Department facilities. The Biomass Tree Farms project was mandated by the legislature in late 1980 under sponsorship of Senator Greene. The purpose of the legislation is to demonstrate the production of biomass on marginal sites. The Department of Forestry has contracted for establishment of 9 plantations throughout the state, which include 8 genera and 17 eucalyptus species. We have also established our own program within the Department to grow fuelwood. This project is in conjunction with our energy conservation program to provide alternative energy for CDF facilities such as fire stations and offices. At some CDF facilities we are growing our own fuelwood to burn in woodstoves. This fuelwood program provides a demonstration to small landowners, reduces our energy costs, and provides research information. Most of the plantations were established in early 1982, and it is too early to present results to make recommendations. However, after one year of experience, we can present some general observations on our initial experiences.

The high rainfall and late rains in the winter of 1981-82 kept soils at field capacity and delayed site preparation and planting until late spring. Adequate soil moisture at the time of planting, relatively mild summer temperatures, and irrigation provided favorable growing conditions. The survival rate in most plantations exceeded 90 to 95 percent. Planting stock was commercially grown containerized seedlings. The most injurious agents we have noted are rodents and deer. *Eucalyptus camaldulensis* has been

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Wood Energy Program Manager, California Department of Forestry, Sacramento, California.

heavily browsed in San Luis Obispo and Lake counties by both deer and rabbit. In Lake County, rabbits browsed seedlings to the root collar, but they are sprouting back vigorously. Animal repellents will be used to discourage browsing, and pruning may be required in order to stimulate apical dominance; growth form is very poor.

Gophers were a severe problem in San Mateo County. Site preparation consisted of scalping, and the root mass of competing vegetation provided food supply for gophers. Eucalyptus seedlings which were being irrigated became a preferred food during the dry period when annual grasses died. These incidents reconfirm the importance of adequate site preparation. Control of surrounding vegetation is important because it decreases the competition for seedlings and reduces protective cover for rodents. An aphid species was observed on one specimen of *E. gunnii* in Fresno County, but no other insect or disease problems have been observed. In Yolo County under similar conditions, black locust (*Robinia pseudoacacia* L.) was killed by phytophtora root rot while *E. camaldulensis* showed no sign of infection.

One plantation was established in Merced County on saline alkaline soils; of five species, only *E. grandis* and *E. viminalis* survived, but their growth is not robust. The mild winter temperatures throughout the state may have given us more favorable results than usual. Slight frost damage was noted on tips of *E. camaldulensis* at 750-foot altitude because trees did not harden off. At an 1800-foot site, no damage on *E. globulus* or *E. dalrympleana* was observed. At 3500 feet, all *E. robusta* near the bottom of a drainage were killed by frost; *E. globulus, E. rudis,* and *E. macarthurii* at the same site, but higher on slope, received some slight frost damage.

Various silvicultural trials including spacing, fertilization, and irrigation are being performed on the plantations; but it is too early to present any results. Information from these plantations can be used by the small landowner wishing to put marginal lands to use. At the present, we see fuelwood plantations being established for personal use or the commercial firewood market. Large-scale plantations to supply wood-fired power plants are farther in the future. The current supply of boiler hog fuel is adequate since demand is low. As more wood-fired boilers come on line and hog fuel demand goes up, the feasibility of large-scale plantations will be more practical. At the present time, a small woodlot is the most logical choice. The small plantation of 1 to 10 acres offers many advantages; once established, a fuelwood plantation has fairly low maintenance costs, and the coppicing characteristic of eucalyptus eliminates replanting costs. Fuelwood also stores (and grows) quite well on the stump so harvest is up to the desires of the landowner. This characteristic also allows one to take advantage of changes in the marketplace. The fuelwood market is the least value use for the trees. As fiber values rise from increased demand, we can look forward to higher values and potential pulp or composite markets.

The Department has just completed work with GeoProducts Corporation testing manzanita (*Arctostaphylos* spp.) using the acid hydrolysis process developed by Dr. David Brink at the University of California Forest Products Lab. Tests of manzanita and other types of wood have yielded impressive results. From 1 ton of chipped manzanita, we were able to extract 514 pounds of hexose sugars and 341 pounds of pentose sugars. Fermentation of the sugars produced 36.7 gallons of ethanol. A variety of other chemicals including furfural, torula yeast, and butanol can also be produced. Lignin waste from the chemical process can be used as boiler fuel to complete utilization of the feedstock. Eucalyptus has not been tested, but we would expect it to be a suitable feedstock.

GeoProducts Corporation is studying the feasibility of constructing its first operational plant in another state. This type of plant creates demand for woody material unacceptable for lumber or pulp and provides jobs. Within the next decade I anticipate that one or more wood chemical facilities will be operating within California.

Demand for fiber, energy, and other products from forestlands will require intensive management of our resources. Research we are doing now may provide information key to the most efficient production. Hybrids, eucalyptus, and other exotics can help us meet these challenges.

Large-Scale *Eucalyptus* Energy Farms and Power Cogeneration[1]

Robert C. Noroña[2]

Abstract: A thorough evaluation of all factors possibly affecting a large-scale planting of eucalyptus is foremost in determining the cost effectiveness of the planned operation. Seven basic areas of concern must be analyzed:

1. Species Selection
2. Site Preparation
3. Planting
4. Weed Control
5. Irrigation
6. Harvest Planning
7. Economics of Co-generation

Only after detailed analysis has been completed, can the decision to move forward with major capital expenditures be made.

Present pay-back is marginal depending on cost of installations, operating expenses and "avoidable rate" payments from utilities.

The initiation of a large-scale cogeneration project, especially one that combines construction of the power generation facility as well as the establishment of the fuelwood source, is a major undertaking worthy of extensive preliminary investigations.

For the purposes of this paper a large-scale energy farm shall be one in excess of 100 acres. This size of wood producing farm by itself will not support a large commercial cogeneration facility (i.e., 1 mega watt or more), thus it will be assumed that some supplemental fuel source must be sought if the cogeneration facility will consume more fuel than the available acreage will supply.

Because a thorough analysis of fuelwood cost must be an integral part of the overall economic evaluation, all aspects of establishment of a stand, processing and handling of the fuelwood must be investigated.

Seven basic areas of concern must be studied for a complete economic analysis. A detailed discussion of all these is not possible in such a limited paper, however, each will be outlined. to indicate specific items which can considerably affect the cost effectiveness of the installation.

Selecting Your Eucalypt Species

Site evaluation -- is extremely important in determining which species will adapt well to the existing conditions. An exhaustive soil analysis is prerequisite to the successful establishment of any stand of trees and should be studied thoroughly to determine what problems if any might exist. The following outline lists several important factors which will weigh heavily on the decision as to the correct eucalypt species for the site in question. These factors are not, however, the only factors which will influence the final selection decision. Each site is a separate case in point and must be treated as such.

A. Site Evaluation
   1. Fertility
   2. Slope
   3. Water Table
   4. Site Specific Problems
      a. Alkalinity/Acidity
      b. Clay/Hardpan
      c. Salt Deposits
   5. Soil Type Variability

B. Species Evaluations
   1. Adaptability to Conditions
      a. Based on Literature
      b. Existing Site Evaluations
      c. In-House Evaluations

Species evaluation -- is the next step in the analysis procedure. After the site has been evaluated and the species which are compatible with the specific site are selected, the final decision can be approached as to the one species best suited to the site or the combination of species which would give the best overall performance.

The final selection will be tempered by such influences as seed or seedling availability and cost, macro- or micro-climatic conditions, tree growth habit and other unmentioned site specific problems.

As with any intergral part of an economic analysis, the consideration should be the production of the greatest amount of the best quality end product for the least amount of money.

[1] Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, Calif.

[2] Manager of Special Projects - Field Operations, Tri-Valley Growers, Modesto, Calif.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

Site Preparation

As with any farming operation, site preparation is first and foremost to assure a successful conclusion. Without proper site preparation, the successive operations of planting, weed control, irrigation and harvesting become at best difficult and at worst impossible. The proper scheme for land preparation is dependent on soil topography and structure. Obviously, certain operations may not be needed if site conditions do not warrant them. The following outline lists the most common operations that might be required prior to planting.

A. Leveling
   1. Planned for irrigation method

B. Ripping/Chiseling

C. Plowing/Discing

D. Seedling Bed Preparation

E. Pre-Irrigation and Fertilization

Leveling -- may only be needed on sites which are relatively flat and are slated for flood, check or furrow irrigation. Under drip, solid set sprinkler, pull hose, center pivot or other minimal water-use types of irrigation, leveling may be an uneeded and expensive operation. Rolling or hilly sites may do poorly if leveled due to the depth of cut and the consequent loss of fertility. Thus serious consideration should be given to both the economics and prudence of leveling the site.

Ripping/Chiseling -- again may only be necessary where hard or clay pans exist. Sandy or sandy loam soils generally will produce excellent crops of eucalyptus without the use of deep tillage. Many other soils although tighter than the sandy types will also produce well without the expense and trouble of deep tillage.

Plowing/Discing -- is the generally accepted form of ground preparation in California for most soil types, but may not be needed if alternative methods of competitive plant growth control are used. The economics of discing versus chemical control should be investigated if the present cover is not desired for green mulch.

Seedling Bed Preparation -- is only required when future plans are established for furrow irrigation, mechanical planting or where site specific problems such as salt crusting are present. Flat planting (Direct planting into level surface) under most circumstances is much more desirable than bed planting. Later operations such as weed control and harvesting are simplified by the lack of beds.

Pre-Irrigation and Fertilization -- are very desirable when planting eucalyptus. If planting can be scheduled for fall after first rains have arrived or early spring before the onset of hot weather, the need for pre-irrigation is eliminated. If planting is conducted where hot dry conditions exist and follow-up irrigation is not immediately available, the planting is almost assured of failure. With most types of potting mixtures the movement of moisture out of the root ball to the surrounding soil occurs within a few hours. If the dry condition is allowed to persist for 8-12 hours a potting mixture with a high percentage of peat will actually resist the infusion of water into the root ball during irrigation. Thus it is essential that adequate moisture be present at planting or immediately thereafter. Fertilization prior to planting can be accomplished in a number of ways, but must be weighed against post-plant fertilization. Economics and availability of equipment are the deciding factors in this instance. Broadcasting a dry fertilizer such as 16-0-0 is a relatively inexpensive means of applying the seedlings initial nitrogen need, but this method is inefficient with respect to placement of the nutrient near the root zone. Banding a dry or liquid fertilizer below and to the side (4 inches and 6 inches respectively) of the seedling will place the nutrients near the root zone but not so near as to burn the lateral root system or displace the tap root. This probably is the most effective application but not the least expensive. Water-running anhydrous ammonia into the irrigation water source would be the least expensive but is relatively short-lived in its effectiveness.

One other important factor that should be considered during site preparation evaluations is the level of pest infestation within the seedling root zone. Most eucalypts are resistant to Fusarium, Phytopthora, nematodes and other common pests, but under severe infestation conditions the performance of the stand could be impaired. If the eucalypt species has a history of susceptibility to an infestation present at the site, an alternate species or an alternate site should be considered.

Planting

The planting costs may vary widely depending on a number of factors. The first decision to be made is whether the seedlings to be planted will be purchased or propagated. If the decision is to purchase, the cost per seedling need merely be multiplied by the requirement for the planting. If self propagation is selected a much more extensive and tedious analysis is required. In most cases the cost of propagation is much lower than purchasing, however, convenience is lost in the process. Some of the precautions that must be considered when preparing seedlings are listed below. These are only precautions to be taken that are over and above those which are necessary to germinate, transplant and grow viable seed spots. It is assumed that a sound basic knowledge of eucalyptus seedling propagation is already at hand.

Seedling preparation -- must include the following important procedures.

1. Hardening of the seedling
2. On-site protection
3. Proper growing media
4. Topping or pruning
5. Container style

The success of the planting may depend upon close attention to the above procedures as well as the proper planting method for the site.

Mechanical versus hand planting -- is an economic decision to be made based on available equipment and labor.

Root ball coverage -- is very important for survival of the seedling during the first days and weeks after planting. Depending on the composition of the growing medium, any exposed portion of the root ball will act as a wick to allow moisture to leave the root zone and dissipate into the atmosphere. Survival of the plant under these conditions is questionable. Total coverage will assure retention of moisture during the all important first year of growth.

Planting density -- is a widely argued point. Many studies have been conducted with claims of tremendous yields per acre made by the investigators. In practice many different tree spacings can produce comparable yields. The important point to remember is the end product desired should dictate the planting density. Cogeneration facilities differ in their fuel requirements, therefore the composition of the fuel to be grown should be manipulated to match the fuel burning equipment.

High moisture contents can be tolerated by some firebox/boiler combinations. In these intances a very high density planting may be appropriate. High moisture content with a high leaf-to-stump ratio would yield a level of volatile compounds that would increase the BTU per pound and thus the effective output of the cogeneration facility. If very low moisture contents are required by the boiler design, a high stump-to-leaf ratio will be more appropriate.

The planned harvesting method, weed control and irrigation method will all modify the decision-making process. A wealth of publications are available to help a prospective biomass grower decide on an eventual planting pattern and density. Many of these studies have been conducted on the species most adaptable to California conditions and contain valuable statistics. To be prudent one should investigate the method of obtaining the statistics. If extrapolations have been made from single tree samples or very small plots, the results should be viewed with reserve.

Weed Control

Evaluation of weed species -- is the first step in establishing a successful weed control program. Once the full spectrum of weed species has been indentified and the species' growth habits known, a plan for their control can be developed. Many publications are available to assist in species identification, one in particular is the University of California Weed Identification Handbook.

Mechanical versus chemical control -- is a decision to be made early on in the analysis of the entire project. Some soil types do not lend themselves to mechanical weed control, thus it is wise to have an alternative plan that uses either partial or complete chemical control.

Selection of Materials -- should be made with advice of a properly qualified pest control adviser (PCA). Many of the most effective chemicals are restricted materials and therefore cannot be purchased over the counter without proper PCA recommendation or possesion of a commercial applicators certificate.

If farming operations are in existence in the immediate area of the site, it is advisable to ask the operator what materials they have found most effective. Practical experience is worth much in this situation.

Irrigation

For many areas of California irrigation is an absolute necessity. For those areas it is advisable to base the irrigation scheduling on the needs of the trees. There are many types of devices available which will objectively measure soil moisture. Among these are the tensiometers and neutron probes. By the use of these types of devices, the tree's need for moisture can be predicted before it shows any sign of stress. It also allows irrigations to be timed to avoid excessive watering.

Irrigation Method -- is also a very important economic and practical decision to be made. Many sites will only be served well by one type of irrigation method while other sites are adaptable to several types of irrigation systems. In most areas of California irrigation is only needed for the first two or three years of the trees' growth. If plantings can be spaced 3 years apart, the same irrigation equipment can be reused on each successive planting thus reducing the cost per acre for irrigation over the entire planting. This type of planning may preclude the use of the more permanent types of systems such as solid set or underground drip. The cost of the irrigation equipment is of prime concern, however, labor cost and the cost of water and/or pumping will weigh heavily on the eventual selection of the irrigation method to be used. Again, the cost of all components of the irrigation system will determine which system is the most economical.

In some irrigation districts in California the cost of water can be as low as $3.00 per acre for as much as 6 acre feet per year with very low labor costs to apply the water. In other areas the cost can be as high as $4.00 per acre for a much lower quantity of water per unit of area. These cost differences make it impossible to recommend one best system for all circumstances. In some cases the high initial cost of a drip system may be quickly offset by the savings in high cost water. In other cases the low cost of water may make it unjustifiable to make any capital expenditures.

The final concern with regard to irrigation is selecting the proper system for the site. The economic concerns mentioned above are in no way the only considerations. If a sprinkler system is to be used, the prevailing wind patterns are a very important consideration. Soil type will also determine the adaptability to such systems as drip or mist application. Extremely sandy soils will not disperse water well and may require several emitters to give adequate coverage. Topography will determine the initial selection of irrigation equipment. Irrigation specialists are available through the cooperative extension offices to assist in the proper selection of irrigation equipment or, if desired, private consultants can be hired to supply more detailed and specific economic information.

Harvest Planning

The planning of the eventual harvest of the biomass crop is difficult because estimates must be made a minimum of 4 years in advance and in some cases as much as 8 years prior to the first harvest. Several factors are important to consider and are discussed briefly below.

Labor Cost -- is always the first cost input to consider. If the projected wage rate is low enough to offset equipment purchase or rental, the biomass farmer may consider total harvest of the crop by manual means. For large acreages it is unlikely that hand labor can compete with some form of mechanical harvest.

Hauling Cost -- is another cost input that must be estimated far in advance with a high likelihood of error in the estimates. With fuel and labor rates fluctuating as they have in the past 5 years, an accurate estimate of future hauling cost will be extremely difficult. Costs may be reduced or virtually eliminated if the cogeneration facility is located at the farming site, but this sometimes is difficult when cost of land and the eventual point of usage of the power to be generated are conflicting.

Processing Equipment -- is available in several forms. All of the types mentioned below have their proper application, economics and efficiencies being the deciding factors.

1. Tub Grinders - have been adapted from use on hay processing to biomass use with some success. Biomass materials which are brushy and tend to bridge across the tub are not handled well in tub grinders that have no positive feed system. Tub grinders are the least expensive of the systems presently available. Examples: Medallion 905, W.H.O. 400NP.

2. Hoggers/Chippers - are more adapted to in-field processing where the chips are fed directly into a transport hopper from the hogger. With this type of system the hogger is semi-stationary and has facility for feeding whole trees of the diameter specified by the manufacturer directly into the chipping drum. Again, extremely brushy material is not handled well by this type of equipment, but is very efficient when processing whole trees 3" to 6" in diameter. Example: Nicholson PRC.

3. Down-The-Row Harvesters - are new and experimental at this point, but show a good deal of promise for the future. The only operational unit presently working, to the knowledge of the author, is the Nicholson-Koch mobile chipper. This unit is capable of felling and chipping trees up to 12 inches in diameter at a speed of 1 M.P.H. It is also capable of picking up and chipping previously felled trees up to 19 inches in diameter. The operational production rate is approximately 1 acre per hour on sites yielding 25 tons per acre or green biomass. For very large farms this type of machinery may be worth the investment of $200,000 to $300,000.

On-Site Drying or Direct Firing -- of biomass fuel is a decision to be made based on two basic factors.

1. Is the biomass farm located at the cogeneration site?

2. Is the cogeneration plant capable of burning high moisture fuel (40 percent - 60 percent moisture).

If the answer to the first question is positive, the decision to dry the fuel or not stands on its own without consideration for the cost of hauling wet fuel. The decision is then whether to dry the fuel and/or how much to dry it.

The drying process need not be expensive. Proper stacking of the wet fuel will cause internal heat to build in the stack without running the risk of spontaneous combustion. Fuel can be dried to 10 percent to 20 percent by this method. Caution should be exercised is stacking high moisture fuel above 12 feet in height unless the stack can be turned before combustion temperatures are reached.

The simplest of all worlds is to have the biomass fuel source and the cogeneration facility on the same site, and to purchase a firebox/boiler combination that is capable of producing the desired power output using high moisture fuel.

Economics of Cogeneration

Cost of installations -- will vary as with any major cogeneration installation based on the design and location of the facility. Most large cogeneration facilities will cost approximately 1 million dollars per megawatt of power produced if the facility is in the 1 to 20 megawatt range. Beyond the 20 megawatt capacity the cost per megawatt begins to rise rapidly.

Interest costs are a major concern for the cogeneration facility builder. If the return on investment from the sale of the power is not significant on a yearly basis, it may be difficult to repay the debt on construction. To be safe, the interest rate to be paid must be balanced against the revenue to be received using the lowest possible ROI rate for the life of the indebtedness.

Operations Problems -- will in all liklihood spell the difference between success and failure. Most cost estimations are based on relatively efficient operation of all components of the generation facility, while in actual practice many problems arise that prevent operation of the facility for extended periods of time. A list of recommendations follows that may be helpful in anticipating where problems will occur and how to contend with them.

A. Downtime will be encountered over and above the scheduled yearly maintenance procedures. Knowing that unexpected mechanical failures will occur, protection from income loss during these periods is a necessity. Insurance policies are available to assure income when manufacturer-caused mechanical failures cause loss of income beyond a specified period of time. Depending on premiums paid, a delay in payments from the insurance carrier is made to give the operator time to correct mechanical problems to the best of their abilities. When the more severe failures occur, payments from the insurance carrier will begin after the delay period and will continue for a specified period of time or until the failure is corrected.

B. To abide by the contracts for power production arranged with the utility destined to receive the power, the facility should be designed to operate at the rated output capacity of the generator with the boiler operating at 75 percent of capacity. If at all possible, the design of the boiler should be such that a partial shutdown of the boiler may be accomplished while continuing to operate at the rated output of the generator. A modular design or multiple cell boiler would accomplish this end.

Contracts being signed at this time have capacity guarantee clauses which allow for higher payments to the energy producer if specified levels of production are adhered to.

C. Consideration must be given to obtaining a sufficient quantity of high yielding fuel to supplement existing supplies. If price movement on fuel supplies appears to be stable or moving up, it would be wise to establish long-term contracts with suppliers. If movement is downward, of course one would want to withold contracting until the price is more favorable. In any event, the fuel should be well matched to the firebox conditions. Some boilers operate at very high temperatures (2000°F+). In these instances a fuel with a high percentage of ash, especially ash with a low fusing temperature is highly undesirable. The following sample analysis would be very helpful in determining the suitability of the potential fuel to the boiler. Boiler manufacturers can assist in evaluating a potential fuel to assure the proper operation of their equipment, and should be consulted well in advance of facility construction.

Fuel Analysis

Source of Sample: Biomass Fueled Boiler

Sampling Date: November 4, 1980

Appearance: Almond Shells (Fines)

pH of 1% solution in water	11.0	
Moisture	= 5.98 %	
Ignition Loss	=74.34 %	Ash = 19.68%
Sulfur (as SO_3)	= %	(Via $BaCl_2$ on aliquot of HCl extract)
Silicon (as SiO_2)	= 9.91 %	

The following elements are determined by atomic absorption spectrophotometry on appropriate aliquot portions of a stock solution which contains the hydrochloric acid extraction of the deposit.

Vanadium	(as V_2O_5)	Nil ppm
Nickel	(as NiO)	48 ppm
Iron	(as Fe_2O_3)	10310 ppm
Copper	(as CuO)	105 ppm
Manganese	(as MnO)	136 ppm
Aluminum	(as Al_2O_3)	60940 ppm
Sodium	(as Na_2O)	2700 ppm
Potassium	(as K_2O)	14060 ppm
Magnesium	(as MgO)	3010 ppm
Calcium	(as CaO)	4206 ppm
Zinc	(as ZnO)	ppm
Cobalt	(as CoO)	ppm

Accounted for: (including Ignition Loss, Sulfur as SO_3, and Silicon as SiO_2). 98.8 %

As can be seen this fuel would be undesirable because of the high ash content and high silicon content in the ash. In high temperature fireboxes this fuel could cause serious problems with fusing of the silicon on the boiler tubes.

D. Emissions control is of prime concern to any operator, in particular to those who will operate within metropolitan areas. No shortcuts should be considered in this area of concern. Many facilities recently constructed have gone through extensive and costly modifications to meet emission control standards as a result of incomplete consideration during the engineering stages.

Adequate equipment is available to control any emission problem that may arise in a biomass boiler. It would be wise prior to engineering a system to contact as many cogeneration facilities as possible to ascertain what the potential problems might be.

E. The boiler and firebox are generally trouble free if operated within design limitations. Problems arise in attempting to operate a piece of equipment above its rated capacity.

In the design phase of developing a cogeneration facility, a sufficient amount of excess capacity should be designed in to allow for such eventualities as low B.T.U. fuel, partial loss of heat transfer due to silicon fusing on boiler tubes, low fire temperature due to firebrick or refractory disintegration or mechanical problems in fuel feed systems.

By always assuming that a portion of the boiler system will be inoperable, the chance of not meeting the rated output of the generator will be greatly reduced.

F. A good deal of consideration should be given to the selection of the turbine and generation equipment. Users of operating facilities should be contacted for their opinions on the performance of the machinery being considered.

Because the entire effort of the operation culminates in the generation of power, an inadequate turbine or generator would be disastrous to the operation. Some typical problems that the manufacturer should be questioned about are:

Turbine

1. Performance history at existing facilities.
2. Seal construction and leakage control.
3. Gearbox reliability.
4. Oil supply and leakage control.
5. Scheduled maintenance shutdown requirements.

Generator

1. Performance history at existing facilities.
2. Bearing life.
3. Scheduled maintenance shutdown requirements.
4. Parts availability and major repair procedures.

Return on Investment -- can be measurably affected by the variable rate of the "avoidable cost" payments from the utility company.

The tables below are taken from the PG&E publication "Cogeneration and Small Power Production Quarterly Report."

PACIFIC GAS AND ELECTRIC COMPANY

PURCHASE PRICES (¢/kWh) FOR ENERGY FROM QUALIFYING FACILITIES
FEBRUARY 1980 THROUGH JULY 1983

Seasonal Period*	Time of Delivery Basis			Avera Basi
	On-Peak	Partial-Peak	Off-Peak	All k
Period B				
February '80 thru April '80	4.496	4.250	3.794	4.12
Period A				
May '80 thru July '80	5.675	5.459	4.700	4.99
August '80 thru September '80	6.100	5.868	5.052	5.36
Period B				
October '80	5.858	5.536	4.943	5.36
November '80 thru January '81	6.226	5.884	5.254	5.70
February '81 thru April '81	6.580	6.219	5.553	6.03
Period A				
May '81 thru July '81	7.783	7.487	6.446	6.85
August '81 thru September '81	8.072	7.765	6.685	7.10
Period B				
October '81	7.752	7.326	6.542	7.10
November '81 thru January '82	7.725	7.302	6.519	7.08
February '82 thru April '82	7.759	7.334	6.548	7.11
Period A				
May '82 thru July '82	6.397	6.102	5.895	6.17
August '82 thru September '82	5.967	5.692	5.499	5.64
Period B				
October '82	6.049	5.912	5.769	5.85
November '82 thru January '83	6.049	5.912	5.769	5.85
February '83 thru April '83	6.209	6.068	5.922	6.00
Period A				
May '83 thru July '83	6.108	5.826	5.629	5.77

* Period A comprises May through September, and Period B, October through April.

PACIFIC GAS AND ELECTRIC COMPANY

TIME PERIODS

	Monday through Friday[2]	Saturdays[2]	Sunda and Holi
Seasonal Period A (May 1 through September 30)			
On-Peak	12:30 p.m. to 6:30 p.m.		
Partial-Peak	8:30 a.m. to 12:30 p.m.	8:30 a.m. to 10:30 p.m.	
	6:30 p.m. to 10:30 p.m.		
Off-Peak	10:30 p.m. to 8:30 a.m.	10:30 p.m. to 8:30 a.m.	All Da
Seasonal Period B (October 1 through April 30)			
On-Peak	4:30 p.m. to 8:30 p.m.		
Partial-Peak	8:30 p.m. to 10:30 p.m.	8:30 a.m. to 10:30 p.m.	
	8:30 a.m. to 4:30 p.m.		
Off-Peak	10:30 p.m. to 8:30 a.m.	10:30 p.m. to 8:30 a.m.	All Da

The tables show that by manipulation of peak production of the cogeneration facility to hours in which the higher rate of return prevails, the amount of return can be significantly increased. Also it is obvious that if a cogeneration facility is planned and returns calculated with "avoidable cost" payments such as were made during August, 1981 through September, 1981, the downward trend in recent payments could render the facility nonprofitable.

Another set of factors that weigh heavily on the eventual success of the facility are the variable cost factors. Three of the major factors are listed below and should be given very serious consideration.

1. Labor
2. Materials
3. Fuel

Wherever possible, long-term commitment should be made to guarantee profit for the supplier as well as the cogeneration facility. If possible, contracts for the three factors listed above should be tied closely to fluctuations in "avoidable rate" payments so the facility will remain viable throughout its life.

Misconceptions -- abound in the biomass cogeneration industry. Many assume the return on investment is very high, when in fact it can be marginal to unprofitable. Only the most astute operators can be guaranteed a profit. Systems efficiencies are generally overrated. Fuel sources are estimated to contain more B.T.U.s per pound than they actually contain, boilers are overrated in their efficiency, turbines and generators are generally more prone to maintenance problems than manufacturers will admit and many more exaggerations of performance exist. The potential operator must keep all of these factors in mind to assure a successful conclusion to the establishment of a biomass farm and cogeneration facility.

Economic Evaluation of Eucalypt Energy Plantations[1]

Richard B. Standiford and F. Thomas Ledig[2]

Abstract: An analysis is made of the break-even price at a 6 percent and 10 percent real interest rate for "intensive" and "minimally managed" scenarios for managing eucalypt energy plantations. The break-even price is greater than the average stumpage price reported for firewood and chipwood by the State Board of Equalization. However, a conversion surplus approach shows that eucalypt firewood plantations are profitable for both the intensive and minimally managed scenario. For plantations producing chips for energy, only the minimally managed scenario, with yields greater than 58 dry tons per acre at harvest, appears to be profitable, assuming delivered chip prices of $35 per bone dry ton. The benefit-cost ratio for a commercial planting of eucalypts at the Concord Naval Weapons Station, California, showed that a return of at least 10 percent on establishment costs was highly probable with proper choice of species.

An evaluation of the economic feasibility of investment in a eucalypt energy plantation must involve an assessment of the costs of the various cultural practices (planting, weed control, irrigation), the costs of processing the standing tree into a usable form (logging costs, transportation costs, chipping, cutting to firewood length) and the returns expected from the sale of the processed product (firewood, chips), all compounded or discounted to a constant point in time at an interest rate selected on the basis of management objectives.

Presented below are two different analyses of eucalypt energy plantations. First, two possible management scenarios are presented, drawn from a survey of planting and cultural practices throughout California, and a "break-even" price is calculated. This break-even price is the necessary return on a cord of firewood or ton of chips, to earn a given rate of return on money invested in the plantation. The second analysis calculates a benefit-cost ratio from an actual case study of a commercial planting of eucalypts at the U.S. Naval Weapons Station in Concord, California, using actual cost and return data from early trials by the USDA Forest Service's Institute of Forest Genetics.

BREAK-EVEN PRICE ANALYSIS

With the new flurry of interest in planting eucalypts, there have been many proposed management scenarios statewide. These range from the use of intensive agronomic practices such as cultivation, irrigation and fertilization, to a more extensive "wildland" type of planting, with little management input after initial tree planting. For the purpose of this analysis, two theoretical cases were developed to represent the range of management proposals. Table 1 presents the cost data for two different levels of management, namely intensively managed and minimally managed eucalypt energy plantation. The cost data presented are based on some average figures for actual eucalypt plantations in California and some general costs derived from managed plantations of other tree species (Klonsky et al, 1983; Rose et al, 1981). All costs and returns in this analysis are in constant 1982 dollars, and the interest rates used are real interest rates (net of inflation).

Methods

The objective of the analysis was to calculate a break-even price for a eucalypt energy plantation for the two levels of management. The first step in the process was to discount all costs back to the present time at a 6 percent and 10 percent real interest rate using equation 1 below. Costs were assumed to occur at the beginning of the year.

$$DC = C/((1+i)\exp(n-1)) \qquad (1)$$

where:
DC = discounted cost
C = actual cost
i = interest rate
n = year when cost occurs.

An 8-year rotation length was chosen for this analysis because it is near the point of culmination of mean annual increment for several species reported in the literature (FAO, 1981; Metcalf, 1924). Because many eucalypt species coppice readily from the stump following harvest, no additional investment in stand establishment costs are

---

[1] Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2] Forestry Specialist, Cooperative Extension University of California, Berkeley; Project Leader, Institute of Forest Genetics, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Dep. Agric., Berkeley, California

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

Table 1--Costs per acre for intensively and minimally managed eucalypt energy plantations in California. 1st rotation assumed to be 8 years and the 2nd and 3rd rotations assumed to be 7 years.

		Cost/Acre (1982 Dollars)		Discounted Cost (1982 Dollars)			
		Intensive	Minimal	Intensive		Minimal	
Cultural Practice	Year(s)	Management	Management	6 pct.	10 pct.	6 pct.	10 pct.
Site Preparation[1]	1	150.00	50.00	150.00	150.00	50.00	50.00
Pre-emergent Herbicide	1	27.00	27.00	27.00	27.00	27.00	27.00
Seedlings[2]	2	363.00	204.00	342.45	330.00	192.45	185.45
Planting Labor	2	62.40	35.36	58.49	56.36	33.96	32.73
Irrigation[3]	Annual	100.00	--	620.98	533.49	--	--
Initial Watering	2	--	200.00	--	--	188.68	181.82
Weed Control	2	40.00	40.00	37.74	36.36	37.74	36.36
Fertilization[4]	2	30.00	--	28.30	27.27	--	--
	3-8	56.00	--	294.93	247.85	--	--
Management Costs	Annual	5.00	5.00	31.05	26.67	31.05	26.67
Land Rental	Annual	150.00	40.00	931.47	800.24	248.39	213.40
TOTAL DISCOUNTED COSTS-- 1 Rotation				2522.41	2235.24	809.27	753.43
TOTAL DISCOUNTED COSTS-- 3 Rotations				4009.51	3111.58	1071.70	908.08

[1] Intensive-- Disc and rip; Minimal-- Disc only
[2] Intensive-- 1210 seedlings/acre at $.30/each; Minimal-- 680 seedlings/acre
[3] Includes labor, depreciation, water
[4] 76 lbs.-N 1st year, 152 lbs.-N subsequent years

needed for at least the next two or three harvests. In subsequent rotations, some replanting may be necessary to replace stumps which fail to coppice (Fahraeus, 1974). For this analysis, the break-even price was calculated on the basis of 3 rotations. The second and third rotations were assumed to be 1 year shorter than the first rotation because the well-developed root system of the coppiced trees will allow full site occupancy more quickly than occurs with seedling trees. The total period for the 3 rotations is 22 years. The discounted costs for the first rotation were summed up, and the results are shown in table 1. It was assumed that all costs except stand establishment costs (site preparation, seedlings, planting labor) would remain the same for the second and third rotations. These costs were also discounted back to the present, and table 1 shows the total discounted cost for the 3 rotation period.

Based on the costs presented in table 1, the break-even price is calculated for the sale of eucalypt stumpage for the intensive and minimally managed scenarios, at the 6 percent and 10 percent real interest rate. Break-even price has been defined as the necessary price per unit required to earn a given rate of return on money invested in the plantation. To solve for this value, the discounted costs are set equal to the discounted returns.

$$DC = DR \tag{2}$$

where: DC = discounted costs
DR = discounted returns.

Since the discounted returns can be expressed as:

$$DR = (Y x BEP)/((1+i) exp(r)) \tag{3}$$

where: DR = discounted returns
Y = yield
BEP= break-even price
i = interest rate
r = rotation length.

then equation 2 can be transformed to:

$$DC = (Y x BEP)/(1+i) exp(8) + (Y x BEP)/(1+i) exp(15) + (Y x BEP)/(1+i) exp(22). \tag{4}$$

This equates the discounted costs from the three rotations to the discounted returns from the three rotations (occurring in years 8, 15, and 22 respectively). Equation 4 is transformed to:

$$DC = Y x BEP((1+i) exp(-8) + (1+i) exp(-15) + (1+i) exp(-22)). \tag{5}$$

Because the merchantable yields for these management scenarios are not precisely known, the break-even price (BEP) is calculated for a range of potential yields. For each assumption about merchantable yield, the break-even price was calculated using equation 6.

$$BEP = DC/Y((1+i) exp(-8) + (1+i) exp(-15) + (1+i) exp(-22)). \tag{6}$$

Table 2--Break-even stumpage price per cord and per dry ton for intensive and minimal management of eucalypt biomass plantations based on merchantable yield and interest rate. Rotation length for the first rotation is 8 years and 7 years for the second and third rotations.

Merch. Yield at Rotation			Intensive Management				Minimal Management			
			6 pct.		10 pct.		6 pct.		10 pct.	
Cubic Ft.	Cords[1]	Dry Tons[2]	$/cord	$/Ton	$/cord	$/Ton	$/cord	$/Ton	$/cord	$/Ton
1360	16	29					50	28	68	38
2720	32	58					25	14	34	19
4080	48	86	63	35	78	43	17	9	23	13
5440	64	115	47	26	59	33	13	7	17	10
6800	80	144	38	21	47	26				
8160	96	173	32	18	39	22				

[1] Assumes 85 cubic feet of solid wood per cord
[2] Assumes 1.8 Tons per cord

Results

The results of the analysis are shown in table 2. For example, for a merchantable yield of 64 cords of firewood at the end of an 8-year rotation (or 7-year coppice rotation) using the intensive management scenario, the grower needs $47 per cord for firewood stumpage to receive a 6 percent real return on the planting investment, or $59 per cord to receive a 10 percent real return on the investment. For comparison, under the minimally managed strategy, with yields only half of the intensive management option, or 32 cords, then table 2 shows one would only need to receive $25 for a 6 percent return on investment and $34 for a 10 percent return. Table 2 also shows the break-even price per dry ton for individuals selling eucalypt trees on that basis of measure.

The differences between the break-even price for the intensive and minimally managed cases points out that one must carefully evaluate whether the intensive cultural costs and the resulting yields would really give an acceptable return on a tree planting investment.

Assessing Market Prices

Once the break-even price for an investment in eucalypts has been calculated, an assessment is needed of how this compares with the actual market price being received for stumpage in an area. Many owners are looking at the delivered firewood prices being paid in metropolitan areas in the state, and assuming they will receive the same price for their standing trees. This does not consider the considerable costs involved in getting a standing tree harvested, processed into firewood, and transported to a market. Owners who consider marketing chips to a biomass cogeneration facility need to assess the costs of harvesting, chipping, and transportation.

Firewood

Since the California Yield Tax applies to harvested firewood, the California State Board of Equalization (SBOE) annually collects information on the average stumpage price received for firewood statewide, and reports the figures in the Harvest Value Schedules to serve as the basis for the yield tax owed by the landowner. In the most recent Harvest Value Schedule, the average stumpage value for hardwood fuelwood was $15 per cord, and $8 per cord for non-hardwood fuelwood (SBOE, 1982). It is quite obvious that for the relationships shown in table 2, only the minimally managed management scenario at yields greater than 48 cords per acre would be close to this statewide average for fuelwood stumpage. These figures, however, tend to be collected mainly from commercial forest areas of the state, and due to the rugged terrain, which results in high harvesting costs, and the long distance to market, the Harvest Value Schedule values may be lower than individuals would receive for planting eucalypts on fairly level terrain, close to the eventual firewood market.

To get a better idea as to what market price might be possible, we worked backward from a final delivered firewood price to arrive at a stumpage value using a "conversion surplus" approach.

In general the final market price for any wood product can be expressed as:

$$SP = STP + HC + PC + TC + MPR \quad (7)$$

where:
SP = selling price
STP = stumpage price
HC = harvesting cost
PC = processing cost
TC = transportation cost
MPR = margin for profit & risk.

Table 3 gives the result of a study of firewood harvesting and processing carried out in New England (Dammann and Andrews, 1979). The study calculated the most efficient mix of equipment for a firewood harvest based on the average log skidding distance and the annual production of the firewood harvesting/manufacturing firm. The average harvesting, processing, and transportation cost, including a 15 percent margin for profit and risk (HC, PC, TC, MPR terms in equation 7) ranged from $33 to $48 per cord for a 20-mile one-way distance to market, and from $66 to $94 per cord for a 90 mile one-way distance to market.

Table 3--Contract harvesting, processing and transportation costs for firewood, 15 percent margin for profit and risk (1982 dollars). Source: Dammann and Andrews, 1979.

Transportation Distance	Cost/Cord [1]	Equipment Type [2]
20 miles	$33-48	Chainsaw; Ground Skidder; Splitter; Loader
90 miles	$66-94	Dump Truck

[1] Cost varies based on skidding distance, yearly production, and type of equipment.

[2] Type of equipment chosen on basis of skidding distance and yearly production to minimize total harvesting, processing and transportation costs.

If we assume a final selling price of $150 per cord (SP term in equation 7) for firewood, then by subtracting these figures in table 3, we can get an idea as to the conversion surplus left for firewood stumpage. For a 20-mile haul, the maximum possible value for stumpage using these harvesting and processing costs would be $102 to $117 per cord. This would require a commercial firewood planting located in very close proximity to a major market center such as Sacramento, the San Francisco Bay Area, or Los Angeles. It can be seen that the conversion surpluses exceed the break-even price figures in table 2, and thus the return on planting would exceed the 6 to 10 percent real interest rates used in the analysis.

It is much more likely, based on the high land prices of areas surrounding the major market centers, that eucalypt planting would be distributed 90 miles from a final market center. If this were the case, the conversion surplus left after subtracting the harvesting, processing and transportation costs from the firewood selling price would be $56 to $84 per cord, which also appears feasible at our expected levels of yield.

Biomass Chips

The California State Board of Equalization (SBOE) also reports the average stumpage price for chipwood in its Harvest Value Schedule. The most recent schedule reports average stumpage for hardwood and softwood chipwood as $1 per green ton, which would convert to $2 per bone dry ton, assuming a moisture content of 100 percent on an oven-dry basis. This average stumpage price is far below the break-even prices reported per dry ton in table 2.

We used the conversion surplus approach to calculate the residual value left after harvesting, processing, transportation, and a margin for profit and risk were subtracted from the delivered price for chips at a biomass cogeneration facility. According to a recent Pacific Gas and Electric (PG&E) report, there are currently 13 biomass cogeneration facilities in California, and another 15 facilities projected to be in operation in the near future (PG&E, 1982). To date, these plants mainly operate on residue from wood product and agricultural processing industries. Some residue from orchard prunings and urban tree removals are also purchased. A survey of several of these purchasers shows that the delivered prices paid by the facilities ranges from $22 to $35 per bone dry ton.

Table 4 shows the costs of harvesting, processing, and transporting biomass chips to a cogeneration facility. These data were collected from various studies. All the reports calculated costs on the basis of approximately 2000 hours of equipment use per year, which means that a considerable acreage would be needed to justify the capital expense of purchasing the equipment.

At the $35 per bone dry ton for delivered chips, and $22 per ton for harvesting, chipping, and transportation on level terrain with a high level of mechanization, then the conversion surplus for stumpage would be $13 per ton. Table

Table 4--Contract harvesting, processing and transportation costs for wood chips, 20 mile haul, 15 percent margin for profit and risk (1982 dollars).

Costs ($/Dry Ton) [1]	Terrain	Equipment Type	Reference
$21.95-28.70	level to rolling	Feller buncher, grapple skidder, chain flail, whole tree chipper, chip van	Arola & Miyata, 1981
$19.56-24.45	level to rolling	Same as above	Rose, Ferguson, et al, 1981
$34.50	>50% slope	Spyder feller buncher, Skyline yarder,	Schiess, 1982
$47.15	>50% slope	Chainsaw, accumulator, Pewee yarder,	Schiess, 1982

[1] Range in price due to different average tree diameters and volume per acre harvested.

Table 5--Costs for establishment of eucalypt plantations with contract labor at Concord Naval Weapons Station (Data on file at USDA Forest Service Pacific Southwest Forest and Range Experiment Station).

Operation	Year	Current Costs($)		Discounted Costs($)					
				Interest Rate/Seedlings per Acre					
		Seedlings per Acre		5 pct.		6.2 pct.		10 pct.	
		435.6	810	435.6	810	435.6	810	435.6	810
Site Preparation									
Discing	1	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Spraying	1	44.00	44.00	44.00	44.00	44.00	44.00	44.00	44.00
Discing	2	20.00	20.00	19.05	19.05	18.83	18.83	18.18	18.18
Spraying	2	44.00	44.00	41.90	41.90	41.43	41.43	40.00	40.00
Planting									
Seedlings	2	130.68	243.00	124.46	231.43	123.05	228.81	118.80	220.91
Planting	2	56.63	97.20	53.93	92.57	53.32	91.53	51.66	88.36
Cultivation									
Spraying	3	44.00	44.00	39.91	39.91	39.01	39.01	36.36	36.36
Irrigation									
Monthly	3	178.60	332.13	162.00	301.25	158.35	294.48	147.60	274.49
TOTAL				505.25	790.11	497.99	778.09	475.60	742.30

2 shows $13 per ton to be greater than the break-even price for only the minimally managed scenario at yields greater than 2720 cubic feet (58 dry tons) per acre. At $22 per bone dry ton for delivered chips, then only the costs of harvesting, chipping, and transportation are covered, which means no price could be paid to the landowner for stumpage.

In Washington on very steep terrain for mechanized harvesting of biomass, preliminary studies shown in table 4 indicate that the costs of harvesting, chipping, and transportation alone are greater than the delivered price of wood chips.

It is anticipated that as more biomass conversion facilities come on line, and as the real price of energy continues to increase, competition will drive the real price of wood chips up, although it is difficult to predict to what level. Our analysis shows the sensitivity of a eucalypt energy plantation to the delivered price for wood chips.

CASE STUDY-- CONCORD NAVAL WEAPONS STATION

Our objective in this section is to evaluate the economic viability of a eucalypt planting program at the Concord Naval Weapons Station by dividing present value of benefits by present value of costs, both discounted at various interest rates. The benefit-cost ratio is useful to determine if a project is returning an acceptable return on the public resources invested.

Actual costs of the various cultural operations required to establish eucalypts at Concord refer to contract labor, and include a margin for profit and risk (table 5). Experience at Concord indicates that the site requires intensive cultivation for eucalypt production. The planting site should be disced and sprayed with herbicide for one year before planting, at the time of planting, and one year after planting. Summer irrigation by tank truck is budgeted for the first year. Two planting densities were considered, namely 435.6 seedlings per acre, which was the density used for species trials at Concord, and 810 seedlings per acre, which should produce a well-stocked stand even after considerable mortality.

Methods

The analysis reported here was completed in 1980 and is reported in 1980 dollars. All costs were discounted to the (then) present time using equation 1 at a 5 percent, 6.2 percent, and 10 percent real interest rate. The bulk of evidence suggests that 5 percent is the rate most commonly applied to public investments (D.E. Teeguarden, pers. comm.). The rate actually used by the Forest Service in its analyses under the Resources Planning Act is 6.2 percent. The 10 percent rate was chosen because it was felt to be closer to the

Table 6-- Yields and current value for 9-year-old eucalypt plantations at Concord Naval Weapons Station. Source: King and Krugman, 1980.

Species	Survival (pct.)	Trees (#/acre)	Volume (cords/acre)	Green Weight (tons/acre)	Current Value	
					Firewood ($25/cord)	Chips ($8/ton)
E. dalrympleana	60	261	25.86	77.58	646.50	620.64
E. grandis	91	396	24.21	72.63	605.25	581.04
E. nitens	94	409	26.60	79.80	665.00	638.40
E. viminalis	75	327	15.98	47.94	399.50	383.52

Table 7--Benefits per acre on a 9-year coppice rotation for E. dalrympleana (D) and E. viminalis (V) fuelwood at Concord Naval Weapons Station (Assuming stumps will coppice 4 times before replanting is necessary.

Cutting Cycle	Year	Value at Harvest[1] ($/acre)		Present Value ($/acre)				
				D			V	
		D	V	5 pct.	6.2 pct.	10 pct.	5 pct.	6.2 pct.
1	11	761.54	470.59	467.52	417.30	293.61	288.89	257.87
2	20	870.74	538.07	344.58	277.67	142.37	212.93	171.53
3	29	995.60	615.22	253.97	184.76	69.04	156.94	114.17
4	38	1138.36	703.44	187.19	122.93	33.48	115.67	75.97
5	47	1301.58	804.31	137.96	81.80	16.23	25.25	50.55
TOTAL				1391.22	1084.46	554.73	859.68	670.14

[1] Assuming a real price increase of 1.5 percent per year and a current stumpage of $25 per cord.

rate of return for private investors. Table 5 gives the actual and discounted costs per acre in 1980 for the two planting densities.

Data from a eucalypt species trial at Concord (King and Krugman, 1980) were used to estimate yields (table 6). These yield data were collected from trees planted at the 435.6 seedling density level and reduced by natural mortality. Mean annual increment was probably at a maximum around 8 to 9 years.

In one respect the yield data could be considered inflated: trees were planted in small plots (16 trees) and because of mortality in adjacent plots, trees of the successful species were relatively free of competition at the plot edge. On the other hand, it is now obvious that these early trials were not planted with the best seed sources and current tests indicate that yields could well be doubled with proper choice of seed. Furthermore, yields were certainly underestimated for the coppice rotations. The eucalypt species mentioned here, with the exception of shining gum (Eucalyptus nitens Maid.), will sprout back readily after cutting, and regeneration by sprouting is anticipated for at least four cutting cycles. The sprout generations should grow more rapidly than the initial seedling generation because they begin on an established root system. Because there was no way to estimate the increased growth, yields were assumed to be the same as those for the first generation, giving a conservative estimate of returns.

For the higher planting density, there was no data to evaluate yields. Volume per tree will likely be less at the higher density, but volume per acre may well increase, particularly at rotations as short as 9 years. The higher density option was included because it is a commonly used spacing in eucalypt plantations around the world. For our analysis we used a conservative assumption; i.e., that yields at the closer spacing would be the same as yields at the wider spacing. Although we do not have a good estimate of the benefits of closer spacing, the scenario may have importance in evaluating the profitability of a high planting density when high mortality is expected. Plantings on a large scale and at various spacings are needed to develop better estimates of yield, but on balance, the present estimates seem to be conservative.

The discounted benefits (returns) from 5 cutting cycles for mountain and manna gums (E. dalrympleana Maid. and E. viminalis Labill.) are shown in table 7. As the previous section pointed out, it is difficult to assess the stumpage price for eucalypt energy products. Our analysis assumed a stumpage price of $25 per cord, which is close to the stumpage price of $8 per ton for chips. Since stumpage prices for wood products in general are projected to increase at about 1.5 percent annually in real dollars (Haynes, Connaughton, Adams, 1980), a real price increase was included in the calculation of the benefits.

Results

Table 8 shows the benefit/cost ratio, determined by dividing the discounted benefits in table 7 by the discounted costs in table 5. It appears that planting mountain gum on Navy land will return at least 6.2 percent on the investment (the B/C ratio is greater than 1), and even 10 percent at the low planting density. It will not return 10 percent on the investment at the high planting density (the B/C ratio is less than 1), at least with our conservative estimates of yield and liberal estimates of costs.

Table 8--Benefit/Cost ratio for plantations of E. dalrympleana and E. viminalis at the Concord Naval Weapons Station using contract labor.

Seedlings per acre	E. dalrympleana			E. viminalis	
	5 pct.	6.2 pct.	10 pct.	5 pct.	6.2 pct.
435.6	2.75	2.18	1.16	1.70	1.35
810.0	1.76	1.39	0.75	1.09	0.86

In general, the economic returns used in these calculations were probably conservative. Yields will be higher because coppice growth is more rapid than seedling growth; biologic productivity is probably not maximized at the 435.6 seedling density level which is the limit of this data; and selection within species can be used to improve yields (Ledig, this proceedings). Contract costs are often higher than in-house costs, so the benefit-cost ratios reported may be higher if in-house labor is used. All of these factors suggest the economic outlook for eucalypt production is even better than that summarized in table 8, yet even the present scenario indicates that eucalypt culture is quite profitable.

Acknowledgements: We appreciate the cooperation of the Western Division, Naval Facilities Engineering Command, U.S. Navy and the Public Works Office, Concord Naval Weapons Station, and especially thank Dave Sikes for information on contract costs.

REFERENCES

Arola,R.A. and E.S. Miyata. 1981. Harvesting wood for energy. USDA Forest Service Research Paper NC-200, 25 pp.

Dammann,J.C. and R.A. Andrews. 1979. Economies in fuel wood supply firms in New Hampshire. University of New Hampshire Agricultural Experiment Station Research Report No. 76, 23 pp.

Fahraeus,L. 1974. Manual of logging and transport in Eucalyptus plantations. Food and Agriculture Organization of the United Nations, Swedish Funds-In-Trust TF-INT74 (Swe.), 50 pp.

FAO.1981. Eucalyptus for planting. FAO Forestry Series No. 11. Food and Agriculture Organization of the United Nations, Rome, Italy, 677 pp.

Haynes,R.W., K.P. Connaughton, and D.M. Adams. 1980. Stumpage price projections for selected western species. USDA Forest Service Research Note PNW-367, 9 pp.

King,J.P. and S.L. Krugman. 1980. Tests of 36 Eucalyptus species in Northern California. USDA Forest Service Research Paper PSW-152, 6 pp.

Klonsky,K., R. Standiford, B. Krueger, T. Bailey. 1983. Sample costs to produce Eucalyptus for firewood. Univ. of California Cooperative Extension, Glenn County mimeo, 6 pp.

Metcalf,W. 1924. Growth of Eucalyptus in California plantations. University of California Agricultural Experiment Station Bulletin 380, 61 pp.

PG&E.1982. Pacific Gas and Electric co-generation and small power production quarterly report, third quarter, 1982.

Rose,D., K. Ferguson, P.C. Lothner, and J. Zavitkowski. 1981. An economic and energy analysis of poplar intensive cultures in the Lake States. USDA Forest Service Research Paper NC-196, 44 pp.

SBOE.1982. California State Board of Equalization Harvest Value Schedules, effective January 1, 1983 through June 30, 1983. Sacramento, CA.

Schiess,P. 1982. College of Forest Resources, University of Washington, Seattle. Presentation made at: The Western Fuelwood Management Seminar, October 25-28, 1982, Pack Forest, Eatonville, Washington.

Teeguarden,D.E. 1982. Chairman, Department of Forestry and Resource Management, University of California, Berkeley. Personal Communication.

Part 4. Growth and Yield

Growth and Yield of Some Eucalypts of Interest to California[1]

Roger G. Skolmen[2]

Abstract: Eucalyptus globulus ssp. globulus, E. viminalis, E. grandis, and E. camaldulensis were selected as the species of interest in California. Yield data for these species from around the world indicate that wide variation can be expected among species, provenances, sites, and management systems. Large gains in yield can be achieved by careful selection within this wide variation to suit California conditions. Growth characteristics of the eucalypts and distribution of the more important plantation species around the world were also reviewed.

For more than 100 years, eucalypts have been generally recognized around the world as among the fastest growing trees. Height growth of 10 m (32 ft) a year during the second or third year of growth has frequently been recorded. Yields of 20 m^3 per ha per year (286 ft^3/acre/yr) are generally considered as only better than average in Brazil and the Republic of South Africa. Even in California with its long summer drought, some remarkable yields have been measured. In addition, the trees will often grow reasonably well on impoverished sites where other species barely survive.

Everywhere Eucalyptus has been introduced, there has been, and still is, an ongoing search for better-growing species. I, for one, suspect that the nine best eucalypt species for pulp or timber plantations have already been identified for most parts of the world.

In the moist tropics, E. deglupta and E. urophylla; in the intermediate tropics to warm temperate zone, E. grandis (saligna), E. robusta, E. citriodora, E. tereticornis; and in the cooler humid temperate or semi-arid and arid temperate zone, E. globulus ssp. globulus, E. viminalis, and E. camaldulensis.

I have combined E. grandis and E. saligna because they are so frequently mixed. So actually, there are 10 species, perhaps even 11 if E. sideroxylon is thrown in, and that illustrates the problem. It is very easy to just go on adding species.

For this discussion, I have arbitrarily chosen four species that I consider to be of most economic interest to California:

Eucalyptus globulus ssp. globulus
Eucalyptus viminalis
Eucalyptus camaldulensis
Eucalyptus grandis (saligna)

I will discuss their behavior as plantation trees in various countries around the world.

GROWTH

Height

Many eucalypts have a capacity for phenomenal height growth. The tallest hardwood tree in the United States is a E. saligna growing in North Kona on the island of Hawaii, which in 1980 was about 50 years old and 84 m (276 ft) tall (Petteys 1983). Most height growth occurs while the trees are still young. Usually, within the first 5 to 10 years of age, 60 to 70 percent of total height growth is achieved among the tall forest eucalypts. As an example, in the course of a plantation spacing study in Hawaii, one tree measured was 32 m (106 ft) tall at 5 years of age. In the same stand at 15 years dominants were 43 to 46 m (140 to 150 ft) (Walters 1980). These trees grew 4.3 m (14 ft) per year for 5 years, then 1.2 m (4 ft) for 5 years, and then 0.3 m (1 ft) per year for 5 years.

Diameter

Diameter growth, although quite rapid, is less dramatic than height growth. In Hawaii, in the saligna/grandis complex we work with, we find that for trees up to 5 years old, spaced at 2 by 2 to 3 by 3 m (6.5 to 10 ft), the ratio of height in meters to diameter in centimeters is close to 1.0. A tree 4 m tall will usually be about 4 cm in diameter-at-breast-height (d.b.h.) (3 ft of height per 0.4 inch of diameter). This ratio, of course, varies with species, site, climate, stocking, and age.

A comparison of 10-year growth of three species at different locations indicates that the height-to-diameter ratio in trees of this age is usually more than 1.0 (table 1). In widely spaced stands, such as those of

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Research Forester, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley, California, stationed in Honolulu, Hawaii.

E. camaldulensis in Morocco, diameter growth is still sufficient at age 10 to maintain the ratio at about 1.0. Site has a stronger influence on the ratio with the other species and levels of stocking. Eucalyptus grandis in South Africa greatly exceeds the other species in height growth. The criteria for separating good, fair, and poor sites are height measurements at age 10.

Table 1--Ratio of height in meters (h) to diameter in centimeters (d) at age 10 by species, site, and stocking.

Species and location	Stocking (stems/ha)		Site: Good	Fair	Poor
Eucalyptus globulus North Spain	2500	Height h/d	22.0 1.57	16.0 1.42	13.0 1.31
Eucalyptus globulus Portugal	1100	Height h/d	27.0 1.39	19.0 1.26	11.0 1.29
Eucalyptus camaldulensis Morocco	800	Height h/d	15.6 0.95	13.0 0.95	10.4 0.95
Eucalyptus grandis South Africa	1100	Height h/d	34.8 1.76	28.4 1.55	20.2 1.19

Source: FAO 1979, p. 310.

YIELD

Volume

Tree volume is measured and reported in many different ways around the world, so it is important to look at what is being measured when reviewing the literature. Frequently, this important information is not reported. Most commonly, total stem volume over bark is used. It is determined with d.b.h., total height, and a form factor, which in Third World countries is usually a ratio of volume to basal area times height--the old "artificial form factor" of European forestry (Assman 1970). Some volume tables allow for stump height, some are to a top diameter, some are for volume under bark, and some are of stacked volume (FAO 1979). The volume figures I report here are all for total height over bark, unless otherwise specified.

Biomass

Data on total biomass are scarce, but of great interest currently. In Australia, Cromer and others (1975) found E. globulus ssp. globulus seedlings to have a weight yield at 4 years made up of 55.5 percent stemwood, 11.5 percent bark, 16.5 percent branchwood, and 16.5 percent leaves (table 2). At age 6, the percentage of stemwood had increased slightly while the percentage of branchwood decreased (FAO 1979); percentage of leaves remained the same. Data I collected in three ssp. globulus coppice stands in Hawaii gave 72 percent of the dry weight yield in stems and bark at age 3, 76 percent at age 4, and 77 percent at age 5. So it appears that with both seedlings and coppice of this species we can expect 70 to 75 percent of weight yield of young trees to be in stems and bark.

Other data (FAO 1979) indicate that by volume rather than weight, stems of ssp. globulus in Italy were 15 to 20 percent bark, depending on their diameter. For pulp yields this is important because ssp. globulus bark is used in most pulping processes. On the other hand, E. camaldulensis bark, which is not used in pulp, made up 20 to 30 percent of stems under 20 cm (8 inches) in Italy. Eucalyptus grandis bark, also not desired in pulp, was about 15 percent in small trees in three countries reported.

Table 2--Biomass percentages in Eucalyptus globulus grown in Australia.

Material	Age (years): 4	6
Stem	67.0	71.7
Wood	55.5	57.1
Bark	11.5	14.6
Branches	16.5	12.7
Live	12.0	9.8
Dead	4.5	2.9
Leaves	16.5	15. 6

Source: FAO 1979, p. 315.

Weight

Weight is an important consideration in growing fuelwood or pulpwood. Most eucalypts produce light-weight wood when very young and then increasingly denser wood with age. During the first 5 to 10 years, wood density increases along radial and height gradients, and in trees of the same age, the wood of highest average specific gravity will be found in the largest and tallest trees. Rapid diameter and height growth do not necessarily result in reduced average wood density as would be expected (King 1980). However, wood density of young trees is often much less than that of mature trees, which is the density usually reported in the literature. In Hawaii, a study done in 1978 indicated that dry weight of 2- to 5-year-old ssp. globulus coppice ranged with stand age from 421 to 494 kg/m^3 (26 to 31 lb/ft^3) in samples from the lower 2 m (6.5 ft) of the stem (Skolmen 1980). This is only 70 percent of the dry weight of mature wood. Three years later, in 1981, we sampled 40 trees in the stands, which were then 7 and 8 years old. Specific gravity at breast height remained the same, but samples from 6 m (20 ft) averaged 511 kg/m^3 (32 lb/ft^3). The wood density increased with height. Elsewhere in Hawaii, specific gravity at 2 years of age was 0.39 for E. saligna and 0.36 for E. grandis (BioEnergy Dev. Corp. 1983). Mature trees of these species have wood that ranges from 0.50 to 0.60 in specific gravity. It may be necessary to carry eucalypts for a longer rotation than planned merely to increase average density.

EUCALYPTUS GLOBULUS SSP. GLOBULUS

Eucalyptus globulus ssp. globulus is the common bluegum that was originally introduced into California from Tasmania or the southern part of the state of Victoria. Probably because its juvenile foliage is unpalatable to cattle, it was favored in early introductions and widely planted (FAO 1979). Today, because of its rapid growth and adaptability to a wide variety of site conditions, it is one of the most planted of all eucalypts around the world. It has been particularly successful in countries with a Mediterranean climate such as California, Portugal, Spain, Chile, and the western part of the Republic of South Africa.

In Portugal, where it is by far the most common species planted, there are 238,000 ha (588,000 acres) of E. globulus (FAO 1979). Most plantations are near the coast in northwest Portugal where the annual rainfall normally exceeds 850 mm (33 inches). Stands are worked on a coppice rotation of 10 to 12 years for the production of paper pulp and firewood. Mean annual increment (MAI) ranges from 12 to 30 m^3/ha/yr (172 to 429 ft^3/acre/yr) (Turnbull and Pryor 1978).

In Spain, bluegum grows on 205,000 ha (492,000 acres) (FAO 1979). In the Huelva Province near sea level, where the very seasonal annual rainfall is 440 mm (17 inches) bluegum produces only 4 to 8 m^3/ha/yr (57 to 114 ft^3/acre/yr) of wood which is used for pulp and mine props. In the north, where rainfall is evenly distributed and exceeds 1000 mm (39 inches), production is more like that in Portugal, ranging from 12 to 20 m^3/ha/yr (172 to 286 ft^3/acre/yr).

In Chile, large areas of bluegum are managed on coppice rotations of 5 to 20 years for firewood, charcoal, and mine props. In a zone of annual rainfall of over 1200 mm (47 inches), ssp. globulus withstands temperatures down to -7° C (20° F) and is reported to grow in areas with annual rainfall as low 350 mm (14 inches). It also grows extensively in Argentina, Uruguay, Peru, Bolivia, and Ecuador (Turnbull and Pryor 1978).

In Hawaii, bluegum was planted in the early 1900's and did quite well at higher elevations of 1200 to 1800 m (4000 to 6000 ft). At this elevation range, good yields sometimes exceed 1400 m^3/ha (100,000 fbm/acre) in 60-year-old stands. At lower elevations in Hawaii, the species frequently produces short, stunted trees with extremely spiralled grain.

Bluegum coppices very well and forms lignotubers, which will live for many years in the soil if the stem dies back due to suppression. These will sprout after the rest of the stand is logged. In our coppice stands in Hawaii we normally get coppice on the stumps as well as coppice from these buried lignotubers. In addition, a stand of seedlings usually becomes established along with the coppice (Skolmen 1980).

In Hawaii we studied E. globulus coppice that came in after logging four 64-year-old stands. These bluegum stands were similar to those in California of about the same age and diameter. Four stands involved in this study were growing at an elevation of about 1200 m (4000 ft) and receiving 1250 to 2000 mm (50 to 80 inches) of rain per year. The four stands had been logged during consecutive years between 1973 and 1976. When measured, 2, 3, 4, and 5 years had passed since logging. Despite the age of the stumps, 70 to 80 percent of them had coppiced. But we found that about half the volume in the stands was from stems that had sprouted from buried lignotubers that had been present before logging. These lignotubers were the remnants of suppressed stems that had died and disappeared. In addition to the coppice, all stands had seedlings, which made up more than 20 percent of the total number of stems in all stands but contributed very little to the volume as they were usually suppressed by the coppice. MAI varied from 10.4 to 14.0 m^3/ha/yr (150 to 200 ft^3/acre/yr) among the unmanaged 2- to 6-year-old coppice stands over two years of measurement (Skolmen 1980).

In this coppice study, stems with bark intact averaged 60 percent moisture content calculated on a fresh weight basis. During normal logging in Hawaii, when stems are converted into chips we find that moisture content is generally reduced to about 50 percent if the bark is included. This is often considered high moisture content by boiler engineers who usually specify no more than 42 percent. In Hawaii, we cannot deliver freshly felled E. globulus with this low a moisture content unless the stems are debarked.

In coppice yields worldwide, first coppice crop volume generally exceeds the volume of the seedling crop by 20 to 25 percent (FAO 1979). Studies in Portugal (FAO 1979) indicated that the second coppice crop with E. globulus ssp. globulus should be about 80 percent of the initial seedling crop and the third coppice crop less than 80 percent. In our coppice study in Hawaii, the mean annual increment of total above-ground biomass ranged from 7.8 to 10.6 t/ha/yr (3.5 to 4.7 tons/acre/yr). Seventy percent of the weight was in the stems (Skolmen 1980). Distribution of weight among the different types of stems was 50 percent coppice on stumps, 11 percent seedlings, and 39 percent coppice from buried lignotubers.

In Australia, Cromer and others (1975), found that at age 4, unfertilized seedlings of ssp. globulus produced 12 t/ha (5.3 tons/acre) of total biomass (dry) including branches and leaves. These same plots at age 6 produced 25 t/ha (11.1 tons/acre) for a mean annual increment in weight of 4 t/ha/yr (1.8 tons/acre/yr). Plots that were fertilized produced 90 t/ha (40 tons/acre) or 15 green t/ha/yr (6.7 tons/acre/yr). It was further found that the percentage of weight in stems versus branches and leaves did not vary with the various fertilizer or control treatments.

With bluegum, MAI of 10 m^3/ha/yr (143 ft^3/acre/yr) is considered typical on poor sites, while very good sites yield up to 35 m^3 (500 ft^3) (FAO 1979).

Considerable growth information has been gathered for ssp. globulus in Portugal and Spain (FAO 1979). For a good site in Portugal, at age 2, there was a MAI of 10 m^3/ha/yr (143 ft^3/acre/yr), which peaked at age 12 (fig. 1). At age 10 MAI was 38 m^3 (543 ft^3). The dry weight of ssp. globulus wood is about 600 kg/m^3 (37 lb/ft^3). The green weight, because the stem is about 50 percent water, would be 1200 kg/m^3 (74 lb/ft^3). The weight increment at 10 yr is therefore about 45.6 t/ha/yr (20 tons/acre/yr) on the best site. This is the elusive 10 dry tons/acre/yr of biomass that managers strive for. The poor site at 2 years had a MAI of only 2 m^3 (28.6 ft^3) and similarlv at age 10 only 8 m^3 (114 ft^3), so site has a major effect on yield.

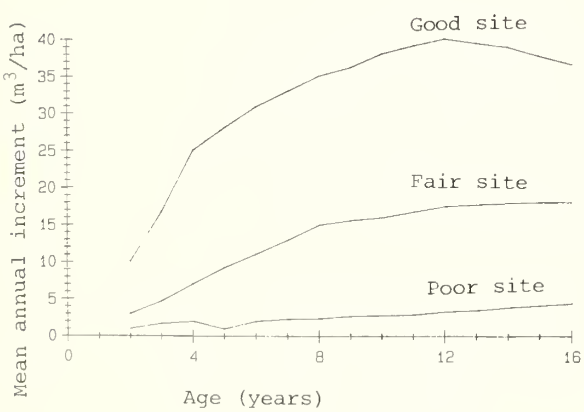


Figure 1--Eucalyptus globulus ssp. globulus, Portugal 1100 per hectare.

In northern Spain, with stocking double to triple the stocking of the stands in Portugal, at age 4, MAI was 27.5 m^3 (393 ft^3) on the best site (fig. 2). At age 10, it was up to 44 m^3 (629 ft^3). The northern Spain sites are quite comparable to the sites in Portugal. On the fair site in northern Spain, MAI began to

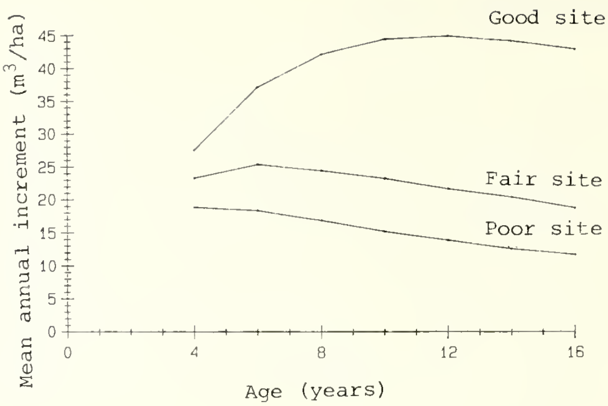


Figure 2--Eucalyptus globulus ssp. globulus, N. Spain 2700 per hectare

drop off after 6 years. By age 10, on the poor site, yield was down to 15.2 m^3/ha/yr (217 ft^3/ha/yr), whereas at the close spacing used, 18.8 m^3 (263 ft^3) was achieved at age 4.

In southwestern Spain, on a much drier site, a much wider spacing had to be used, and MAI was much less (fig. 3)--at age 9, on the very best site, only 8 m^3/ha/yr (114 ft^3/acre/yr). On the worst site at age 9, yield was only 0.8 m^3/ha/yr (11.4 ft^3/acre/yr). I suspect this might be comparable to the conditions in southern California in most years. At a somewhat better area in southwestern Spain at 9 years on the good site, MAI was 16.2 m^3/ha/yr (232 ft^3/acre/yr) (fig. 4). On the poor site, this went down to 0.9 m^3/ha/yr (13 ft^3/acre/yr).

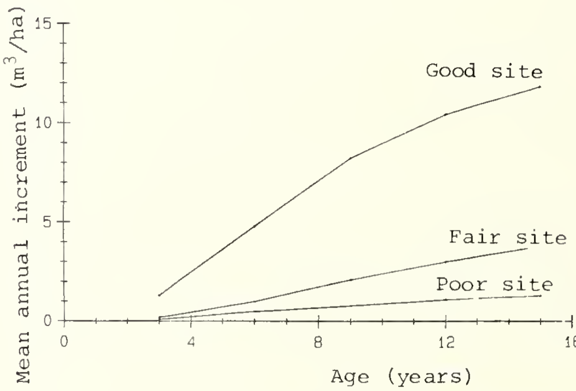


Figure 3-- Eucalyptus globulus ssp. globulus S. W. Spain (sandy) 600 per hectare.

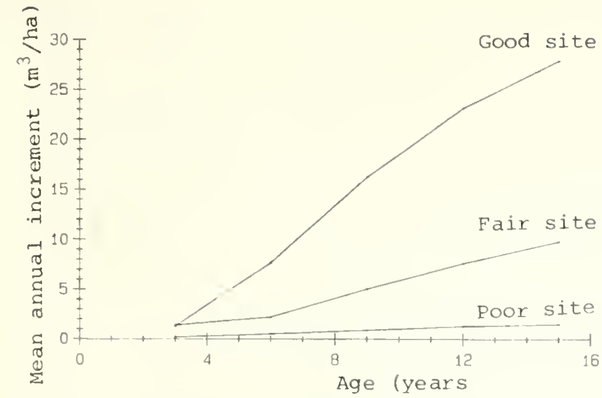


Figure 4--*Eucalyptus globulus* ssp. *globulus*, S.W. Spain (shale) 600 per hectare.

EUCALYPTUS VIMINALIS

The principal advantage of *E. viminalis* as a plantation tree over the other three eucalypts is that it will withstand cooler temperatures. It is suitable for cool climates such as in northern California, that are subject to moderate frosts. This species has been widely planted in southern Brazil, Argentina, Italy, and the Black Sea area of the Soviet Union. It is also considered promising in Chile, Portugal, Spain, and Turkey.

Its main use is as a short-rotation fiber crop for pulp and hardboard production. In Spain, several thousand hectares have been planted on sites that are too cold for ssp. *globulus*, and at 450 m (1500 ft) elevation it yields about 12 m^3/ha/yr (172 ft^3/acre/yr) (FAO 1979). *Eucalyptus viminalis* is considered a good plantation species. It coppices very well, and the coppice does not die back easily in winter. In Australia, the species has a wide latitudinal range and many provenances, so is a very suitable one for provenance testing. The trees can withstand temperatures of -10° C (15° F), but in Russia were killed by temperatures of near -16° C (0° F) (FAO 1979).

EUCALYPTUS CAMALDULENSIS

Eucalyptus camaldulensis is the widest ranging eucalypt in Australia, so there are many provenances suitable for a great many different sites. Its principal desirable feature as an introduced plantation tree is its ability to withstand lengthy and severe drought. The tree can also withstand periodic flooding and was one of the first species to be taken from Australia and planted elsewhere, having been planted in Italy as early as 1803. Today, around the world, there are estimated to be more than a half million hectares of *E. camaldulensis* in plantations, especially around the Mediterranean. Spain has more than 100,000 ha (247,000 acres). In Morocco, there are about 87,000 ha (215,000 acres). It is also the tree most commonly planted in Israel.

In addition to its ability to withstand long drought, *camaldulensis* also has some resistance to frost and is a vigorous coppicer. However, the stem is usually more crooked than *E. globulus* or *grandis*, two of the other most frequently used trees. Also, the crowns are rather thin so stands are more prone to weed invasion than those of some of the other denser crowned eucalypts. This, incidentally, might be considered a desirable characteristic by those concerned about creating biological deserts by planting eucalypts that prevent understory growth. The wood is heavier, harder, and, more deeply colored than *E. globulus* or *grandis* and therefore, not as good for pulp. However, the wood is better than either of the other species for fuelwood because of its high density (FAO 1979).

There has been more provenance testing with this species than any other of the eucalypts, probably because it has more provenances. Some of the results obtained suggest the extreme importance that provenance testing be done in the areas where unknown seed sources are already doing well. An example is a test done at Afaka in Nigeria (table 3). Five-year-old trees had MAI that ranged from 17.3 m^3/ha/yr (247 ft^3/acre/yr) to 5.1 m^3/ha/yr (73 ft^3/acre/yr), depending on where in Australia the seed had come from. This demonstrates a possible three-fold increase in yield achieved simply by selecting seed source location.

Table 3--*Eucalyptus camaldulensis* provenance test at Afaka, Nigeria.

Seed source	Latitude	Rain-fall	Eleva-tion	5-year growth Height	MAI
		mm	m	m	m^3/ha/yr
Petford, Q.	17°20'	716	518	17.8	17.3
Katherine, N.T.	14°20'	958	110	15.1	14.1
Wiluna, W.A.	26°38'	249	490	14.2	11.3
Alice Springs, NT	23°08'	252	580	14.8	9.4
Bourke NSW	31°54'	234	210	11.4	8.3
Wohlpooer V	37°00'	606	300	13.2	7.6
Menger's Hill S.A.	34°30'	1182	610	10.4	5.4
Walpole NSW	34°10'	247	90	12.4	5.1

Source: FAO 1979, p. 375.

[1]MAI = Mean annual increment.

Growth varies greatly according to climate and soil. On good sites MAI of 2 m (6.5 ft) in height and 2 cm (0.8 inch) in diameter may be maintained for the first 10 years. But on poorer and drier sites, growth is reduced to 1 m (3.3 ft) in height and 1 cm (0.4 inch) in diameter per year. Volume yields of 20 m^3/ha/yr (286 ft^3/acre/yr) are reported from Argentina, and on the very best sites in Israel, as much as 30 m^3 (425 ft^3) may be obtained. In Turkey, 20 m^3 (286 ft^3) can be obtained on good sites in the initial seedling rotation and 30 m^3 (425 ft^3) in subsequent coppice rotations. However, on poorer and drier sites,

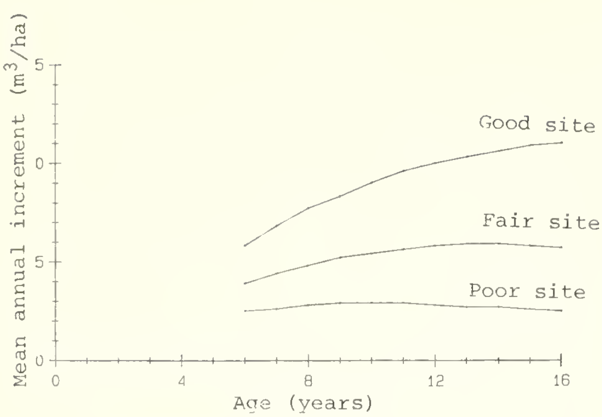


Figure 5--Eucalyptus camaldulensis, Morocco 800 per hectare.

much lower yields can be expected. Other countries report corresponding yields (FAO 1979).

Most E. camaldulensis plantations are managed on coppice rotations of 7 to 10 years on better sites, and longer on poor sites. In Spain, for example, rotations are 14 to 15 years. The first coppice rotation is expected to produce a higher yield than the initial seedling rotation and the length of the rotation may be adjusted accordingly. For example, in Morocco, a seedling rotation of 12 years is common followed by 7 years for the first coppice rotation and 10 years for the second (FAO 1979).

Yield variation of E. camaldulensis on three sites in Morocco at a spacing of 3.5 by 3.5 m (11.5 by 11.5 ft) is believed to be typical for this species (fig. 5). MAI at age 6 was 5.8 m^3 (83 ft^3) and at age 10 it was 9 m^3 (129 ft^3) and still rising. On the medium site, at age 6, MAI was only 3.9 m^3 (56 ft^3) and at age 10, 5.4 m^3 (77 ft^3). On the poor site, at age 6 MAI was 2.5 m^3 (36 ft^3) and at age 10, 2.9 m^3 (4 ft^3). On the medium site, MAI peaked at 14 years. On the poor site it peaked at 11 years. On the good site, the trees at this somewhat wide spacing of 800 stems/ha (324/acre) were 16.5 cm (6.5 inches) diameter at 10 years (FAO 1979).

EUCALYPTUS GRANDIS

Eucalyptus grandis is more suited to the semitropics and in California is probably limited to the southern part of the state in those locations where water is sufficient. It is killed back by frost and in general has about the same temperature sensitivity as citrus. This species was not segregated out by botanists until 1918. Before then, much of the E. saligna that was introduced around the world was really E. grandis because until 1918, the trees that were recognized as E. saligna included E. grandis. For this reason, in many parts of the world, there is a mixture of E. grandis and E. saligna present and also hybrids between them. This is particularly true in South Africa and also in Hawaii. South Africa has now taken to calling their trees E. grandis, while in Hawaii, we call them E. saligna. Many trees in any stand in Hawaii will show the characteristics of either species. However, E. grandis is a distinct species and where it has been compared, it has usually been found that E. grandis will outgrow E. saligna on the same site. On the other hand, saligna has somewhat denser wood than grandis and for that reason may be preferred on some sites as a fuelwood producer (FAO 1979).

Provenance comparisons in Hawaii (BioEnergy Dev. Corp. 1983) have shown average yields at 3 years of 15 and 42 m^3/ha/yr (215 and 600 ft^3) for E. grandis at two different sites where E. saligna in the same tests produced 12 and 32 m^3/ha/yr (172 and 458 ft^3/acre/yr). At the better site the best E. grandis provenance had an increment of 56 m^3/ha/yr (800 ft^3/acre/yr) while the worst provenance had 28.8 m^3/ha/yr (412 ft^3/acre/yr). On the poorer site this 2:1 ratio between the best and the worst was increased to 2.5:1, so seed source selection clearly pays dividends. These provenance test yields are blown up from trees growing in randomized plot designs which create reduced competition for the best growing provenances. Therefore they are overestimates of true yield.

Eucalyptus grandis is one of the most important introduced eucalypts. There are well over half a million hectares planted in countries other than Australia, particularly South Africa and Brazil, and also in Angola, Zimbabwe, East Africa, India, Argentina, and Uruguay. If we combine what is called saligna with grandis as one species, then this E. grandis/saligna complex is unquestionably the most widely planted eucalypt in the world with well over 1 million ha (2,470,000 acres) planted (FAO 1979).

Eucalyptus grandis/saligna is the most commonly planted eucalypt because it is the fastest growing exotic that has been found for vast semitropical areas in the southern hemisphere that have been developed in the 1900's. It grows very rapidly in height at 2 to 3 m (6.5 to 10 ft) a year over the first 10 years. The excellent self-pruning stem is very straight. It forms a dense crown which will shade out weed competition at an early age. It flowers and seeds at 3 to 4 years and coppices freely when young. Coppicing has become more difficult after 10 to 12 years in stands in Zambia. The tree will not withstand a severe frost and generally does best where rainfall is evenly distributed, although in some locations, it has been shown to withstand droughts of 3 to 4 months. Eucalyptus grandis can be propagated from cuttings relatively easily so long as the cuttings are taken from young coppice on stumps. By using this method it may be that soon seedling plantations will become rare (FAO 1979). A prime example of this is at the Aracruz Corporation's holdings in Brazil, where they have not only increased growth to the phenomenal rate of 73 m^3/ha/yr (1044 ft^3/acre/yr) by using clonal plantations, but have also increased cellulose yield by 10 percent over initial seedling plantations (Campinhos 1981).

Generally, around the world, a 6- to 10-year rotation is used for pulpwood, fuelwood, or wood for mine supports. In most countries, short rotations are not thinned. Spacing of 2 by 3 m (6.5 by 10 ft) is most commonly used in such plantings. Usually, one seedling rotation is followed by at least two coppice rotations (FAO 1979). Aracruz Corp. in Brazil buries the stumps of the seedling crop to prevent them from coppicing and replaces them with clonal plantations. With these they expect to grow one rotation from planted ramets followed by four rotations from coppice, although at this point this is still speculation (Campinhos 1981).

Generally, in the countries where E. grandis has been most widely used, reported annual yield figures fall in the range of 14 to 35 m^3/ha/yr (200 to 500 ft^3/acre/yr). A yield of 20 m^3/ha/yr (286 ft^3/acre/yr) is considered normal above average growth for stands less than 15 years old (FAO 1979).

Because the species has been widely planted around the world, yield information is abundant (FAO 1979). Data from Uganda show some of the highest yields; with stocking of 1680 trees per ha (680/acre) even average sites maintained more than 20 m^3 (286 ft^3) over 15 years (fig. 6). This figure gives stem volume under bark, rather than over bark as with the previous data presented. On the poor site, stem volume had already peaked at age 4 with 24 m^3/ha/yr (343 ft^3/acre/yr). On the medium site it had also already peaked at 4 years at 36 m^3/ha/yr (514 ft^3/acre/yr), but on the good site, MAI did not peak until age 6 or 7, when it achieved an amazing 52.4 m^3/ha/yr (750 ft^3/acre/yr).

On a good site in South Africa, with a stocking of 1100 trees per ha (445/acre), the MAI (under bark) at age 3 was 19.1 m^3 (273 ft^3) and at age 9 was 45.5 m^3 (650 ft^3) (fig. 7). On the medium site at age 3 MAI was 10.7 m^3 (153 ft^3) and at age 10, 27.4 m^3 (392 ft^3). On the poor site, MAI was 5.1 m^3 (73 ft^3) at age 3 and 12.5 m^3 (179 ft^3) at age 10. On the poor site MAI peaked at 12 or 13 years whereas on the medium site it peaked at 10 years (FAO 1979).

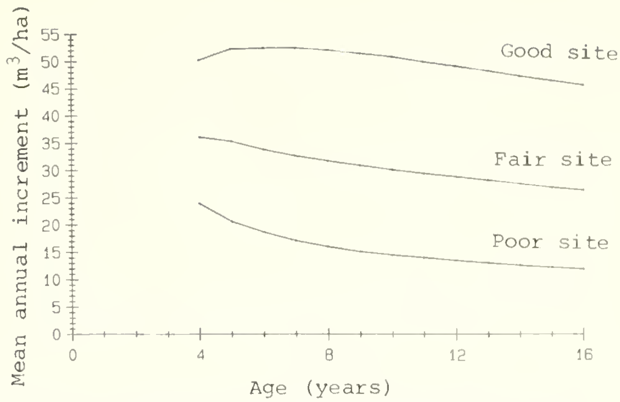


Figure 6--Eucalyptus grandis, Uganda 1680 per hectare (volume under bark).

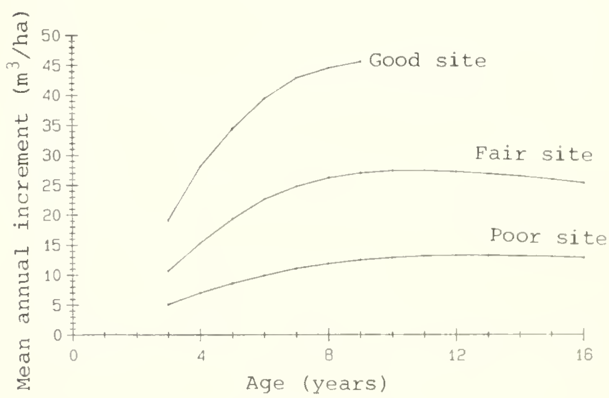


Figure 7--Eucalyptus grandis, South Africa 1100 per hectare (volume under bark).

Four years after cutting a 44-year-old mixed stand of E. saligna, E. grandis, and E. microcorys in 1978 in Hawaii, we found the coppice stand to contain 5200 stems per hectare (2080/acre)--most of which were seedlings rather than sprouts. These stems contained 197 m^3/ha (2810 ft^3/acre), representing MAI of 49 m^3/ha/yr (700 ft^3/acre/yr). A sample of 20 stems in the stand gave a moisture content of stems with bark of 60 percent of the fresh weight and specific gravity of 0.41. The green weight increment was 50 t/ha/yr (28 tons/acre/yr), which is a dry weight yield of 20 t/ha/yr (11.2 tons/acre/yr) and the highest we have measured in an unmanaged coppice stand in Hawaii.

Walters (1980) found that saligna/grandis spaced at 2.4 by 2.4 and 3.0 by 3.0 mm (8 by 8 and 10 by 10 ft) in Hawaii achieved peak MAI at just under 5 years on a particularly good site. The MAI (over bark) at 2.4-mm (8-ft) spacing was 59 m^3/ha/yr (844 ft^3/acre/yr). Also on this site was a tree 106 feet tall at age 5. This growth is quite exceptional and generally requires year-round rainfall with perhaps 254 mm (10 inches) of rain per month and rapid soil drainage. The four spacings compared in this study were 2.4, 3.0, 3.7, and 4.3 m (8, 10, 12,

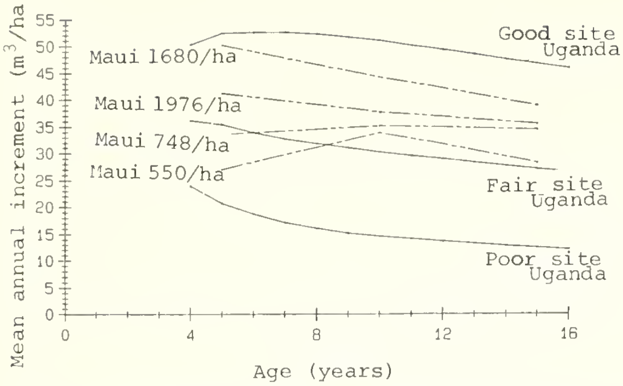


Figure 8--Eucalyptus grandis Uganda (1680/ha), Eucalyptus saligna, Maui (var. spacing) (volume under bark).

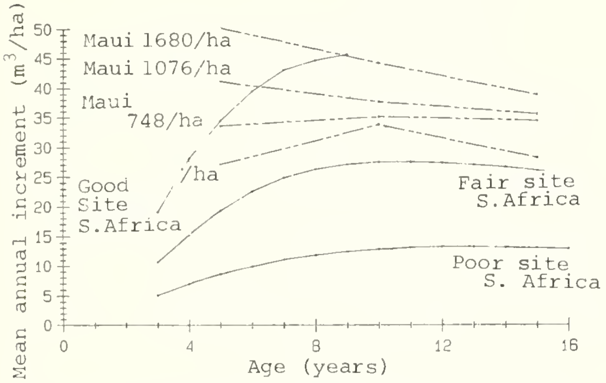


Figure 9--Eucalyptus grandis, South Africa (1100/ha), Eucalyptus saligna, Maui (var. spacing) (volume under bark)

and 14 ft). When the MAI at ages 5, 10, and 15 years, here reduced by 15 percent to adjust for overbark measure, are superimposed on the curves for Uganda, it can be seen that spacing has a large influence on yield (fig. 8). The yield curve at 8-ft spacings (1680 trees/ha) generally follows beneath the best Uganda site, whereas wider spacing produced lower yields on the Hawaii site. The Hawaii data bracketed the good site data for South Africa (fig. 9). Again the most similar spacing, 1076 trees per hectare, had a yield most similar to that in South Africa. It should not be assumed that close spacing is most desirable because it produces higher yields. It also reduces diameter growth and increases the number of trees per unit land area, both of which increase harvesting costs if short rotations are intended. Trees that are 12.5 cm (5 inches) in diameter are the most expensive to harvest with modern feller-bunchers.

CONCLUSIONS

Eucalyptus should certainly have a place in fulfilling California's fuelwood and pulpwood needs. It might even supply an exportable crop.

The national standard for identifying prime forest land in the United States was that it can produce at least 3.1 m^3/ha/yr (45 ft^3/acre/yr). This standard was intended for natural forests rather than plantations. However, it provides a basis for comparison of the many yield figures presented here. Few of them, even for the most arid sites, are as low as 45 ft^3, which serves to illustrate that the eucalypt growth is very good.

The importance of provenance selection for different sites was brought out in the data for E. camaldulensis. In addition, the various annual increment graphs on different sites indicated that plantation spacing must be increased on arid or difficult sites. The large differences in yield on different sites were also apparent as were those caused by spacing variation on the same site.

For convenience some of the data presented earlier are combined in tabular form for comparison (table 4).

This review is intended to help potential California eucalyptus growers recognize the need to: (1) select the proper species for the site; (2) test provenances of the selected species; and (3) adjust cultural practices, such as plantation spacing, rotation, and harvesting techniques, to fit the site and the species.

REFERENCES

Assman, Ernst. The principles of forest yield study. (Translated by Gardiner, S. H.) Davis, P. W., ed. New York: Pergamon Press; 1970. 506 p.

BioEnergy Development Corporation. Annual Report 1982--Eucalyptus plantations for energy production in Hawaii. Hilo: BioEnergy Development Corp.; 1983. 172 p.

Campinhos, E. Talk presented at Institute of Pacific Islands Forestry, Honolulu, HI. Oct. 1981.

Cromer, R. N.; Rampach, M.; Clark, A. R. P.; Cameron, J. N. Eucalypt plantations in Australia. The potential for intensive production and utilization. Appita 29(3):165-173; 1975 November.

FAO--Food and Agriculture Organization of the United Nations. Eucalypts for planting. FAO Forestry Series 11. Rome, Italy; 1979. 677 p.

King, James P. Variation in specific gravity in 3-year-old coppice clones of Eucalyptus saligna growing in Hawaii. Aust. For. Res. 10:(4):295-299. 1980 December.

Petteys, E. Q. P. 1983. Survery Forester, Hawaii Division of Forestry & Wildlife, Honolulu, Hawaii (conversation with author) March 1983.

Skolmen, Roger G. Growth of four unthinned Eucalyptus globulus coppice stands on the island of Hawaii. In: Whitmore, J. L., ed. Wood production in the neotropics via plantations. Proceedings, IUFRO/MAB/FOREST SERVICE SYMPOSIUM, Working Group S1-07-09, 1980 September 8-12; Institute of Tropical Forestry; Rio Piedras, Puerto Rico. 1981; 87-95.

Turnbull, J. W.; Pryor, L. D. Choice of species and seed sources. In: Hillis, W. E.; Brown, A. G., eds. Eucalypts for wood production. Canberra, Australia: CSIRO; 1978:6-65.

Walters, Gerald A. Saligna eucalypts growth in a 15-year-old spacing study in Hawaii. Res. Pap. PSW-151. Brekeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 6 p.

Table 4--Site characteristics, growth, and yield of three Eucalyptus species at various locations.

Species	Location	Mean annual rain-fall (mm)	Min. temp. (°C)	Dry season (mo.)	Typical stocking (no/ha)	Size and yield[1] Good site Dia (cm)	Ht (m)	(m^3/ha)	Max. MAI (yr)	Average site Dia (cm)	Ht (m)	(m^3/ha)	Max. MAI (yr)	Poor site Dia (cm)	Ht (m)	(m^3/ha)	Max. MAI (yr)
Eucalyptus globulus ssp. globulus	N. Portugal	1100	5	2	1100	19	27	380	12	15	19	160	15	8	11	28	20
	NW Spain	1200	7	0	2700	14	28	443	12	11	21	232	6	10	18	152	4
	SW Spain[2]	550	4	3	500	15	17	91	18	11	11	24	18	9	7	9	16
	SW Spain[3]	550	4	3	500	20	21	190	20	15	15	61	20	8	8	10	20
Eucalyptus camaldulensis	Morocco	500	8	5	800	16	16	120	18	14	13	54	13	11	10	29	9
Eucalyptus grandis	Uganda	1100	12	4	1680	-	40	508	5	0	30	301	4	-	20	145	3
	S. Africa	900	4	2	1100	20	40	450	10	18	32	274	10	15	23	129	12

[1]At age 10 and age at culmination of mean annual increment by site.

[2]Sandy soil.

[3]Shale soil.

Evaluating Trees as Energy Crops in Napa County[1]

Dean R. Donaldson and Richard B. Standiford[2]

Abstract: An evaluation of tree species for energy crops was initiated at two areas in Napa County, California. At one area, Eucalyptus viminalis at 39 months was significantly taller than E. camaldulensis at 50 months. Also evaluated were five clones of Pinus radiata, Juglans regia X hindsii, and Sequoia sempervirens; and these were 1/4 to 1/2 the height of the Eucalyptus species in this time period. At the second area, after 27 months, Eucalyptus camaldulensis was significantly taller and had a larger diameter-at-breast-height than Eucalyptus dalrympleana.

The Cooperative Extension office in Napa County started a biomass evaluation project in 1977 in cooperation with several local landowners. The purpose was to: (1) evaluate several tree species for potential as a biomass crop; (2) develop baseline growth and yield data for future economic feasibility studies; (3) serve as demonstration areas to illustrate management required for silviculture biomass farming; and (4) evaluate several experimental designs for efficient data collection for future biomass trials.

STUDY SITES

Two study areas were established in 1977 and 1979 near Calistoga, California, at the north end of Napa Valley. Areas planted are on the Napa Valley floor and receive 34 to 36 inches of rainfall per year, most of which occurs between November and March.

Virtually all of the interest in growing trees as an energy crop in Napa County has come from individuals owning small farms, usually less than 10 acres. Experimental design at the two areas had to meet three requirements: (1) to fit into the small space available for trials at the cooperator's property; (2) to obtain the maximum possible information from a small number of trees planted; and (3) to allow for sufficient replications for valid statistical conclusions to be made from the planting. Since there was no benchmark data on expected variance from these trials, each of the two study areas had a different experimental design so that the efficiency of each in giving reliable answers could be evaluated.

Area 1, Grant Street

Six species were chosen for evaluation at this site: Eucalyptus viminalis (manna gum), E. camaldulensis (river red gum), E. dalrympleana (mountain gum), Pinus radiata (Monterey pine), Juglans regia X hindsii (Paradox hybrid, a sterile walnut hybrid), and Sequoia sempervirens (coast redwood. All trees were first-year seedlings, except Monterey pines, which were rooted cuttings from five different clones collected from the Monterey peninsula and from New Zealand. There were five individuals of each of the five clones in each Monterey pine replication.

Ground preparation included cross-ripping and disking before planting. Trees were planted by hand, except walnuts, which were planted with an auger. Each species was block-planted, 5 trees by 5 trees (25 per block), at a square spacing of 2.4 by 2.4 meters (8 by 8 feet). Replications of species were arranged in a randomized block design.

In May 1977, river red gum, mountain gum, and walnut were planted. Due to poor survival, mountain gum was discontinued and replaced by manna gum in April 1978. Coast redwood was also planted in 1978. Young trees received periodic overhead sprinkler irrigation the first two seasons, and no irrigation since. Chemical weed control has been carried out annually.

Area 2, Bale Lane

River red gum and mountain gum were evaluated at this site. The area was cultivated and hand-planted in April 1979. Two blocks of each species were planted with approximately 100 seedlings per block. Trees were planted at a square spacing of 1.5 by 1.5 meters (5 by 5 feet). The area has been irrigated with an overhead sprinkler system during the summer. Chemical weed control has been carried out annually.

All trees were measured in July 1981 (39 and 50 months after planting in area 1, 27 months after planting in area 2). Diameter at 1.4 meters (breast height [DBH]) and total height were measured. Tree measurement comparisons between outside border trees and inside trees were statistically evaluated. Wood volume per block of trees to a 5-cm (2-inch) top was calculated for the eucalyptus species in area 1 using the following volume equation derived from work reported by W. Metcalf in 1924 and J.P. King and S.L. Krugman in 1980:

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Farm Advisor (Napa County) and Forestry Specialist (Berkeley) respectively, Cooperative Extension, University of California.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

Volume (cubic feet) = 0.00245 (DBH [inches])^2 X height [feet]) - 0.3318

Volume converted to cubic meters using 1 cubic foot = 0.02832 cubic meters

This 5-cm small-end diameter is felt to be the approximate minimum size of a firewood product. Other species have not reached a size to allow calculation of volume using this standard.

RESULTS

No statistical differences in tree diameters and heights among these trees were found between the interior and exterior portions of each planting. Therefore, all tree measurements were combined for volume estimation.

At area 1, eucalyptus were by far the fastest growing of the four genera evaluated (see table 1). The two eucalyptus species were 1½ to 2 times taller in height and 1½ times larger in diameter than the next fastest growing species, Monterey pine (Clone Z-6). Manna gum, Eucalyptus viminalis, at 39 months was already significantly taller in total height than river red gum, E. camaldulensis, at 50 months.

At area 2, river red gum was significantly larger than mountain gum at 27 months (table 2). The trees were still too small for volume to be calculated.

Average volume yields for the two fastest growing species in area 1 were 24.7 and 19.1 cubic meters per hectare (353.3 and 272.8 cubic feet per acre) for manna gum and river red gum, respectively, and from these figures the mean annual increment was calculated (table 3). Manna gum is producing an estimated total energy yield of 20 million kcal per hectare (32 million BUT per acre) per year, and river red gum 15 million kcal per hectare (25 million BTU per acre) per year.

Future growth will be periodically measured, and height, DBH, volume, and energy yield will be calculated. It is expected that these future measurements will show higher annual wood volume increments, because root and canopy development will allow for more complete utilization of the resources at the site. This information will be useful to landowners evaluating the potential of growing biomass crops. Similar trials should be established in other areas of the state where energy plantations are being considered.

Table 1 -- Summary of data from area 1, Grant Street, Calistoga, Napa County, July 1981[1]

Species	1981 age (mo)	Survival	Average height[2] meters	(feet)	Average DBH[2] cm	(inches)	Average volume/area[2] cu. m/ha	(cu. ft/a)
Eucalyptus viminalis	39	56/70	8.3	(27.3)	7.9	(3.1)	24.7	(353.3)
Eucalyptus camaldulensis	50	[3]88/100	6.7	(21.9)	7.9	(3.1)	19.1	(272.8)
Pinus radiata (5 clones)	39	62/72						
Z-6		14/15	4.4	(14.4)	5.2	(2.0)	--	--
Z-3		13/15	4.3	(13.8)	5.1	(2.0)	--	--
MM-13		10/15	3.8	(12.5)	5.0	(2.0)	--	--
MM-6		11/15	3.4	(11.2)	4.0	(1.6)	--	--
Z-5		14/15	3.0	(9.8)	2.9	(1.2)	--	--
Juglans regia X hindsii	50	[3]99/100	2.2	(7.1)	2.1	(0.8)	--	--
Sequoia sempervirens	39	66/75	1.5	(5.0)	--	--	--	--
Eucalyptus dalrympleana	Survival less than 50%, terminated March 1978.							

[1]Soil: Bale Loam (Rocky Phase), irrigated by overhead sprinklers first two growing seasons. Chemical weed control. Area average annual rainfall = 36 inches. Planted 2.4m x 2.4m (8' x 8') square spacing.

[2]Means connected by bars do not differ significantly at 5 percent level.

[3]Planted during a drought year (1977); first-year sprinkler irrigation could not be carried out after July.

Table 2 -- Summary of data from area 2, Bale Lane, Calistoga, Napa County, July 1981[1]

Species	Age (mo)	Survival	Average height meters	(feet)	Average DBH cm	(inches)
Eucalyptus camaldulensis	27	179/198	4.9	[2](16.1)	5.1	[2](2.0)
Eucalyptus dalrympleana	27	156/212	3.8	(12.5)	3.6	(1.4)

[1]Soil: Bear Creek clay-loam, irrigated with overhead sprinklers during summer. Spacing: 1.5m x 1.5m (5 ft x 5 ft). Chemical weed control. Average annual rainfall: 34 inches.
[2]Means significantly different at the 0.01 percent level.

Table 3 -- Volume and energy calculations for two field-planted eucalyptus species in area 1, at Calistoga, Napa County[1]

Species	Age (yr)	Average volume yields m^3/ha	Calculated mean annual yield m^3/ha/yr	cords/a/yr	Total energy yields[1] million btu/a/yr	million kcal/ha/yr
E. viminalis	3.2	24.7	7.8	1.3	32	20
E. camaldulensis	4.2	19.1	4.3	0.8	25	15

[1]Using specific gravity information reported by H.E. Dadswell, 1972, "The Anatomy of Eucalypt Woods," Commonwealth Scientific and Industrial Research Organization, Australia, For. Prod. Lab. Div. of Applied Chemistry Technological Paper No. 66, and wood energy values in A.J. Panshin and C. deZeeuw, 1970, "Textbook of Wood Technology," Vol. 1, McGraw-Hill Book Co.

Growth and Yield in *Eucalyptus globulus*[1]

James A. Rinehart and Richard B. Standiford[2]

Abstract: A study of the major Eucalyptus globulus stands throughout California conducted by Woodbridge Metcalf in 1924 provides a complete and accurate data set for generating variable site-density yield models. Two models were developed using linear regression techniques. Model I depicts a linear relationship between age and yield best used for stands between five and fifteen years old. Model II depicts a sigmoidal relationship between age and yield with slightly poorer statistical fit but greater reliability beyond fifteen years of age. Significant independent variables used in Model I are: initial plantation density; site index; and an interaction variable consisting of age x site index. Significant independent variables in Model II are: natural log of initial plantation density; site index; and inverse age. Variable site and density yield tables are developed from Model II for stands under minimal management. Culmination of mean annual increment occurs at age ten under all conditions. Assuming a goal of maximization of mean annual increment of merchantable cordwood, planting densities of 435, 680 and 1210 trees per acre are recommended for low, medium, and high sites respectively.

Various species of Eucalyptus have been of interest in California since their introduction in 1860 (Metcalf, 1924), with Eucalyptus globulus (Blue Gum) being the most widely planted. While its wood has limited use as lumber, its rapid growth has caused it to be favored as windbreaks and ornamentals. The recent increase in demand for firewood and a growing market for hardwood fiber has caused renewed interest in planting eucalyptus.

The purpose of this article is to present a model for growth of Eucalyptus globulus and to use this model to generate variable site-density yield tables. These yield tables are then used to determine optimum stocking levels and rotation length under various site conditions. This model deals solely with biological growth and does not consider economic implications of stand establishment and management.

The models derived represent unmanaged stands only. Certain management practices increase site quality and some means of assessing this increase must be applied in order for the models to be meaningful under intensive management conditions.

Within this article, the following topics are discussed:

-- The source, limitations, and adjustments made to the data used to generate the model.

-- A description of the model itself and how it is used to generate variable site-density yield tables.

-- Conclusions drawn from analysis of the yield tables.

-- Suggestions for further analysis and research.

THE DATA

The data used in this analysis was gathered by Louis Margolin in 1910 (Margolin, 1910) and by Woodbridge Metcalf in 1924 (Metcalf, 1924) in their studies of the major Blue Gum stands in California. As described in his article, in order to generate site and yield functions, Metcalf used data collected in these two studies, which included a total of 96 stands. This data was adjusted to result in the data set used in the current analysis.

The Metcalf and Margolin Data

Location of Stands

Stands were located in 19 counties throughout California, from Arcata in Humboldt County to Escondido in San Diego County, representing a wide variety of soil and climatic conditions.

Information Collected

Information collected for each stand includes the following:

-- Stand age
-- Initial plantation density in trees per acre
-- Surviving trees per acre

---

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Staff Research Associate and Statewide Forestry Specialist, respectively, Cooperative Extension, University of California, Berkeley, California.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

-- Average diameter, height, and volume of surviving trees
-- Volume per acre in cubic feet and cords
-- Soil and water characteristics

Also, in order to develop a measure of site quality, height was measured on the tallest 10 percent of trees in most of the stands.

Methods of Collection

Selection of Plots--In the data collected by Metcalf, "one or more of the rows running through representative portions of the stand" were selected for measurement. The method of row selection was not described and therefore randomness of the sampling procedure is not assumed.

In the Margolin data, sample areas were ¼-acre plots within the interior of each grove. Usually only one such plot was taken per stand and these were selected to show average conditions. This method of plot selection is not random and could result in bias toward higher yield.

Surviving Trees Per Acre--Metcalf states that "each surviving tree" was measured, as well as blank spaces and "scrubby trees." A scrubby tree is not defined and no lower diameter limit is given for surviving trees. In assessing trees per acre at time of measurement, one must assume that none of the "scrubby" trees are survivors of the original plantation.

In the Margolin study, all trees with dbh of 1½ inches or more were measured. As with the Metcalf data, one must assume that trees less than 1½ inches dbh were not counted as survivors of the original plantation.

Average Diameter of Surviving Trees--In the Metcalf data, since "scrubby" trees are assumed not to be survivors, it must also be assumed that the distribution of diameters of surviving trees has some lower diameter limit. Since we do not know what this limit is, it is difficult to assess the amount of variation around the average diameter. Diameters measured by Margolin, however, were recorded by 1-inch diameter class, giving a diameter distribution, or stand table, for each stand sampled.

Height of Surviving Trees--Total heights, including stump and top were measured for as many trees as possible. A height-diameter curve was derived in order to estimate heights on trees not measured.

Calculation of Volume--Volumes were calculated using the following formula:

$$V = BA \times H \times ff \times TPA$$

where: V = Volume in cubic feet per acre
BA = Basal area in square feet of the average single tree. (BA = [Average Diameter/24]^2)
H = Total height of the average single tree
ff = Form factor relating stem volume to (BA x H). Stem volume is from the top of a one-foot stump to a minimum diameter of two inches at the top.
TPA = Number of surviving trees per acre at time of measurement

Site Classification

In order to develop a height-age relationship as a measure of site quality, Metcalf measured the tallest 10% of the trees sampled and plotted heights of these dominant trees against age. Groves in which overcrowding was thought to have interferred with height growth were not included. In all, Metcalf included 45 of the Metcalf groves and 26 of the Margolin groves in his site classification.

An average age-height curve was drawn through the data and harmonized curves were drawn to intersect with maximum and minimum values. The area between the maximum and minimum curves was then divided into three zones, labeled Site I, II, and III. Figure 1 represents the Metcalf site classification curves.

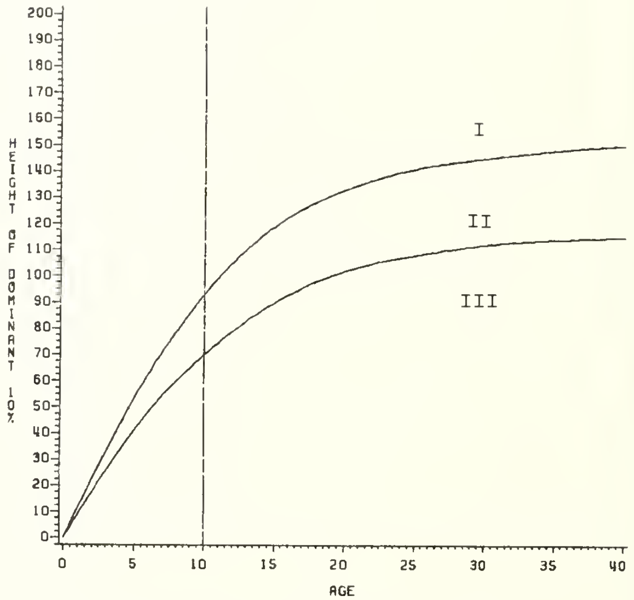


Figure 1 -- Metcalf Site Classifications

The Current Data Set

Adjustments

The following adjustments were made in the above data to result in the data set used in the analysis.

Elimination of Observations--Only those stands for which the height of dominant trees was recorded are included, thus eliminating 20 of the stands. An additional stand was eliminated because it had been thinned.

Addition of Observations--Eight of the Metcalf stands were measured twice at different points in time. Metcalf used only the first measurement in his estimation of site. The current data set includes the eight remeasurements, with the assumption that site remains constant over time. A total of 78 stands are included in the current data set.

Volume Estimation--The method used by Margolin to estimate volume was not specified other than by reference to volume tables. In order to merge the two data sets, volumes for Margolin stands were recalculated using the formula noted above.

Developing a Site Index Measurement

Metcalf's site quality measure resulted in site ratings of I, II, or III. In order to be consistent with other yield studies for Eucalyptus globulus, a site index was developed from Metcalf's age-height curves in figure 1, using a base age of 10. The following table represents the relation between Metcalf's site class and the site index derived from it.

Table 1 -- Site Class-Site Index Relationship

Site Class	Site Index (Height of Dominants at 10 Years)
I	Greater than 93
II	65 to 93
III	Less than 65

Site indices for the stands in the data set ranged from a low of 41 to a high of 118.

The method used was to locate age and height of dominants for a given stand on figure 1 and then to follow a harmonized curve through that point to its intersection with the base age 10 reference line. For instance, a dominant height of 126 feet at age 25 would equate to a site index of 82. In this way, figure 1 can be used to determine site index for any stand where age and height of dominants are known.

Range of Ages

The ages of stands in the current data set ranged from 2 to 40 years. Only 12 (15.4 percent) of the stands were in excess of 15 years of age. Models derived from this data show best fit in younger age classes and caution must be used in estimating volume in age classes between 15 and 40. Models should not be used for extrapolation beyond age 40. This limitation is not significant for commercially-grown stands since harvest is likely to occur prior to age 15.

ANALYSIS

Analytical Systems Used

Linear regression analysis was performed using the Statistical Analysis System -- General Linear Model (SAS-GLM) program package.

Yield Models

The analysis yields two production models with statistically significant fit. The first gives a linear plot of predicted yield against age. The second gives a plot of predicted yield against age which more closely approximates a sigmoidal biological production function which one might anticipate. Figure 2 depicts these models for a given site and initial plantation density. Both models can be used, given certain constraints, as explained below.

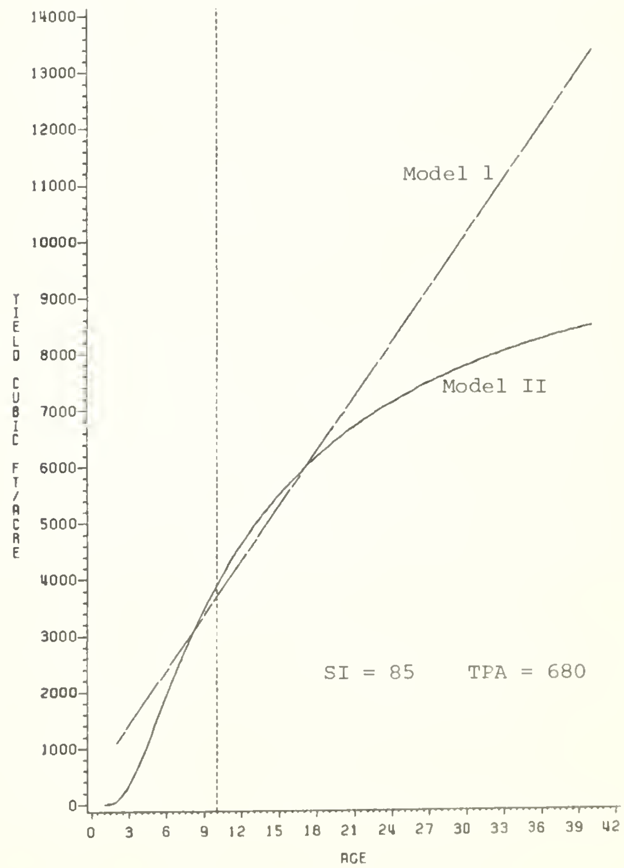


Figure 2 -- Model I and Model II Yields

Model I

Model Form--Model I takes the form of:

$$Y = -3177.17 + 1.70(TPA1) + 29.47(SI) + 3.77(AGSI)$$

where: Y = Yield in cubic feet per acre
TPA1 = Initial plantation density in trees per acre
SI = Site index in feet at age 10
AGSI = Age x site index

Analysis of Variance--Table 2 presents the analysis of variance for Model I.

Table 2 -- ANOVA - Model I

Source of Variation	DF	Sum of Squares	T	F	R^2	C.V
Intercept			-4.28			
TPA1	1	3.19×10^7	3.07			
SI	1	30.15×10^7	2.95			
AGSI	1	53.34×10^7	18.95			
Residuals	74	11.04×10^7				
Total	77	97.72×10^7		193.7	.887	34.6

Note the high correlation coefficient (R^2) of .887 and the coefficient of variation (C.V) of 34.6.

Discussion -- Because site index appeared to have a greater effect on yield with increasing age, an interaction variable consisting of Age x Site was anticipated. As indicated by its high T value relative to other variables, AGSI is the most significant independent variable. This is logically sound since, with a given initial plantation density, site quality will have a strong effect on rate of growth while total volume will vary most directly with age.

While this model gives a good prediction of volume within the range of most of the data, it does not give an intuitive depiction of growth, as shown by figure 2. The linear relationship between age and yield results from the fact that 80 percent of the data falls between the ages of 5 and 15, the linear range of the anticipated sigmoidal function. This data so weights the model in this form that statistical significance is high even though the model is linear.

Model II

Model Form--Model II takes the form of:

$$\ln Y = 4.86449 + .02547(SI) + .34896\,(\ln TPA2) - 10.41628(I/A)$$

where: lnY = The natural log of yield in cubic feet per acre
SI = Site index in feet at age 10
lnTPAI = The natural log of initial stocking density in trees per acre
I/A = Inverse age

Analysis of Variance--Table 3 presents the analysis of variance for Model II.

Table 3--ANOVA - Model II

Source of Variation	DF	Sum of Squares	T	F	R^2	C.V.
Intercept			5.80			
SI	1	27.11	8.52			
lnTPA1	1	1.34	2.75			
1/A	1	42.38	-15.81			
Residuals	74	12.54				
Total	77	83.37		139.3	.850	5.3

Note that while the statistics for Model I are slightly better than those for Model II, the differences are relatively minor. The lower C.V. for Model II is a result of the dependent variable being a logarithm. Exponentiating results in a coefficient of variation similar to that of Model I.

Discussion--Schumacher (1939) and Clutter (1963) suggested methods of generating linear models to express nonlinear production functions by transforming dependent and independent variables into natural logarithms. Model II is essentially the Clutter model using lnTPA1 rather than Clutter's ln of Basal Area.

As shown in figure 2, when lnY is transformed back to cubic foot yield and plotted against age, the result is close to the expected sigmoidal curve. Since the Clutter-based model gives nearly as good a fit as Model I with greater confidence when using the model for stands older than 15 years, this model was used to generate subsequent yield tables.

Variable Site-Density Yield Tables

In generating yield tables under varying site and initial stocking conditions, one will wish to know average diameter of the stand as a measure of merchantability, as well as total yield. A diameter of two inches is generally considered to be the lower merchantable limit for cordwood and the diameter distributions shown in the Margolin data indicate that for an ASD of six inches, virtually all trees in the stand will be in excess of two inches dbh. The expression for average diameter of the stand is:

$$AD = \sqrt{\frac{BA}{TPA2 \times .00545}}$$

where: AD = Average diameter of the stand in inches
BA = Basal area per acre in square feet
TPA2 = Surviving trees per acre

In order to predict AD, then, it is necessary to construct models for basal area and surviving trees.

Basal Area Model

Because basal area is also a measure of production, it is logical that BA could be predicted by the same independent variables as cubic foot yield. The following model results:

$$\ln BA = 2.07854 + 0.496(SI) + .33354(\ln TPA1) - 6.55518(I/A)$$

where: lnBA = Natural log of basal area per acre
SI = Site index in feet at age 10
TPA1 = Initial stocking in trees per acre
I/A = Inverse age

The correlation coefficient for this model is .79. Affective coefficient of variation is about 40.0.

Surviving Trees Per Acre

The only significant predictor of surviving trees per acre is initial stocking density, which gives the following model:

$$TPA2 = 183.69 + .56\ TPA1$$

where: TPA2 = Surviving trees per acre
TPA1 = Initial stocking in trees per acre

While R^2 for this model is only .54, it is acceptable since it is used only to calculate a rough estimate of the average diameter of the stand.

Final Yield Tables

The final yield tables were generated by combining the three models derived above and iterating through variations in site index, initial stocking, and age. Tables 4a-c are representative tables for SI = 60, 85, and 105 and initial stocking of 680 trees per acre.

Variable Site Yield Functions

By plotting yield against age for a given stocking level under varying site conditions, one may see graphically how yield varies with site. Figure 3 represents yield with initial plantation density of 680 under three site conditions.

DISCUSSION

Refer to table 4 and figure 3 for the following discussion.

Explanation and Interpretation of Yield Tables

Surviving Trees Per Acre (TPA2)

Note that TPA2 varies only with TPA1 and that mortality occurs immediately. This indicates that survival is linked with establishment and that once established, the stand remains stable over time.

When initial stocking is 300 trees per acre, TPA2 exceeds TPA1. This may be loosely explained by sprouting on under-utilized sites, though this explanation is somewhat weak. As noted earlier, the mortality issue is clouded by problems in interpreting the data as well as by ingrowth from sprouts and volunteers. TPA2 is a rough estimate of survival.

Table 4a--Yield Table (SI = 60, TPA1 = 680)

SITE INDEX = 60			TREES/ACRE: Initial = 680; Surviving = 519					
Age (years)	Average Diameter (inches)	Basal Area (Ft^2/Ac)	Yield		Mean Annual Incr.		Current Annual Incr.	
			Ft^3/Ac	Cds/Ac	Ft^3/Ac/Yr	Cds/Ac/Yr	Ft^3/Ac/Yr	Cds/Ac/Yr
2	1.5	6.5	31.8	.4	15.9	.2		
4	3.4	33.5	430.3	4.8	107.6	1.2	199.3	2.2
6	4.5	57.9	1025.1	11.4	170.9	1.9	297.4	3.3
8	5.2	76.1	1582.2	17.6	197.8	2.2	278.5	3.1
10	5.6	89.7	2052.9	22.8	205.3	2.3	235.3	2.6
12	5.9	100.0	2442.1	27.1	203.5	2.3	194.6	2.2
14	6.2	108.1	2764.5	30.7	197.5	2.2	161.2	1.8
16	6.4	114.6	3033.9	33.7	189.6	2.1	134.7	1.5
18	6.5	120.0	3261.5	36.2	181.2	2.0	113.8	1.3
20	6.6	124.4	3455.8	38.4	172.8	1.9	97.2	1.1
25	6.9	132.9	3835.2	42.6	153.4	1.7	75.9	.8
30	7.0	138.8	4111.0	45.7	137.0	1.5	55.2	.6
35	7.1	143.2	4320.1	48.0	123.4	1.4	41.8	.5
40	7.2	146.6	4483.8	49.8	112.1	1.2	32.7	.4

Table 4b--Yield Table (SI = 85, TPA1 = 680)

SITE INDEX = 85			TREES/ACRE: Initial = 680; Surviving = 519					
Age (years)	Average Diameter (inches)	Basal Area Ft^2/AC	Yield		Mean Annual Incr.		Current Annual Incr.	
			Ft^3/Ac	Cds/Ac	Ft^3/Ac/Yr	Cds/Ac/Yr	Ft^3/Ac/Yr	Cds/Ac/Yr
2	1.8	9.5	60.2	.7	30.1	.3		
4	4.1	48.8	813.5	9.0	203.4	2.3	376.6	4.2
6	5.5	84.2	1937.9	21.5	323.0	3.6	562.2	6.2
8	6.3	110.6	2990.9	33.2	373.9	4.2	526.5	5.9
10	6.8	130.3	3880.6	43.1	388.1	4.3	444.8	4.9
12	7.2	145.4	4616.3	51.3	384.7	4.3	367.9	4.1
14	7.5	157.2	5225.8	58.1	373.3	4.1	304.7	3.4
16	7.7	166.6	5735.1	63.7	358.4	4.0	254.7	2.8
18	7.8	174.4	6165.3	68.5	342.5	3.8	215.1	2.4
20	8.0	180.9	6532.6	72.6	326.6	3.6	183.7	2.0
25	8.3	193.1	7249.8	80.6	290.0	3.2	143.4	1.6
30	8.4	201.7	7771.1	86.3	259.0	2.9	104.2	1.2
35	8.6	208.1	8166.3	90.7	233.3	2.6	79.0	.9
40	8.7	213.1	8475.8	94.2	211.9	2.4	62.0	.7

Table 4c--Yield Table (SI = 105, TPA2 = 680)

SITE INDEX = 105			TREES/ACRE: Initial = 680; Surviving = 519					
Age (years)	Average Diameter (inches)	Basal Area (Ft^2/AC)	Yield		Mean Annual Incr.		Current Annual Incr.	
			Ft^3/Ac	Cds/Ac	Ft^3/Ac/Yr	Cds/Ac/Yr	Ft^3/Ac/Yr	Cds/Ac/Yr
2	2.1	12.8	100.1	1.1	50.1	.6		.
4	4.8	65.8	1353.9	15.0	338.5	3.8	626.9	7.0
6	6.3	113.5	3225.1	35.8	537.5	6.0	935.6	10.4
8	7.3	149.2	4977.8	55.3	622.2	6.9	876.3	9.7
10	7.9	175.8	6458.5	71.8	645.8	7.2	740.3	8.2
12	8.3	196.1	7682.9	85.4	640.2	7.1	612.2	6.8
14	8.7	212.0	8697.2	96.6	621.2	6.9	507.1	5.6
16	8.9	224.8	9544.9	106.1	596.6	6.6	423.8	4.7
18	9.1	235.2	10260.9	114.0	570.1	6.3	358.0	4.0
20	9.3	243.9	10872.2	120.8	543.6	6.0	305.6	3.4
25	9.6	260.5	12065.8	134.1	482.6	5.4	238.6	2.7
30	9.8	272.1	12933.4	143.7	431.1	4.8	173.6	1.9
35	10.0	280.7	13591.1	151.0	388.3	4.3	131.6	1.5
40	10.1	287.4	14106.2	156.7	352.7	3.9	103.0	1.1

Average Diameter of the Stand (AD)

This variable behaves as one might expect, increasing with age and site index, but decreasing as initial plantation density increases.

Yield (YFT3)

Gives volume at various ages.

Cords

Gives volume in cords where:

CORDS = YFT3/90

Mean Annual Increment (MAIFT3 and MAICD)

Gives mean annual increment in cubic feet and cords per acre per year, where:

MAI = Yield/Age

Note that for all variations of site and initial stocking, MAI culminates at age 10. Thus, for maximum biomass production, given the two-inch merchantability standard for volume determination, harvest will occur at about age 10.

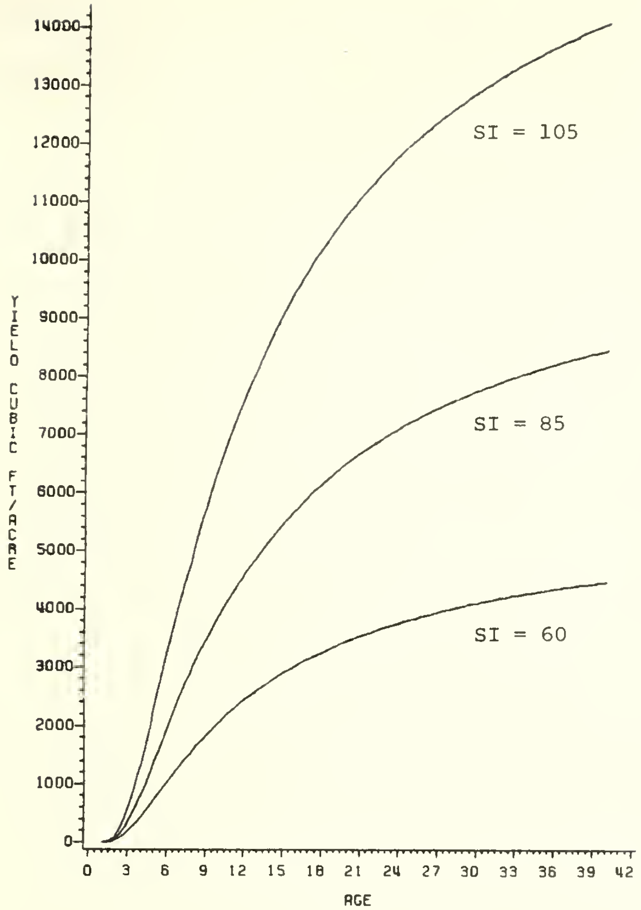


Figure 3--Yield-Age Relationships Varying Site Index (TPA1 = 680)

Current Annual Increment (CAIFT3 and CAICD)

Gives current year's growth in cubic feet and cords. Note that CAI culminates at age 6, somewhat before MAI, as one would anticipate. Note also that at culmination of MAI, MAI approximately equals CAI, again as one would expect.

Recommended Planting Densities

Assuming a goal of maximum merchantible cordwood, the yield tables generated from the models in this analysis can be used to determine optimal spacing for any given site. Optimal spacing will be that which yields highest MAI at age 10 with minimum ASD of 6 inches. Table 5 represents recommended planting density to achieve this goal for a range of site indices.

NEEDS FOR FURTHER RESEARCH

Site Quality - Soil Correlation

The above analysis assumes that a 10-year site index for *Eucalyptus globulus* is known at time of planting. If Blue Gum has not been grown before

Table 5 -- Recommended Planting Densities for Maximum Merchantable Cordwood

Site Index	Recommended Planting Density
55	300 TPA
60	435
65	435
75	680
85	680
95	1210
105	1210
115	1210

on the site, and if there are no stands growing on similar sites available for comparison, this assumption may not be met. *E. globulus* appears to grow best on well-drained, sandy-loamy soils with a 10- to 12-foot water table. This relationship between edaphic-climatic-geomorphological conditions and site index requires further research so a site index may be estimated prior to planting.

For the present time, individuals who wish to use these models and yield tables to assess growth and yield can use some general observations of the soil-site quality relationship provided by Metcalf. This information is shown in table 6.

Table 6 -- Relationship Between Site Index and Soil-Site Characteristics

Approximate Site Index	Soil-Site Characteristics
Greater than 93	. Soils - loamy-sandy loam - deep bottomland . Agricultural quality -- high . Water table -- near surface during most of the year . Slope - flat
65-93	. Soils - sandy-sandy loam . Agricultural quality -- fair to good under irrigation . Water table -- low; irrigation required . Slope -- medium to flat
Less than 65	. Soils - sandy, adobe . Agricultural quality - low . Water table - low; irrigation infeasible . Slope - steep . Windy

Older Stands

As noted earlier, the data analyzed was heavily weighted to stands 5 to 15 years old, making extrapolation of the model to older stands somewhat risky. Similar data should be gathered for stands 15-60 years old to see if a better fit can be obtained.

Economic Analysis

This analysis assumes that maximum biomass production is the only management goal. Costs of site preparation, irrigation, fertilization and harvest are not considered; nor are projected stumpage prices or demand for fuelwood or chips. Further analysis should combine biological growth potential with economic factors to give a return on investment analysis for Eucalyptus globulus plantations.

REFERENCES

Connell, M.G.R.; Smith, R.I. Yields of minirotation closely spaced hardwoods in temperate regions: review and appraisal. Forest Science 26(3); 1980.

Clutter, Jerome L. Compatible growth and yield models for loblolly pine. Forest Science 9(3); 1963.

Eucalypts for Planting. Food and Agriculture Organization of the United Nations, Rome; 1979.

Margolin, Louis, Yield from eucalyptus plantations in California. California State Board of Forestry, Bulletin N.1; 1910.

Metcalf, Woodbridge. Growth of eucalyptus in California plantations. University of California College of Agriculture, Agric. Exper. Station, Bulletin N.380; November 1924.

Schumacher, F.X.; Coile, T.S. Growth and yield of natural stands of the southern pines. T.S. Coile, Inc.; 1970.

Industrial Planting of *E. viminalis* in Mendocino County[1]

Peter C. Passof and John W. Sweeley[2]

Abstract: The authors trace the development of a Eucalyptus reforestation program on private industrial forest land from early testing to production planting. Data is presented on a 14.2 hectare manna gum plantation which has produced an estimated yield of 481 cubic meters/hectare after 20 years. Because manna gum has about 60 percent greater density than Douglas-fir or redwood, total dry weight yield from such stands may be about 3 times the equivalent of the two native species.

The Masonite Corporation started up its forestry operations in Mendocino County in 1948 with the acquisition of approximately 21,044 hectares (52,000 acres) of mixed Douglas-fir (Pseudotsuga menziessii (Mirb.) Franco) and redwood (Sequoia sempervirens (D. Don) Endl.) timber including oak-grass woodland. Their only manufacturing facility was a hardboard plant at Ukiah although beginning in 1969 they did acquire several lumber mills in northern California.

In 1956, Masonite forester Jack Sweeley became interested in testing and evaluating several species of Eucalyptus as potential sources of fiber for the hardboard plant. A total of 32 plots involving a variety of species were planted throughout the County in an attempt to observe growth performance over a range of environmental conditions.

Sweeley established some basic selection criteria to help narrow down the vast array of species. These characteristics were as follows: (1) fast-growing (2) ability to coppice (3) frost-resistant (4) easy to plant as bare root seedlings and (5) compatibility with the hardboard plant's processing requirements.

The latter criterion was provided by Masonite's wood technologists in Australia who rejected certain species such as Karri (E. diversicolor F. Muell.) because of the undesirable red color of the wood and Messmate stringybark (E. obliqua L'Herit.) because of fiber instability.

In the next four years (1957-61) Masonite expanded its small plot testing program to a few larger plantings. Seedlings were raised under contract to the Parlin Fork Nursery operated by the Department of Forestry. It should be pointed out that Masonite was also interested in spot seeding as a regeneration method. They borrowed an idea from Australia using pelletized seed where fertilizer and peat was added to the seed and then cubed. However, their preliminary trials indicated the procedure was not effective.

Early problems with deer browsing the first growing season were resolved with deer-proof exclosures. The foresters also found that site preparation procedures such as brush raking and burning helped to improve survival and growth performance.

It was during this period that Masonite's interest in Eucalyptus attracted scientists from all parts of the world who came to see how the various species were doing in north coastal California. Each scientist contributed views as to which species might do best under Mendocino's growing conditions.

By 1962, Sweeley had come to the conclusion that two species, manna gum (E. viminalis Labill.) and mountain gum (E. dalrympleana Maid.) had passed all the preliminary screening and therefore deserved special recognition for production planting. In February 1963, a 14.2 hectare (35 acre) planting was established in the Albion River drainage at a location romantically called Slaughter House Gulch. It was on an east-facing site with slopes ranging from 30 to 70 percent. Elevation averaged 122 meters (400 feet) with an average minimum January temperature of 4.4° C (40° F) with extremes to -6.7° C (20° F). It had been clearcut of redwood, Douglas-fir and grand fir (Abies grandis (Dougl. ex D. Don) Lindl.) and then prepared for burning. The burning was not completed successfully because of changing climatic conditions. Mean annual rainfall is 114 cm (45 inches). About half the area was fenced to reduce deer browsing pressure. A total of 14,000 E. viminalis and 5000 Monterey pine (Pinus radiata D. Don) were planted on an approximate 2.4 x 2.4 meter (8 x 8 foot) spacing.

A total of 10 plots were established to check survival and growth. After 3 years the plots averaged 78 percent survival and the average

---

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, Calif.

[2]Extension Forest Advisor, University of California Cooperative Extension, Mendocino County; and former Chief Forester, Masonite Corporation, Ukiah, California.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

height of the seedlings was 95 cm (38 inches). There were no significant differences between the 5 plots in the exclosure and the 5 outside the fenced area.

In 1968, the senior author and Masonite forester Ralph Duddles returned to the Albion site and measured several trees as part of a preliminary yield study of manna gum existing on the Company's various plantations.

At Slaughter House Gulch, the trees averaged 7 meters (23 feet) in total height, and 3 meters (10 feet) to a 5 cm (2 inch) top. Average diameter at a .46 meter (1.5 foot) stump was 6.8 cm (2.7 inches). These last two measurements were incorporated into a volume equation known as Smalian's formula where $V = A_1 + A_2/2 \times (L)$. The geometric figure is a truncated paraboloid and most nearly represents a log that has one end larger than the other and uniform taper.

Assumptions were made that annual radial growth would continue over the next 15 years as it had over the previous 5 years. However the same could not be said for height growth. The literature indicated that a flattening of the height/diameter curve occurs before age 20. By adjusting height growth, we estimated that heights would range from 22 to 31.7 meters (72 to 104 feet) at age 20 with an average of 27.1 meters (89 feet).

The last ingredient in this yield study was to project the number of trees/hectare. Our estimate called for 520 trees/hectare (210 trees/acre) and thus our yield prediction to age 20 was estimated to be 378 cubic meters/hectare (5408 cubic feet/acre) for the plantation.[3]

Fifteen years elapsed with only an occasional visit to the site. About two months ago, a mixed contingent of "Eucalyptus enthusiasts" decided to spend some time remeasuring the trees to get an accurate estimate of current volumes/acre. Trees were measured at d.b.h. (diameter-at-breast-height) and total height. A newer volume equation (King and Krugman 1980) was applied to the stand data and with the aid of a computer program, we found that the average stand volume equalled 481 cubic meters/hectare (6870 cubic feet/acre).

Instead of the 520 trees/hectare stocking, our data indicated we had a range from 667 to 865 trees/hectare (270 to 350 trees/acre). If we were permitted to adjust the original estimate upward to 660 trees/hectare our projected volume yield using the crude Smalian formula would produce a perfect match!

However it should be noted that only a small number of trees were selected and measured in 1968 and although we used a much greater number in 1983, great statistical variability in the data were found.

Nevertheless, a current volume of 481 cubic meters/hectare for 20 years is quite respectable growth for an area that has had no supplemental irrigation and considerable competition from brushy species such as blueblossom (*Ceanothus thyrsiflorus* Eschsch.). The site is listed as a Site III, Hugo soil series with an average depth of 1.5 meters (5 feet).

It is important to note that *E. viminalis* is approximately 60 percent heavier than the average of redwood and Douglas-fir; this is of great importance to the perspective of a hardboard plant that buys its raw material on a bone dry weight per unit volume basis. This means that the equivalent dry weight yield of manna gum, measured in tonnes/hectare, is about 3 times that of our native fast-growing redwood in a short rotation of 20 years.

By 1969, Masonite's wood technologists discovered that Eucalyptus' unique fiber properties could be emulated by the native conifers and thus the technical demand for Eucalyptus came to a rapid close.

At the conclusion of the Corporation's Eucalyptus reforestation program in the winter of 1968-69, a total of 104 hectares (256 acres) of manna gum and mountain gum had been planted, thus ending a period of 13 years of intense forestry interest in a most promising species.

ACKNOWLEDGMENTS

We thank Tom Ledig, Pacific Southwest Forest and Range Experiment Station, Forest Serv., U.S. Dep. Agric.; Cliff Low, Department of Environmental Horticulture, U.C. Davis; and Rick Standiford and Jim Rinehart, University of California, Cooperative Extension for 1983 data collection.

REFERENCES

King, James P.; Krugman, Stanley L. Tests of 36 Eucalyptus species in northern California. Res. Paper PSW-152. Berkeley, California: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 6 p.

---

[3]Data on file, Timber Realization Co., Calpella, California.

Yields in High Density, Short Rotation Intensive Culture (SRIC)—Plantations of *Eucalyptus* and Other Hardwood Species[1, 2]

R.M. Sachs and C.B. Low[3]

Abstract: Initial high density (17,200 trees ha^{-1}, 6961 trees a^{-1}) plantations of *Eucalyptus grandis* yielded up to 22 oven dry tons (ODT) ha^{-1} yr^{-1} (10 ta^{-1} yr^{-1}) on an approximate 6 month rotation. Border effects could not be eliminated from the small sized plots used. Also within 4 years of planting there were substantial differences in tree vigor and survival such that the effective density was reduced by half. Subsequent plantations of several hardwood species at 5000 trees a^{-1} and with somewhat better border protection were harvested 2 years after planting; tree survival was greater and in some *E. camaldulensis* plantings yields were in excess of 37 ODT $ha^{-1}yr^{-1}$ (16.5 ta^{-1} yr^{-1}). Accounting for border pct. *E. camaldulensis* and *E. cam* x *rudis* outyielded *Salix*, *Acacia*, *Populus* and *Ailanthus* sp. tested. Current trials are with greater border thickness and compare seedling and clonal plantations of some fast growing eucalyptus selections at planting densities from about 1900 trees a^{-1} down to 600 trees a^{-1}.

From the outset the major goal of our research has been to determine the feasibility of growing fuelwood as an alternate crop on underutilized but otherwise high valued farmlands (say \$1500 a^{-1}). An economic analysis, which has essentially driven our studies on yields, revealed that profitability of fuelwood plantations depended upon production rates greater than 15 tons per acre per year (t a^{-1} yr^{-1}) of oven dried wood.

Methods

The parameters used in the analysis are listed in table 1. The costs assumed are those applicable for well-managed farmlands in the Central Valley of California. Budget generators, available from the department of Agricultural Economics, University of California, Davis, have many more line items from detailed studies with several field crops. A goal of our research was to verify or alter the assumed costs that we have used in our analysis, using input data from cooperators wherever possible. Keeping the limitations in mind, the break-even, farm-gate price for wood chips, with a 15 t a^{-1} yr^{-1} yield, is about \$43 t^{-1} for the first harvest and \$20 t^{-1} for subsequent harvests. These prices are competitive with wood chip prices quoted in the Sacramento area for March 1983.

Results

Survey Studies

Small *E. grandis* plantations at Santa Ana, Calif., with over 6900 seedlings per acre (on 30 in. centers) and harvested twice annually yielded about 10 t a^{-1} yr^{-1} in the third year following planting out (table 2), and the 4th year from seeding (Sachs and others 1980). Although at the time this yield was considered high for plantations at this latitude and climate, we realized that it was probably substantially below what could be achieved with altered management practices and better selection of planting material (Skolmen, 1983). (Many herbaceous crops, C_4 plants well-adapted to the Central Valley, could outyield the eucalypts, although higher cultural costs may be required annually raising the breakeven price for biomass above that for perennial species. These herbaceous species could well be utilized as primary fuel crops under certain economic and fuel delivery systems). The *E. grandis* seedlings were from a non-selected seed lot in which some of the individuals were quite vigorous, but also in which variability was extremely high. (Seed from collection of A. Leiser, Professor of Environmental Horticulture, University of California, Davis, Calif.). The plots were self-thinning in that weak individuals could not compete and large holes developed in the borders as well as sampling areas. In 1982 the blocks were thinned with trees on approximately 5-ft centers, to about 1700 trees a^{-1}. These plots can no longer be used to obtain accurate estimates of yields for large-scale plantations because the borders are not sufficiently dense. They will show, however, what is to be expected from wind-break plantings of moderate height. Based on current growth rates we estimate harvest rotations of three to four years and yields approaching 20 t a^{-1} yr^{-1}.

---

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, Calif.

[2]Useful conversion factors:
T ha^{-1} = 2.24 x t a^{-1}
a = 0.4047 ha

[3]Professor of Environmental Horticulture, University of California, Davis, Calif.; Research Associate, Perry Laboratory, Los Gatos, Calif.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

Table 1--Economic Analysis for Woody Biomass (Cordwood and Chips) in Short Rotation, Intensive Culture Plantations in California

Estimated Woody Biomass Costs

Calculations based on:
- Planting approximately 1000 trees per acre for cordwood or 1200 trees per acre for chips.
- 4-year harvest cycle.
- Cost of land, labor, and operations.

Operations	Assumed cost a^{-1} (cordwood)	Assumed cost a^{-1} (chips)
	---- Dollars ----	
Land Rent	150	
Site Preparation	150	
Weed Control	100	
Plant Materials (0.35/tree)	350	420
Irrigation Installation	300	
Planting	75	
Pesticides	50	
Fertilization	50	
Total	1,225	1,295

Annual maintenance	Assumed cost $acre^{-1}$ yr^{-1}
	---- Dollars ----
Land Rent	150
Irrigation	100
Fertilization	50
Subtotal	300
Total for 3 years	900

Harvesting	Cordwood	Chips
	---- Dollars ----	
Cutting and stacking	1,000	400
Total for 4 years (excluding transportation)	3,125	2,595

Estimated Yields for Intensively Cultured Wood Lots

Cordwood
- 7 cords a^{-1} yr^{-1}.
- Harvest 700-1000 trees a^{-1} every 4 to 6 years.
- Wood will have approximately 50 pct. moisture content and need one year to air dry.

Wood Chips
- 15 dry tons a^{-1} yr^{-1}.
- Harvest 1000 trees a^{-1}.
- Whole tree harvesting.

Break-Even Prices

	---- Dollars ----	
First harvest (4th year)	112/cord	43/ton
Subsequent harvests (every 4 years)	43/cord	20/ton

Table 2--Yield from *Eucalyptus grandis* plots, spacing of 2.5' x 2.5' ft at a density of 7600 trees a^{-1}, Santa Ana, California[1].

Plot	Harvest dates 11-77	6-78	9-78	6-79	9-79
	ta^{-1}				
1	7.5	2.5	2.9	6.9	4.3
2	4.6	5.1	2.5	5.1	3.2
3	3.8	5.5	2.8	6.0	3.6
4	3.3	2.1	1.3	5.8	3.5
Avg.	4.8±1.9	3.8±1.7	2.4±0.7	6±0.7	3.7±0.5

Plot	Annual harvest totals [2]11-77 to 9-78	6-78 to 6-79	9-78 to 9-79
	ta^{-1}		
1	5.4	9.8	11.2
2	7.6	7.6	8.3
3	8.3	8.8	9.9
4	3.5	7.1	9.3
Avg.	6.2±2.2	8.3±1.2	9.7±1.2

[1]Source: Sachs and others (1980).
[2]10-month harvest.

Clonal vs Seedling Plantations

The Santa Ana site is being used to obtain performance data for selected seedling plantations of *E. grandis* and clonal plantations of *E. camaldulensis*. (*E. grandis* seedlings were obtained from the Florida Division of Forestry; *E. camaldulensis* clones C-1 and C-2, Low and others, 1983). No yield estimates are yet available for any of the plantations. For *E. grandis* growth rates are very high for selected individuals, but variance is once again very large (fig. 1). Holes are developing in the plantations in the first year from planting; hence, large variations in yield can be expected depending upon the area sampled. In practice variance of this magnitude will result in lower yields on short rotation cycles simply because part of the land area will not be covered with photosynthesizing tissue.

It is too soon after planting to analyze variance in the clonal plantations of *E. camaldulensis* at Santa Ana, but experimental blocks at Davis of a mixture of four clones of *E. camaldulensis* x *rudis* show greatly reduced variance (fig. 2). For this reason establishing clonal

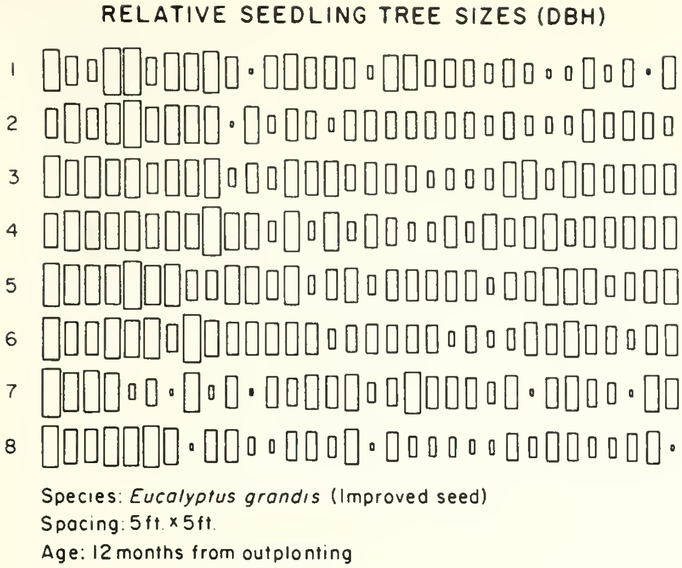


Fig. 1. Schematic computerized diagram of trunk diameters at breast height (dbh) of seedling plantation of *E. grandis*, 1 year after planting out at Santa Ana, California. Trees are on 5 ft centers in and between 8 rows; dbh is not to the same scale as that of the plantation.

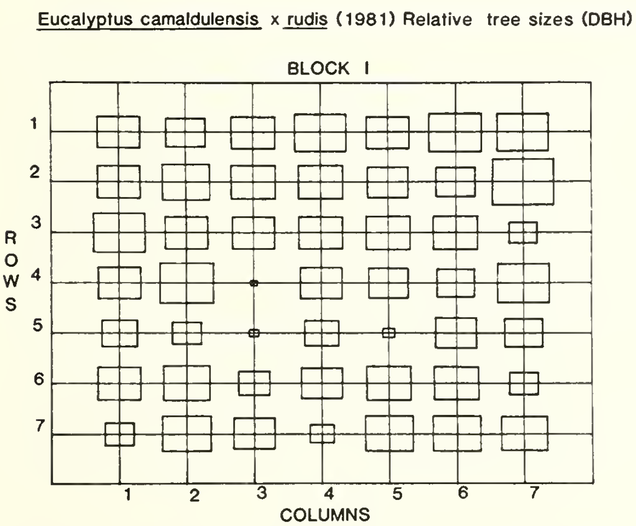


Fig. 2. Schematic diagram of dbh of mixed clonal plantation of *E. camaldulensis* x *rudis*, 22 months after planting out at Davis, California. Trees are on 5 ft centers in and between rows; dbh is not to the same scale as that of the plantation.

plantations of selected seedlings has become an important goal in our program. The clones we now use are limited to species that are easy-to-root, (*E. camaldulensis* and *E. cam.* x *rudis*), and from a very limited examination of performance at relatively few trees (ramets) at relatively few sites (Low and others 1983). We are expanding the program to include clonal propagation of *E. grandis*, cold-tolerant selections of *E. gunii* x *dalrympleana* (see papers by Boulay and Chaperon, this proceedings), as well as improved selections from other eucalyptus species and provenance trials.

Species Selection

There is little question that eucalyptus plantations are very fast-growing, but there is no head-to-head comparative data for yields for other highly touted genera (sequoia, pine, acacia, poplar, willow, etc.) and very little from within the eucalyptus genus (Standiford, 1981; Skolmen, this symposium; Mariani and others, 1981). We made one small study at Davis with high density plantings (3' x 3' ft spacings) of several species (table 3).

Table 3--Species trials of six Eucalyptus species, planted in Oct. 1979 and March 1980, at spacing of 3' x 3' ft and at a density of 5000 trees a , University of California--Davis, harvested 1982.

Species	Block[1] A	Block[1] B	Block[1] C
		ta^{-1}	
Ailanthus altissima	13.05	--	4.36
Acacia melanoxylon	13.40	--	5.09
Salix babylonica	15.11	4.44	7.22
Eucalyptus camaldulensis	16.81	13.28	20.3
E. camaldulensis x *rudis*	16.94	15.9	7.9
Populus ('Fry' poplar)	6.76	3.06	5.17

[1]Yields include leaves and small branches. In some blocks, yield values in error owing to insufficient border. Overestimate incurred is about 10 pct. Missing values and much of the variation among blocks reflect loss of trees when plantings made in late fall.

Results for a few coniferous species are not shown because their two year growth rates were very far below that for any of the hardwood species. Owing to financial limitations these blocks could not be maintained to evaluate coppice yields, long term border effects, management practices and variability. Nevertheless the comparative growth data were highly instructive and permitted us to narrow our search for species adapted to short rotations. Currently we are comparing selected clones of *Populus deltoides* and *E. cam.* x *rudis*. Plantations of *Alnus rhombifolia*, established at the same time are considerably slower growing and could not qualify as a candidate species for prime lands. They are maintained to demonstrate comparative performance of a potential N-fixing species. Absence of mycortizal organisms may account for some of the reduced vigor in the olders. The poplar crop may match that of *E. cam.* x *rudis* in volume growth, even though we had initial establishment problems. Also, at a waste-water treatment plant in

Davis, this same selection of P. deltoides is out performing all other species in the first year from outplanting.

15/Ton/Yr Plantation

At the outset of this paper we stated that approximately 15 dry tons of biomass per acre per year were required to make wood production an economically feasible alternative crop on under-utilized farmland. This yield figure seems achievable with E. camaldulensis and E. cam. x rudis at Davis and probably elsewhere in California's Central Valley. E. camaldulensis plantations in Israel have maintained high yields for more than 80 years and 6 rotations (Kolar 1963) at sites harsher than those typical of farmlands in the Central Valley. Probably higher yields can be expected in the milder winter climates of southern California (e.g., Santa Ana), but cultural costs will be considerably higher there at these locations. For example, irrigation water is sold above \$200 ac. ft^{-1} and at close to \$400 ac. ft^{-1} in some locations below the Tehachapi. In all cases that we have examined waste waters will be required for irrigation of plantations in southern California and we have no idea whether or how much the higher salt contents of such waters will depress biomass yield.

Discussion

There is an obvious paucity of comparative data for species performance in short rotation, high density plantations, and there are many other important unanswered questions concerning yields. Our current tests are limited to examining the problem of density and planting pattern (two-row spacings and three within row spacings). Harvest rotation must be established on the basis of growth rate. Non-destructive methods must be developed to establish growth rate (annual volume increment); in collaboration with F. Thomas Ledig and Richard Standiford, we plan to develop volumetric tables for a few eucalyptus species. If we can accurately establish annual volume increments and can use these figures to estimate when growth rate begins to decline, we will have a relatively simple method to determine optimum harvest rotations (and planting densities).

It seems evident from our early studies with very high density E. grandis plantations that yields are depressed with frequent harvest rotations (semiannual in that case). E. grandis should not be treated as a hay crop (an initial goal in our work) if maximum biomass production is desired. Tree establishment time is probably a species specific trait related to development of the root system. This establishment time is probably of no immediate practical significance if one uses volume increment to estimate growth rate and set the harvest cycle accordingly, but it is of theoretical and perhaps, ultimately, practical interest. One would guess that, everything else being equal, species that require less root system development (that is, have a relatively high shoot-to-root ratio) will be among the highest yielding. Reduced root development is, of course, no advantage under non-irrigated, droughty conditions, but our economic model assumes up to 3-acre-feet irrigation during the spring to fall interval. We are using a soil hydroprobe (neutron meter) to determine soil moisture depletion. In this way we will regulate irrigation frequency and amount to make certain that the plantations are not stressed for lack of available soil moisture.

Yields will be dependent upon providing (or returning) to the root depletion zone the minerals extracted at each harvest. Our current goal for the first harvest cycle is to monitor soluble foliar nitrogen and to feed nitrogen at rates sufficient to maintain levels close to that of trees irrigated with half-strength Hoagland's solution. We are far from understanding the nutritional requirements for species (or clones) in our plantations and, as our experimental data improve, expect future modifications of the current practice of adding 100 lbs a^{-1} nitrogen yr^{-1}.

How many clones should we have in a plantation - or in backup gene banks - to protect against catastrophic losses from environmental hazard? For all their advantages in reduction of variance, mono-cultures are particularly susceptible to environmental disease or pest-related losses owing to the absence of genetic-variation, with inherent resistance in at least part of the population. Libby (1980), in addressing the question of the safe number of clones per plantation, concluded that the answer cannot be simple. Monoclonal plantations are frequently the best strategy because they can maximize genetic gain, but some notion must be had of the maximum acceptable economic loss and likely hazards (risk to genotypes) before one can decide to go with only one clone. For eucalyptus in California the most severe hazard has been the infrequent intrusion of polar air with sustained temperatures below freezing. In December 1972, there were 3 days of temperatures below 20° F and in 1932 there were about 7 days with temperatures below 20° F in the San Francisco Bay area and surrounding counties. With the introduction of cold-tolerant clones we should be able to minimize these losses. In coppiced plantations the freeze-induced losses should be limited to the current rotation and only rarely lead to death of entire trees. Diseases and pests of eucalyptus are not unknown, but we have too little information for California to estimate the risk and economic loss.

REFERENCES

Kolar, M. Financial and timber yeilds in Eucalyptus camaldulensis over six rotations. In: Contributions on eucalypts in Israel, Volume II; Rome, Italy: Mediterranean Forestry Subcommission, FAO: 1963; 53-64.

Low, C. B.; Matson, G.; Sachs, R. M. Propagation fast-growing eucalypts for energy crops. Calif. Agric. 20-22; 1983 May/June.

Mariani, E. O.; Wood, W. A.; Konchonkos, P. C.; Nuriton, M. B. The eucalyptus energy farm. USDOE-HCP/T2557-01. NTIS, U.S. Dep. Commerce. Springfield, Virginia 22161. 1978.

Sachs, R. M.; Gilpin, D. W.; Mock, T. Short rotation eucalyptus as a biomass fuel. Calif. Agric. 18-20; 1980 Aug./Sept.

Skolmen, R. Review of Worldwide Growth and Yield. These proceedings. 1983

Standiford, R. B. The potential for eucalyptus plantations in California. Coop. Ext. Bull. Berkeley, CA: Univ. of Calif.; 1981. 28 p.

Part 5. Cultural Requirements

Vegetation Management in *Eucalyptus*[1]

Clyde L. Elmore[2]

Abstract: Weeds and weed control are a major problem in the growth and management of Eucalyptus trees. Annual, biennial and perennial weed species are common in sites to be planted. These weeds should be controlled before planting. Preplant, preemergence and postemergence herbicides are discussed. Safe preemergence herbicides include oryzalin, napropamide, oxadiazon, linuron and to a lesser degree simazine, atrazine and diuron. Glyphosate, amino triazole and paraquat have been used safely and efficaceously postemergence. Combinations of mechanical and chemical weed control help allow maximum tree establishment and growth.

Weeds are plants that compete for water, nutrients and light, or in Eucalyptus plantations may interfere with the management and operations of the growing and harvesting of trees. Weeds when dry may also be a fire hazard. Eucalyptus species are grown in California for wood products, ornamental trees along roadways or around buildings and as an ornamental for cut foliage. This paper will refer principally to the control of weeds prior to, or during the early establishment of trees.

Unwanted vegetation (weeds) are found in all sites that will be considered for planting. The plants found will generally be a mix of material and will represent broadleaf and grass weeds. The weeds will usually be a mixture of annual, biennial and perennial plants. The majority of plants will be annual and will complete their life cycle from seed to foliage, bloom and seed within a year. Plants that germinate in the late winter and spring are called summer annuals because they mature in the summer but die with a frost. When plants start in the cool moist season (fall) and grow through the winter they are called winter annuals.

Biennial plants usually start in the fall and form a rosette during the first winter. They form a flower stalk in the following year, flower, form seed, then die.

The life cycle of the third type of plant is called perennial. They possess the capability of continuing growth year after year. They not only seed but generally will form an above and/or below ground storage organ that helps maintain the stand of the weed. Perennials may be herbaceous johnsongrass (Sorghum halapense), field bindweed (Convolvus arvensis) or California blackberry (Rubus vitifolius).

TYPES OF CONTROL STRATEGIES

Site selection

The site can be selected to optimize the growth of trees without the interference of unwanted vegetation. Annual weeds though a problem are not as difficult to control as the perennial plants. Sites infested with perennial herbaceous weeds, woody brambles or shrubs should be avoided if possible. Increased costs are required when reducing perennial weed populations. A site that can be cultivated for annual weed control during early tree establishment will reduce chemical costs. A site that has water (irrigation) available allows for controlling moisture for tree growth. The freedom to apply water (time and amount) is beneficial in increasing herbicide efficacy. In an irrigated plantation weed competition for water may not become a limiting factor. In dryland (natural rainfall) sites weeds must be reduced or eliminated to maintain moisture for the trees.

Site Preparation

Weeds should be controlled before planting the trees. Brush species should be removed and resprouting species controlled before planting. Perennial weeds such as bermudagrass, johnsongrass, nutsedge or field bindweed should be reduced before planting. Postemergence herbicides are effective for these weeds. Annual species can be reduced by cultivation followed by an irrigation to germinate new weeds before the second cultivation. A contact herbicide can be substituted for the cultivation.

A cultivation will reduce seed production and subsequent weed infestations. Where erosion can be a concern, mowing the weeds may be more desirable than a cultivation. Mowing weeds promotes low growing (prostrate) species, especially bermudagrass.

Preplant (Aquiar, 1975) and preemergence (Bazan, 1974 and Veiga, 1969) herbicides have been used prior to planting of seedling trees.

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Extension Weed Scientist, University of California Cooperative Extension, Davis, Calif.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

Preplant fumigants have been effective and safe. They are expensive for large areas but reasonable for nursery production sites.

Preemergence herbicides (monuron, diuron, simizine and atrazine) have been injurious when applied prior to planting.

Control in New Plantings

The control of weeds is most critical to the growth of trees during the first 2 years after planting. Various control measures (Starr, 1980) were compared on a sandy clay and podsolic soil. Mowing of weeds allowed greater tree growth than no weeding. On a sandy clay soil the best growth resulted from treatment with a black plastic mulch. In the podsolic soil there was no difference in tree growth when treated with black plastic, wood mulch, hand weeding or a combination of paraquat and diaquat. Ramalho and Zunti (1975) in Brazilian plantations reported using mowing at right angles reduced manual labor. Prolonged weedings (Brandi, 1974) were needed to give maximum tree growth.

Preemergence herbicides (table 1) have been evaluated on Eucalyptus species. The tolerances of the species are listed with the reference. Postemergence herbicides (table 2) can be used selectively as a directed spray. These same preemergence and postemergence herbicides have been evaluated in establishing plantings.

In sloping sites where soil erosion occurs it has been observed in pine plantations that a strip treatment of preemergence herbicide down the tree row and leaving vegetation between the rows reduces erosion. The vegetation between the rows should be mowed periodically to reduce moisture loss and to decrease a fire hazard.

Preemergence studies on E. sideroxylon var. rosea (table 3) indicated no significant phytotoxicity or difference in growth with simazine, napropamide, oxadiazon, or combinations of simazine plus trifluralin or oxadiazon plus trifluralin applied annually over a 3-year period.[3] The control of annual weeds was excellent with all treatments (table 4). Similar studies using the same herbicides were conducted in container grown E. nicholii. Field plantings of E. pulverulenta[4] have been treated with preemergence herbicides (table 5) without phytotoxicity and, in general, good weed control.

Eucalyptus as a Weed Tree

Since some species are very site tolerant, such as moisture, salts, fertility and soil depth, they may be considered weed trees in certain locations. These sites seem to be preferred for pines (Minko, 1981) or in some California Douglas-fir (Pseudotsuga) in some locations, annual crops in others. Eucalyptus found as weed species include E. cambageana, E. largiflorens and E. populnea.

[3]Elmore, C.L. and D. Hamilton. Unpublished data.

[4]Elmore, C.L. and S. Besemer. Unpublished data.

REFERENCES

Aguiar, I. B.; Gurzel, Filho, O.A. 1975. Preventative weed control in nursery beds of Eucalyptus citriodora Hook. Cientifica 3(1):130-146.

Bazan, L. A. C.; Minami, K. 1974. Preliminary results of herbicide trials in a eucalypt. IPEF No. 8:47-48.

Brandi, R. M.; Barrow, N. F. de; Candido, J. F. 1974. Comparison of methods of weeding in the establishment of Eucalyptus alba, E. saligna, and E. botryoides. Revista Ceres 21:118, 427-433.

Brasil, U. M.; Fernandes, P. de S.; Simoes, J. W.; Ferreira, J. E. F. 1976a. Use of weed killers in establishing plantations of Eucalyptus saligna. I.P.E.F. Univ. de Sao Paulo, Piracieaba, S.P. Brazil IPEF 13:123-134.

Brasil, U. M.; Machado, P. R.; Fereira, F. M. 1976b. The use of herbicides in Eucalyptus crops. In Resumos XI Seminario Brasileiro de Herbicides e Ervas Daninhas, Londrina, 108-109.

Chavasse, C. G. R.; Stockley, G. H.; Gleed, J.; Dorsser, J. C. van; Davenhill, N. A.; Preest, D. S. 1976. The use of herbicides in forestry in New Zealand. Chap. 2. Weed control in tree crops in forest nurseries. Chap. 3. Tolerance of trees to herbicides. N. Z. For. Serv. Rotorua, New Zealand. F. RI Symposium New Zealand Forest Service. 18:9-49.

Dorsser, J. C. van. 1973. The use of herbicides in forest nurseries (in New Zealand) Proc. of the 4th Asian-Pacific Weed Sci. Society Conf. Rotorua, 279-283.

Elmore, C. L. 1973. Weed Pollution. Proc. Intern. Plant Progratorʼs Society 23:95-101.

Ethiopia, Chilalo Agri. Development Unit; Crop Protection activities 1974. CADU Publication No. 111, 147-195.

Flinn, D. W.; Stewart, H. T. L. and P. Q. Shaughnessy. 1979. Sciencing of weedicides for overspraying Eucalyptus, Pinus and Casuarina on clay soils irrigated with treated effluent. Australian Forestry 42(4):215-225.

Magnani, G. 1976. Chemical weed control in poplar, eucalypt and conifer nurseries. Notiziario sulle Malattie delle Piante No. 94-95, 225-230. (Weed Absts. 27,2991)

Minko, G.; D. W. Flinn. 1981. Evaluation of herbicides for stem injection of woody weeds in young radiata pine plantations. Australian Forestry 44(4):260-266.

Ramalho, C. P.; Zunti, A. C. 1975. The use of mechanical weedings at right angles in plantations of Eucalyptus spp. Brasil Florestal 23(6):30-55.

Revell, D.; H. Deadman. 1976. Planted hardwoods and weed competition. Proc. of the F.R.I. Symposium No. 18. The use of herbicides in forestry in New Zealand. 1975. 133-137.

Schie, R. van. 1978. Early weed and grass control for plantation establishment in Tasmania. Proc. of the first conference of the council of Australian Weed Science Societies 336-343.

Schonau, A. P. G.; Verloron, van Themaat, R.; Borden, D. I. 1981. Wattle Res. Inst.; Univ. Natal. Pietermaritzburg, South Africa. South Africa Forestry J. 116:1-10.

Starr, R.; J. Clemens. 1980. Weed control for ornamental trees. Abst. Plant Physiology 65 (supplement) 134.

Veiga, R. A. de A. 1969. Phytotoxicity in eucalypt plantations with the use of herbicides. Solo. 61(2):33-38.

Table 1--Preemergence herbicides evaluated on *Eucalyptus* species

Herbicide	Reference	Comments
alachlor	Elmore, 1973	selective
atrazine	Bazan, 1974; Brasil, 1976a; Ethiopia, 1974; Schie, 1978	toxic to seedlings
bromacil	Bazan, 1974; Brasil, 1976a	toxic to seedlings
DCPA	Bazan, 1974; Brasil, 1976b; Elmore, 1973	nontoxic to seed germination
dichlobenil	Flinn, 1979	injured 3 species
diuron	Brasil, 1976a; Veiga, 1969	safe on some species established
EPTC	Veiga, 1969	safe but short residual
hexazinone	Schie, 1978	toxic to *E. globulus*
linuron	Bazan, 1974; Brasil, 1976a; Brasil, 1976b; Dorsser 1973	nontoxic to seed germination
monuron	Veiga, 1969	injures plants
napropamide	Elmore, 1973	highly selective
oryzalin	Brasil, 1976b; Elmore, 1973; Starr, 1980	highly selective
oxadiazon	Elmore, 1973	highly selective
propyzamide	Flinn, 1979	selective for grasses
propazine	Flinn, 1979	selective
secbrometon	Bazan, 1974	toxic to seedlings
simazine	Brasil, 1976a; Elmore, 1973; Ethiopia, 1974; Flinn, 1979; Revell, 1976; Schie, 1978	tolerant on most young or established plantings at low rates and in medium to heavy soil
terbumeton	Bazan, 1974	toxic to seedlings
trifluralin	Elmore, 1973	highly selective

Table 2--Postemergence herbicides evaluated on *Eucalyptus* species

Herbicide	Reference	Comments
aminotriazole	Magnani, 1976; Schie, 1978	effective grass control when used with atrazine or simazine
dalapon	Veiga, 1969	injurious to *E. saligna*
glyphosate	Ethiopia, 1974; Starr, 1980	effective postemergence on grasses and some woody species (brambles)
paraquat	Ethiopia, 1974; Revell, 1976	control of young annuals

Table 3--Phytotoxicity and Growth Indices of *E. sideroxylon* var. *rosea*

		Phytotoxicity[1]			Growth[2]
Herbicide	Rate A.I./A	3 MO.	5 MO.*	2 MO.**	Indices
simazine	0.5	0.0	0.0	0.5	299.2
simazine + trifluralin	0.5 + 2	0.0	0.0	0.6	314.7
napropamide	4	0.5	0.0	0.3	334.8
napropamide	16	0.8	0.0	0.0	280.6
oxadiazon	2	0.2	0.0	0.0	289.8
oxadiazon + trifluralin	2 + 2	0.0	0.0	0.0	270.0
untreated	-	0.0	0.0	0.0	282.3 (N.S.)

[1]Phytotoxicity: 0 = no effect; 10 = dead plants.

[2]Growth indices = $\frac{\text{height (m) x width (m)}}{2}$ mean of 2 plants per plot x 4 replications.

*Months after 2nd application.

**Months after 3rd application.

Table 4--Weed Control in *E. sideroxylon* var. *rosea* [1]

Herbicide	LB. A.I./A	(Months) 3	4	(4)	(5)
simazine	0.5	7.3	6.6	8.4	8.0
simazine + trifluralin	0.5 + 2	6.4	6.8	9.0	9.1
napropamide	4	9.3	8.6	8.6	9.2
napropamide	16	9.6	9.2	9.9	9.9
oxadiazon	2	7.9	7.2	8.5	8.8
oxadiazon + trifluralin	2 + 2	6.7	6.8	9.1	9.0
untreated	--	3.2	4.7	1.8	0.2

[1]Weed control: 0 = no control, 10 = complete control

Applications: 7/23/71, 12/21/71, 11/21/72*, (simazine rate doubled)

Table 5--Preemergence herbicides in field planting of 1 year old *E. pulverulenta*

Herbicide	LB A.I./A	Weed Control[1] 1 Mo. All Weeds	2 Mo. Cheeseweed	Goosefoot	All Weeds	Phytotoxicity[2] 2 Mo.
simazine	1.0	5.5	8.8	10.0	8.5	1.0
simazine	2.0	7.0	10.0	9.0	9.0	1.0
linuron	0.5	6.5	9.8	5.0	7.8	1.0
linuron	1.0	6.8	9.8	8.2	8.8	1.0
diruon	1.0	6.5	9.8	8.5	8.0	1.0
simazine + oryzalin	1 + 4	7.2	9.0	10.0	9.0	1.0
simazine + napropamide	1 + 4	7.0	9.5	9.8	9.0	1.0
oryzalin	4	6.2	9.8	7.2	7.5	1.0
napropamide	4	5.5	8.0	5.8	7.0	1.0
oxyfluorfen	0.5	9.4	10.0	10.0	8.8	1.0
oxyfluorfen	1.0	8.8	10.0	10.0	9.5	1.0
oxyfluorfen	2.0	9.8	10.0	10.0	9.8	1.0
untreated	-	3.8	3.2	1.0	4.2	1.0

[1]Weed control: 10 = complete control; 1 = no control.

[2]Phytotoxicity: 1 = no effect; 10 = dead plants.

Spacing Trials Using the Nelder Wheel[1]

Walter B. Mark[2]

Abstract: The Nelder Wheel is a single tree systematic experimental design. Its major application is for plantation spacing experiments. The design allows for the testing of a number of spacings in a small area. Data obtained is useful in determining the response of stem diameter and crown diameter to spacing. Data is not compatible with data from conventional plots unless single tree modeling is utilized. The design is sensitive to individual tree losses. Nelder Wheels were planted at Cal Poly, San Luis Obispo with eight species of eucalyptus and a hybrid poplar in 1980. First year growth results are presented.

The productivity of short rotation biomass plantations will vary with many factors including the spacing utilized in the planting. The nature of energy plantations, where productivity is to be maximized in an extremely short rotation, necessitates determination of optimum planting density. The early yield studies dealing with eucalyptus plantations made no attempt to determine what the optimum spacing might be (Metcalf 1924). Most of the yield data for eucalyptus are for relatively long rotations, conventional spacing and merchantable volumes. Many of the early feasibility studies on energy plantations utilized this yield data for determination of the production possible. Spacings in these yield studies varied up to 16 by 16 feet (USDA Forest Service 1975). More recent spacing studies have been conducted using several different spacings, such as 8 by 8 feet, 10 by 10 feet, 12 by 12 feet, and 14 by 14 feet (Walters 1980). When a plantation project was planned at Cal Poly, San Luis Obispo one of the first questions was that of the optimum spacing to use for the species that were being considered. No answers to that question were available. As a result, the Cal Poly plantings were made with one of the goals being to determine optimum spacings for the species, products, and rotations desired.

The plantation area was limited to 17.5 acres. The size limitation forced the utilization of an experimental design that would allow the testing of many spacings in a small area. The Nelder Wheel or fan design was selected.

NELDER WHEEL DESIGN

Concept

Experiments designed to produce specific answers to questions are the best source of data for deriving models of growth. Much of the available data on plantation growth was obtained from the measurement of existing plantations that were planted with a specific objective in mind. Most often that objective was not to maximize total biomass production, but rather to produce a certain product. If the productivity of those plantations is measured for that product, the data is valid. If the plantation is measured for another product, the model may not be applied to a stand planted with other products in mind.

Experiments should be set up to answer specific general questions rather than to select the best of a set of treatments. The Nelder wheel design is a single tree systematic design with the main application toward spacing experiments in a uniform forest. Systematic designs like the Nelder wheel are laid out in a specified pattern to economize on the size and cost of the experiment. Treatment locations are not randomized and data generated cannot be analyzed by analysis of variance. The data is useful, however, in regression parameter estimation. Nelder wheel experiments have most commonly been utilized for modeling of individual tree growth.

Design and Layout

Nelder wheels are circular plots with a variable number of spokes per plot and rings per spoke (fig. 1 & 2). In the examples shown the plots have 24 spokes and 10 rings. This design provides 240 planting spots per plot. In the Nelder wheel design the innermost and outermost rings should not be included in the data because these planting spots do not have a uniform spacing. The design shown in fig. 1 and 2 would have 192 data trees, assuming 100 percent survival. Any time a tree dies in the plot the four trees in the adjacent planting spots must also be eliminated from the data, because their spacing has been changed.

Before the plot is laid out in the field, the spacing trials desired should be determined. The plot design works best if the interval spacing or radial spacing for planting spots on the spoke is approximately the same as the cross spacing between the planting spots on the spokes. The

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Academic Program Planner, formerly Professor of Forestry, California Polytechnic State University, San Luis Obispo, Calif.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

cross spacing can be determined from the following formula:

$$C = \sqrt{2a^2(1-\cos\theta)}$$

where C = cross spacing
a = interval spacing
θ = angle between spokes

Plot layout in the field takes a great deal of time and requires a high degree of accuracy. The angle between the spokes must be turned accurately or the spacing between the planting spots will not be accurate. This can be checked most easily by measuring the distance between the spokes at the plot perimeter. The interval spacing along the spokes should also be measured with a high degree of accuracy. Planting spots should be staked prior to planting to assure that planting is carried out over a short time interval.

Nelder wheel plots are frequently divided to provide for varied treatments or replications of species tests. Most frequently the plots will be used for from one to three species or for one to three treatments. This type of plot division can present a problem in data interpretation if the species or treatments vary widely in their growth pattern. Edge effects may be created between treatments or species tests.

Another type of systematic design provides square and rectangular spacing trials. In this design the spacing between trees is increased by a constant for each successive planting in both the x and y axis (fig. 3). This results in spacings of all distances in both a square and a rectangular trial.

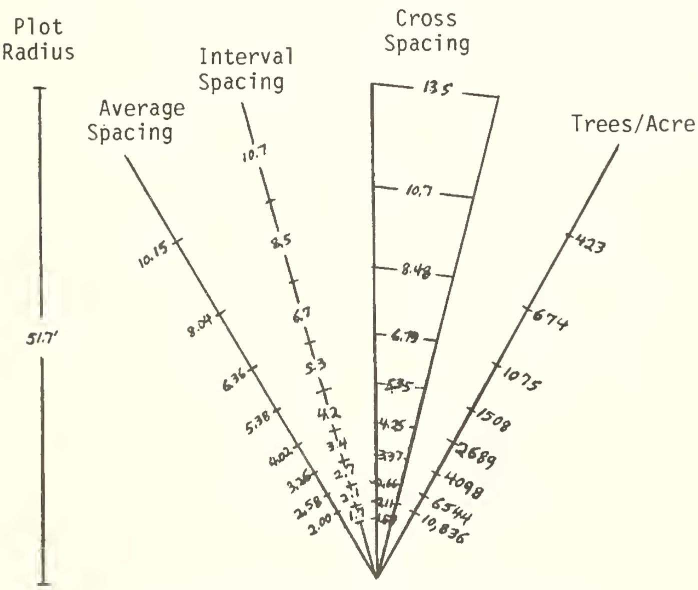


Figure 1--Nelder wheel layout showing planting spots, cross spacing, ring interval spacing, and average spacing.

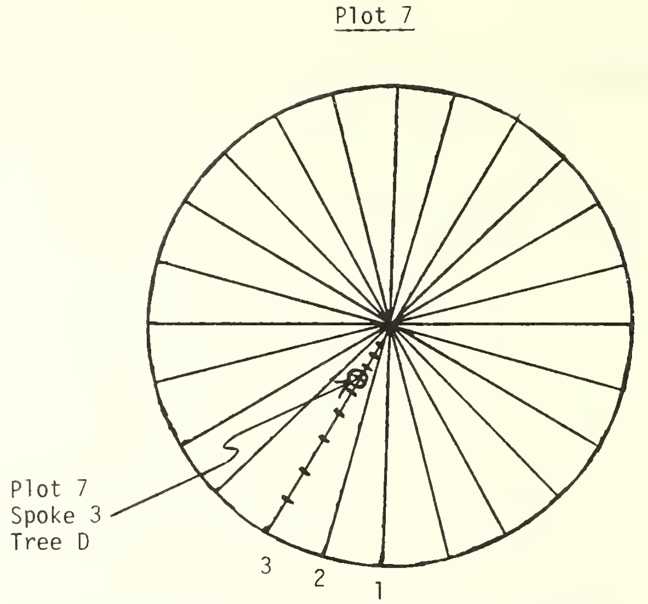


Figure 2--Illustration of labeling of planting spots in Nelder wheels. Planting spot indicated is Plot 7, Spoke 3, Tree D. Tree A is closest to the center.

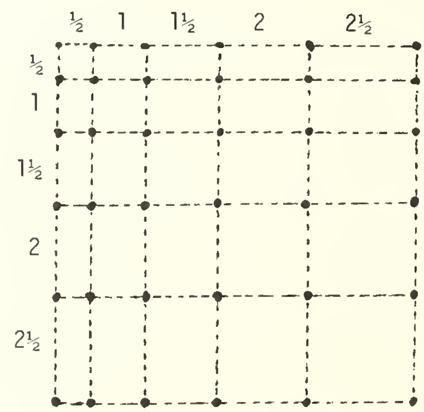


Figure 3--Systematic experiment design using a rectangular design.

CAL POLY NELDER WHEEL EXPERIMENTS

Plot Design

The Nelder wheel design for the Cal Poly spacing trials had 24 spokes with 10 rings on a spoke (fig. 1 & 2) (Kirkley, Pillsbury and Mark 1981). This provided 240 planting spots and 192 data trees per plot. The plot radius to the outermost planting spot was 51.7 feet and each plot occupied 0.23 acres. The average spacing distances varied from 2.01 by 2.01 feet to 10.15 by 10.15 feet (Table 1). The angle between the spokes was 15 degrees. These spacings were selected on the assumption that they would bracket the range of optimum spacing for the species being planted.

Plot Layout

Plot layout on the plantation site was complicated by the variable terrain and soils. The plantation site was range land with slopes varying between 5 and 22 percent. The first step was to map the plantation site, including unplantable sites (gullies and rock outcroppings), developments, soils, and topography. This map was utilized in the office to position the plots prior to field location. Once the plot location was determined on the site map, the plot centers were located at the plantation site. The preliminary site preparation, consisting of bi-directional ripping and tilling with a vibrashank, had been done prior to plot location. Plot layout was done using a transit, Clinometer, and steel tape. Spoke angles were turned from the plot center and the outermost planting spot on each spoke was staked. The spoke spacing was checked before staking planting spots along the spokes. Planting spots were determined on the spokes by measuring out the prescribed horizontal distance from the plot center.

Plantings

Eight species of eucalyptus and hybrid poplars were planted in 26 plots. The species of eucalyptus included *Eucalyptus camaldulensis* (Dehnh.), *E. cinerea* (F. Muell. ex Benth), *E. citriodora* (Hook.), *E. globulus* var. *compacta* (Labill.), *E. polyanthemos* (Schau.), *E. pulverulenta* (Sims), *E. stellulata* (Sieb. ex DC.), and *E. viminalis* (Labill.). All the stock was container stock and was obtained from the California Department of Forestry or commercial nurseries.

Prior to planting, the plots were sprayed with "Round-up" to control vegetation which had emerged after the initial site preparation. Plots were not planted within 48 hours of herbicide application. Planting in each plot was finished in the day it was started. Initial planting was completed between February 13 and March 20, 1980. Planting and fertilizing was done using KBC planting bars. Fertilizer treatments included 10 and 21 gram tablets with a 20/10/5 formulation. All plots were planted with one species; however, the plots were split for fertilizer and herbicide treatments.

Pre-emergent herbicide application was started on April 4, 1980. Two herbicides were utilized, "surflan " and "Devrinol". Applications were made on 10 of the 26 plots with each half of the plot treated with a different herbicide. No detrimental effects were recorded from the application of the pre-emergent herbicide, in fact, the only plot that had no mortality by May 1, 1980 was planted on February 22 and treated. All other weed control was by mechanical means.

RESULTS

The tree growth on the plots was measured in January and February, 1981, approximately one year after planting. The results for six species from the plots of each with the lowest mortality rates are presented in table 2. The tree diameters were measured at the base since the trees had no dbh when planted, and most had none after 1 year of growth. The average height and diameter of the planting stock were as follows:

Species	Height (m)	Diameter (cm)
E. camaldulensis	0.12	0.15
E. cinerea	0.10	0.10
E. citriodora	0.28	0.30
E. globulus var. *compacta*	0.32	0.29
E. pulverulenta	0.54	0.33
E. viminalis	0.11	0.15

Table 1--Nelder wheel spacing and density as utilized in the Cal Poly, San Luis Obispo spacing plantation

Radius (ft)	Interval Spacing (ft)	Cross Spacing (ft)	Average Spacing (ft)	Trees per acre	Tree Code
51.7	--	13.5	-----	---	I
41.0	10.7	10.7	10.15	423	H
32.5	8.5	8.48	8.04	674	G
25.8	6.7	6.73	6.37	1,075	F
20.5	5.3	5.35	5.38	1,508	E
16.3	4.2	4.25	4.03	2,689	D
12.9	3.4	3.37	3.26	4,099	C
10.2	2.9	2.66	2.58	6,544	B
8.1	2.1	2.11	2.01	10,836	A

Table 2--Height and basal diameter after one year of growth in Nelder wheel plots at Cal Poly, San Luis Obispo.

Tree Species	Percent Survival	Plot Number	Measurement	Tree Code B	C	D	E	F	G	H	I
E. camaldulensis	91	32	ave hgt m	0.25	0.30	0.29	0.27	0.30	0.28	0.28	0.25
			ave dia cm	0.73	0.82	0.94	0.82	0.84	0.78	0.77	0.79
			max hgt m	0.52	0.45	0.47	0.49	0.52	0.52	0.52	0.36
			max dia cm	1.47	1.52	1.72	1.53	1.56	1.54	1.36	1.39
E. cinerea	73	2	ave hgt m	0.56	0.55	0.53	0.53	0.58	0.54	0.54	0.59
			ave dia cm	0.74	0.78	0.81	0.89	0.94	0.84	0.82	0.91
			max hgt m	0.77	1.20	0.87	0.87	1.19	1.10	0.95	1.46
			max dia cm	1.39	1.80	2.16	1.58	1.80	2.29	1.69	2.18
E. citriodora	71	12	ave hgt m	0.74	0.92	0.67	0.73	0.74	0.63	0.86	0.57
			max hgt cm	1.39	1.44	1.38	1.13	1.19	0.97	1.42	1.20
E. globulus var. *compacta*	60	6	ave hgt m	0.79	0.63	0.71	0.67	0.58	0.60		
			ave dia cm	0.96	0.69	0.67	0.87	0.74	0.73		
			max hgt m	1.08	0.97	1.05	1.01	0.87	0.87		
			max dia cm	1.78	1.28	1.23	1.46	1.06	1.22		
E. pulverulenta	71	3	ave hgt m	0.61	0.69	0.65	0.68	0.67	0.68	0.68	0.78
			ave dia cm	0.66	0.71	0.67	0.77	0.75	0.76	0.74	0.82
			max hgt m	0.86	1.03	0.91	1.03	1.27	1.21	1.00	1.40
			max dia cm	1.00	1.05	0.96	1.40	1.52	1.24	1.38	1.50
E. viminalis	92	13	ave hgt m	0.94	0.89	0.92	0.93	1.04	0.79	0.86	0.91
			ave dia cm	1.24	1.67	1.71	1.75	1.93	1.65	1.78	1.87
			max hgt m	1.45	1.33	1.36	1.33	1.64	1.28	1.52	1.50
			max dia cm	2.40	3.04	2.80	2.48	2.80	2.65	3.14	3.00

In general the height growth was lowest in the innermost rings, peaked between rings C and F, and dropped off again in the outer rings. Diameter growth generally increased from the innermost rings to the outer rings. This pattern of diameter growth would be expected because of the nearly open-grown status of the trees in the outer rings through the first year. In the Cal Poly unirrigated experiments *E. viminalis* had the greatest average height and diameter growth (1.04 m and 1.93 cm respectively) of all species tested. The best growth occurred in plot 13 ring F, at an average spacing of 6.37 x 6.37 feet. A few trees were remeasured in October, 1982. By that time *E. globulus* var. *compacta* had the best growth with a maximum height of 5.1 m, basal diameter of 10.5 cm, and dbh of 5.7 cm.

The mortality was lowest in plots which had good weed control and which were not on ridgetops. Deer browse was a problem with all the plots planted to *Eucalyptus camaldulensis*, while all other species were lightly browsed or left alone.

LIMITATIONS AND APPLICATIONS OF THE NELDER WHEEL

The Nelder wheel experimental design is well suited to experimentation to determine the optimum spacing for maximum production at a certain rotation. The data will provide single tree data on diameter and crown growth. This data can be applied to uniformly spaced forest situations provided that a single tree model has been developed. The experimental design is excellent for preliminary testing of newly introduced species or for species that are being tested for new product markets or rotation ages.

The Nelder wheel design has also been utilized to make genetic selections based on individual tree performance (Namkoong 1966). The design can be utilized to select trees that will out-perform others at the same spacing distances and can be utilized to choose the maximum performers at varying rotation ages.

CONCLUSIONS AND RECOMMENDATIONS

Application of the Nelder Wheel

The Nelder wheel design is an excellent experimental design for determining the optimum spacing distance for tree species. The design allows for the testing of several different spacings in a relatively small area. The small size of the plots may distort the growth data because of the edge effect that has been observed in small, dense, open sided row plantings of some species (Zavitkovski 1981). The effect has been shown to extend through several rows along the border of small plots. Similar studies have not been conducted on the edge effect in Nelder wheels.

The design should be utilized only for determining optimum spacing distance. It is best applied in situations where the plots are relatively level. If the plots are placed on a slope, the spacing distances do not really represent the distances intended in the design. The plots are laid out using horizontal distance measurements. If the plots are viewed from directly above, they are circular and the crown space is representative of the spacing design. The opportunity for lateral interception of solar radiation is greater and the available rooting zone is larger. If the plot is viewed perpendicular to the slope, the plot will appear elliptical in shape. This distorts growth data because of the varied spacing, especially if the plots are split with different species or treatments. The Nelder wheel design should be applied where the chance for high survival rates are great. Like all single tree experiments the design is highly sensitive to tree mortality. If a single tree dies, not only is the data for that tree lost, but the data on the four adjacent trees is also lost. The death of a tree upsets the arrangement of the design so that the spacing distances are not as planned.

The data must be analyzed using regression analysis. The data is good for predicting regression parameters. The analysis of variance technique should not be applied to the data, since the design is systematic and not randomized.

One common error made in using the Nelder wheel design is to make yield predictions based on an expansion of the growth data obtained. The average growth for a certain spacing is multiplied by the number of trees per unit of land area and a yield is predicted. This is not accurate unless single tree modeling has been applied.

For yield prediction a randomized block design is superior to the systematic design. The plot data is applicable to forest stand yield prediction, is not as sensitive to tree mortality, and can be analyzed using the analysis of variance technique. Stand culture is simpler because of the row arrangement and is better suited to mechanization.

LITERATURE CITED

Alder, D. Forest volume estimation and yield prediction: Volume 2-Yield prediction. FAO Forestry Paper 22/2. Food and Agriculture Organization of the United Nations. Rome, Italy. 1980. 10-15.

King, J. P. and S. L. Krugman. Tests of 36 *Eucalyptus* species in northern California. Res. Pap. PSW-152. Pacific Southwest For. and Range Exp. Stn., Forest Service, U. S. Department of Agriculture. 1980. 6p.

Kirkley, M. L., N. H. Pillsbury, and W. R. Mark. Silvicultural biomass plantation: A renewable fuel source. In Proceedings of the Symposium on Dynamics and Management of Mediterranean-Type Ecosystems, June 22-26, 1981, San Diego, Calif. Gen. Tech. Rep. PSW-58. Forest Service, U. S. Department of Agriculture, Berkeley, Calif. 1982. 609-610.

Metcalf, W. Growth of *Eucalyptus* in California plantations. Univ. Calif. Agric. Exp. Stn., Bull. 380. Berkeley, Calif. 1924. 61p.

Namkoong. Application of Nelder's designs in tree improvement research. Proceedings of the Eighth Southern Conference on Forest Tree Improvement, Savannah, Georgia. June 16-17, 1965. Georgia For. Res. Council. 1966. 161p.

U. S. Forest Service. Cooperative progress in eucalypt research. Southern Forest Exp. Stn. Forest Service, U. S. Department of Agriculture. 1975.

Walters, G. A. Saligna eucalyptus growth in a 15-year-old spacing study in Hawaii. Res. Pap. PSW-151. Pacific Southwest For. and Range Exp. Stn., Forest Service, U. S. Department of Agriculture. 1980. 6p.

Zavitkovski, J. Small plots with unplanted plot border can distort data in biomass production studies. Can. J. For. Res. 2(1):9-12. 1981.

Establishing a *Eucalyptus* Energy Plantation on the Central Coast of California[1]

Norman H. Pillsbury and Nelson L. Ayers[2]

Abstract: A 17.5-acre non-irrigated biomass energy plantation has been established near San Luis Obispo. This joint California Polytechnic State University - California Department of Forestry project is measuring plot growth response of seven eucalyptus species for three spacing trials and for the effect of fertilization. All study plots are replicated. Site preparation strategy, planting, and maintenance and protection problems are discussed. The most important problem is the heavy weed growth. Herbicides and mechanical methods were used to control competing vegetation. A continuous effort is necessary for successful plantation establishment - especially during the first year.

Woody biomass plantations are gaining national attention for their conversion properties into energy feedstocks. Research is continually being conducted to demonstrate this biomass potential for alternative energy sources. Information obtained from biomass studies will help relieve our dependence on fossil fuels. For example, the U.S. Forest Service has set a national goal of an increase of 4 Quads (4 quadrillion BTU's) by 1990 (from wood residue). This represents 5.5% of the nations energy budget. The California Energy Commission has a similar goal of meeting 5% of the States energy budget by the year 2000 from all biomass energy production or 400 trillion BTU's.

THE ENERGY PLANTATION CONCEPT

Tree species selected for biomass production must be resistant to insect and disease, demonstrate rapid growth and have high energy yield during short rotations, and respond to intensive cultural treatments. Additional plantation management may include fertilization and irrigation at various times during the rotation (Pillsbury and Ayers 1982).

Hardwood species are thought to have the greatest potential for energy farming. They have the added advantages of not competing with timber and product uses of commercial conifer species and they can be coppiced. Examples of hardwoods being examined in trial plantings in the United States include Alnus, Eucalyptus, Platanus, and Populus.

A number of Eucalyptus species appear most promising in California. Of the 700 plus species in the genus, perhaps 20 or 30 could be used in the various climate regimes of California (Pillsbury 1980). Their density in the plantation may range from 400 to 11,000 trees per acre.

The energy plantation must be of sufficient size to guarantee a reliable long-term supply of fuel, on scheduled demand, to the power plant. Additional support acreage for storage, road network, and facilities ranges from 10 to 40 percent above the planted area (Kirkley et al. 1981).

Energy yield from plantations is a subject of much debate. Variables to be considered are species selection, spacing, cultural treatments, fertilizers, irrigation, soil and site quality, rotation number since initial planting, and weed control. Estimates obtained from available literature references for model studies and some plot data show yields ranging from 3.5 dry tons/ac/yr for Populus in Wisconsin to 15 dry tons/ac/yr for high-quality tropical fuel plantations. Values used for California range from 5 to 13 dry tons/ac/yr. The lower value assumes minimal management on marginal sites while the higher value reflects intensive management practices on higher quality land. Most authors were optomistic about future increases as management practices are improved and research studies identify optimum yield species and soil conditions. One model study shows California potentially producing 22 dry tons/ac/yr under ideal conditions (Fege et al. 1979).

The cost of producing energy feedstocks is equally debatable. Regional differences are created by land lease, interest and taxes, transportation costs and distances, the cost of investment (affected by current prime lending rates), land steepness (which defines the cost of harvest equipment) and water availability (Fege et al. 1979). Costs per dry ton ranges from $20 to $34 with most authors showing reduced costs following future technological advancements.

---

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California

[2]Professor of Forestry and Graduate Research Assistant in Forestry, respectively, California Polytechnic State University, San Luis Obispo.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

No reliable cost estimates were found for marginal lands in California. Cost per million BTU is $1.20 to $2.50 based on 17 million BTU per dry ton, while 1985 costs for coal are projected at $1.50 per million BTU.

THE CAL POLY - DEPARTMENT OF FORESTRY EUCALYPTUS ENERGY PLANTATION

A joint California Polytechnic State University and California Department of Forestry Eucalyptus Energy Plantation is currently being grown near San Luis Obispo. The plantation is designed to demonstrate the effectiveness of growing non-irrigated eucalyptus trees for biomass energy. The project was initiated in 1979 to evaluate the suitability of several eucalyptus species by measuring mortality and single tree growth rates (Mark et al. 1980). Results from this initial study were used to select species for a second planting currently being evaluated for growth and yield.

The general purpose for this long range biomass study is two-fold. First, the project data will help land owners understand techniques and difficulties involved in establishing a commercial non-irrigated eucalyptus plantation. It will identify management practices and potential problems which influence the success of plantation establishment, maintenance and continued growth. Also, it will provide a source of growth and yield information for energy farmers. Our specific objectives can be best understood by these eight commonly asked questions.

1. What species should be planted?
2. What spacing should be used?
3. What yield can be expected and when?
4. Should the tree be fertilized?
5. What are the requirements for an effective site preparation?
6. How can weed and pest problems be controlled?
7. What is the energy benefit-cost relationship?
8. What rotation age will provide optimum yield?

Site Description

The study area is located about mid-way (6 miles) between the Pacific Ocean and San Luis Obispo. The planted and support area is 17.5 acres in size and is located on sites typically found along the central coast of California. The elevation is approximately 580 feet and the site is predominantly south-facing with slopes ranging from 5-22 percent. Weather patterns are typically Mediterranean with wet winters and dry summers. The mean annual precipitation in San Luis Obispo for the 1963-1983 period is 27.62 inches; 75 percent occurs from December through March. However, rainfall for 1982-1983 was the third wettest on record, 47.59 inches. The average frost free season exceeds 300 days. The mean annual temperature for the last 20 years was 63.8 degrees Fahrenheit. The soils are classified as Los Osos variant clay loam. The surface layer is grayish brown clay loam about 12 inches deep and the subsoil is pale brown clay about 27 inches thick. The underlying material in the subsoil is moderately alkaline and consists of calcareous clay loam extending to a depth of greater than 60 inches. Several rock-outcroppings are located on the site. Grass species such as wild oats (*Avena fatua* L.), annual rye grass (*Lolium multiflorum* Lam.), and soft chess (*Bromus mollis* L.) are prevalent. The land was previously used for cattle grazing.

Site Preparation

The study area was burned in October 1982 to eliminate all weeds and competing vegetation. A single shank was used to rip each row to an approximate depth of 2.5 feet. The site received 2 inches of precipitation prior to cross discing. The purpose of cross discing was to close the gap and seal the moisture into the ground. Planting was delayed several weeks due to high soil moisture conditions; excessive weed growth occurred during that period. To eliminate weed growth prior to planting Round-up, a non-selective post-emergent herbicide, was applied. The rate of application was 4.5 ounces of active ingredient in 2.5 gallons of water per acre. Simazine which is a pre-emergent herbicide will be applied shortly before the first Fall rains to prohibit annual weed emergence. It will be applied at a rate of 4 pounds of active ingredient in 25 gallons of water per acre.

Plantation Design

The Eucalyptus plantation consists of a split plot randomized block design for seven species. Each species is being tested for its response to a fertilizer treatment and for three spacings of 3 x 12 feet, 6 x 12 feet and 9 x 12 feet. The spacing between rows for all plots is 12 feet to accommodate farm machinery sizes normally available for planting, maintenance, and harvesting. Control plots (non-fertilized) were also established for these spacings as shown in figure 1. Each spacing trial contains 6 rows with 6 trees per row or 36 trees. The treatment and control plots contain 108 trees each (36 trees x 3 spacings) or 216 trees per species. Each species was replicated to complete the randomized block design shown in figure 1. The data collected from these plots will be used for yield analysis. Several buffer rows were planted adjacent to the plots to protect yield trees from external influences. These buffer trees will not be used in the evaluation of plantation yield.

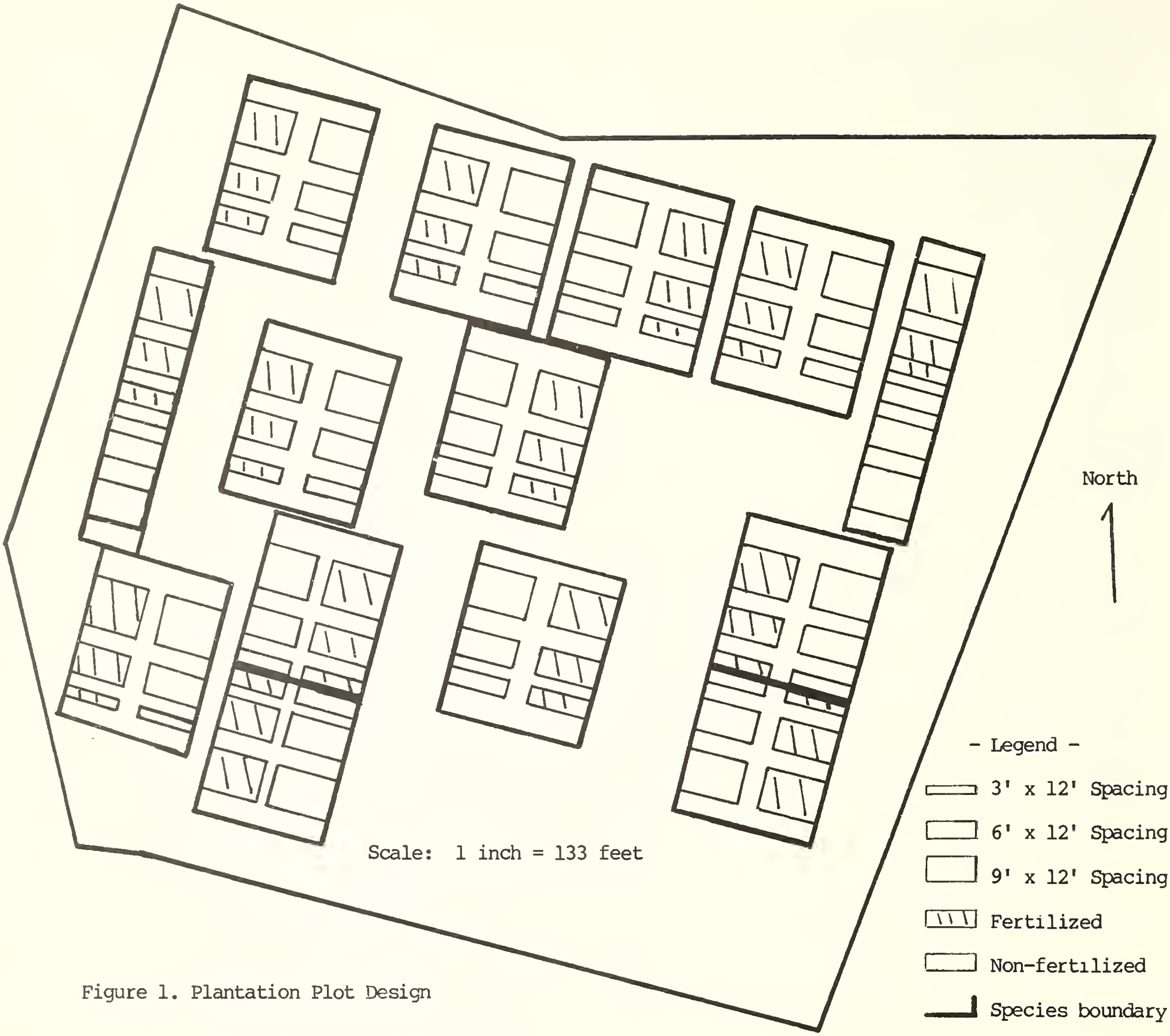


Figure 1. Plantation Plot Design

Species Selection and Seed Source

The seven species to be evaluated are;

1. Eucalyptus camaldulensis (Dehnh. var. camaldulensis)
2. Eucalyptus citriodora (Hook f.)
3. Eucalyptus dalrympleana (Maid. subsp. dalrympleana)
4. Eucalyptus globulus (Labill. subsp. globulus)
5. Eucalyptus grandis (Hill ex Maid.)
6. Eucalyptus sideroxylon (A. Cunn. ex Woolls subsp. sideroxylon)
7. Eucalyptus viminalis (Labill.)

E. dalrympleana, E. grandis, and E. sideroxylon were selected for the study because they have demonstrated excellent potential for biomass production in other regions in California (Mariani et al. 1978 and Sachs et al. 1980). The other species demonstrated rapid growth, ease in regeneration and establishment, tolerance to insects and pathogens, and their suitability to the soil and environmental conditions of the central coast area in a previous study. All species were closely matched to the temperature and precipitation patterns for San Luis Obispo County.

The seed source for all species except E. citriodora originated in Australia. They were propagated in 1 by 6 inch squared plastic containers having a medium of 90 percent peat moss-vermiculite and 10 percent perlite. The California Department of Forestry Nursery at Davis cultivated the seedlings in their greenhouse-nursery complex where seasonal moisture and temperature conditions were simulated. The eucalyptus seedlings were 1 year old at the time of planting. The E. citriodora was purchased from a private commercial nursery and no information was available to describe its origin and propagation history. They were approximately 3 months old when planted.

Planting and Maintenance Problems

The Eucalyptus Energy Plantation was planted during a 2 week period in mid-February 1983. Trees in fertilized plots were given a 21 gram slow-release Agri-form fertilizer tablet containing 20 percent nitrogen, 10 percent phosphoric acid and 5 percent soluble potash. The pellet was placed about 3 inches below the root zone (1 foot from the soil surface) during planting.

During the initial 4 month growing period the plantation became heavily infested by weeds. However, only sparse weed coverage occurred along the rows compared to the inter-row area. It appears that ripping, in this case to a depth of 2.5 feet, in addition to breaking up any hard pan soil layers to provide for better root penetration, also provides a form of weed control.

A preliminary investigation shows that the majority of seedling mortality on the plantation occurred in E. citriodora where over 95 percent died. This exceptionally high rate may be due to age of the delivered stock (3 months) or to improper "hardening" practices. It is recommended that all species be the same age for comparing growth rates.

Deer browsing was prevalent throughout the plantation although most of the damage was located in one area. Species that were browsed include; E. viminalis, E. camaldulensis, E. grandis, E. dalrympleana and E. sideroxylon. Continued deer browse caused the seedlings to develop extensive lateral branching. This may require pruning to maintain the desired tree form.

Several perches will be located throughout the plantation. By attracting predators, it is anticipated that the rodent population will be controlled.

Productivity Measurements

Plot productivity measurements will include height and diameter beginning in the first year. A correlation between height, diameter, weight, and energy yield will start the second year; by the third year sprouts will be evaluated. The data will be used to compare productivity by species and spacing and to test the effect of fertilization.

Project Timetable

In addition to information about site preparation techniques discussed earlier, more information will be available on mortality, weed control, deer browsing and plantation establishment problems by summer 1984. By 1989 the remaining questions relating to yield, energy benefit-cost ratio, optimum spacing, and best rotation age can be more fully answered.

ACKNOWLEDGMENTS

Acknowledgments: We thank Gary Brittner, California Department of Forestry, Sacramento; David Soho, California Department of Forestry, Monterey; and the California Conservation Corps, San Luis Obispo for their project and manpower support. This study is supported by Grant 3-080-019, California Department of Forestry.

REFERENCES

Fege, A.S., Inman, R.E. and D.J. Salo. Energy farms for the future. J. Forestry. June 1979.

Kirkley, M.L., Pillsbury, N.H., and Walter Mark. Silvicultural biomass plantation: A renewable fuel source. Proceedings of the Symposium on Dynamics and Management of Mediterranean-type Ecosystems, June 22-26, 1981, San Diego, Calif. U.S. For. Serv., Pacific Southwest For. and Rge. Exp. Sta., PSW-58. pp 1107-1109.

Mariani, E.O., Wood, W.A., Kouchoukos, P.C. and M.B. Minton. The eucalyptus energy farm feasibility study and demonstration. Phase I: site and species selection. Marelco, Inc. 1978.

Mark, W.R., Pillsbury, N.H. and M. Kirkley. Silvicultural energy plantation establishment, Cal Poly, San Luis Obispo. 1980. Progress Report. Wood Energy Program, Calif. Dept. of Forestry, Sacramento. 36 p.

Pillsbury, N.H. A summary of the potential and problems of silvicultural energy plantations in California. Presented at the July, 1980 Calif. Energy Comm. Biomass/Synfuels Workshop, Sacramento.

Pillsbury, N.H. and N.L. Ayers. The potential and design for California's energy plantations. Presented at Soc. of American Foresters Wood Energy Conference, January 30, 1982, Riverside.

Sachs, R.M., Gilpin D.W., and T. Mock. Yields of short rotation Eucalyptus grandis in high density plantings. Proceedings, Energy from Biomass and Wastes, January 21-25, 1980. Lake Buena Vista, FL.

Fertilization and Irrigation of *Eucalyptus* in Southern California[1]

Paul W. Moore[2]

Abstract: An experiment to determine the interaction of three levels of irrigation, three levels of fertility and three densities of planting was started at the University of California Moreno Ranch in 1982. Differential irrigation and fertility treatments will begin in June of 1983.

Some current practices of irrigation and fertilization by southern California growers are discussed.

In 1981 the California Department of Forestry's Wood Energy Program awarded 9 grants for the establishment of biomass tree farms to satisfy research needs for wood energy production.

One of the grants was made to the University of California at Riverside.

The experiment is located on the Moreno Ranch of the University of California at Riverside. The site is located south-east of the community of Sunnymead, California at 117° 11' W longitude, 33° 54' N latitude.

The soil is classed as Romana Sandy loam with a 1 percent slope.

The source of irrigation water is an on-site well. Total dissolved solids is 550 ppm. Boron is present in the well water at 0.77 ppm. Although the boron content has been toxic to sensitive crops no injury has been observed on previous Eucalyptus plantings served by the same source.

Weed control was started pre-plant by laying out the planting furrows and pre-irrigating to germinate weeds. Germinated weeds were killed by contact herbicides before planting. Subsequent weed control has been done by contact sprays and relative little hand hoeing. Disking was performed between rows following the winter rains. Future weed control will be by a combination of disking and contact sprays as required.

The research at Riverside was designed to study the interaction of:

1. Three planting spacings: 12' x 12', 12' x 8' and 12' x 4' giving stocking densities of 302, 453 and 907 trees per acre.

2. Three irrigation levels: dry, intermediate and wet, and

3. Three levels of fertility: 0, 100 and 300 pounds of nitrogen per acre per year.

Each of the combinations were replicated 4 times. Each plot consisted of 16 trees planted 4 rows wide by 4 trees long. The center 4 trees are the record trees from which all data will be taken. The record trees are E. camaldulensis. The seed source was the Lake Albacutya Provenance of Australia. The surrounding 12 trees are used as guard rows and include a total of 16 Eucalyptus species. Some species are represented by more than 1 provenance. It is anticipated that the use of different species in guard rows will give additional information on their performance compared to E. camaldulensis.

Guard row species are bicostata, camaldulensis, camphora, deanei, globulus, grandis, nova-anglica, saligna, tereticornis, trabuti, urnigera, and viminalis.

The trees were planted during the period of July 21 to August 11, 1982. The seedlings were grown in speedling trays and were approximately 8" tall at planting. Irrigation followed immediately after planting.

Each seedling received 8 to 10 grams of a slow release 21-8-8 fertilizer, broadcast on the soil surface at the base of the plant and irrigated in at the third irrigation.

Irrigation and fertilization were uniform throughout the planting for the remainder of 1982 until the first significant rain which fell on November 11, 1982.

Differential irrigation and fertilization began on June 2, 1983.

For the 1983 growing season the dry plots will be irrigated at 8-week intervals, the intermediate treatments at 4-week intervals and the wet treatments at 2-week intervals.

Water use will be monitored by neutron probe.

Irrigation will be by means of lateral furrows.

The first year fertilizer application was drilled in the furrow bottoms ahead of the June 2 irrigation.

DISCUSSION

Differential treatments were initiated on June 2, 1983. It is much too early to collect any data from the plots. It is anticipated that differences

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2] Paul W. Moore, Specialist, Superintendent of Agricultural Operations Department, University of California, Riverside.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

due to treatments will be observed by the end of the 1983 growing season. The trees were planted on Ramona loam with a water holding capacity of 6" to 8" of water in the soil profile.

Observations On Water Requirements

Prior to establishing the above experiment, water stress measurements were made on 3-year-old E. camaldulensis and E. dalrympleana trees during the 1982 growing season.

The trees were growing in a Sam Amigdio loam with a water holding capacity of 6" to 10" of water in the soil profile.

One treatment was irrigated at 3-week intervals, the second treatment was non-irrigated. Leaf water potential was measured for trees in each treatment by the pressure plate method.

Although drought stress occured in the non-irrigated trees during the day, recovery was complete by the following morning. No significant reduction in tree growth was observed during the growing season.

Greenhouse studies on water stress of E. camaldulensis in containers are being conducted by a graduate student. It has been much easier to produce drought symptoms in containers than in the field.

Tip and marginal leaf tissue necrosis followed by abscision of young mature leaves occurred at tensiometer readings of 70 centibars.

Immature and older mature leaves did not develop necrotic areas.

Inasmuch as no research data from field experiments have been developed, we do not have scientifically based irrigation recommendations to offer.

Three considerations related to irrigation need to be resolved:

1. Consumptive use and timing for optimum growth.

2. Critical timing of irrigation where water supplies are limited.

3. The economics of irrigation based on cost-benefits analysis.

It is anticipated that the experiments which have been described above will provide answers to these questions.

For those who have water available it is suggested that tensiometers could be used to schedule irrigations. Experience with using tensiometers for irrigation management in other tree crops has been good and has proven that the instrument is a reliable tool. Irrigation when tensiometer readings reach 70 centibars is recommended until additional data can be developed.

Some Current Practices

Three irrigation practices are being used in the young Eucalyptus plantings in southern California: drip, sprinklers and furrows.

Drip irrigation is most commonly used on the steeper, rolling terrain, sprinklers are being used on the sandy open soils and furrows on flat lands.

Two growers have irrigated for the first 2 years and have discontinued future irrigations. One grove is planted on river bottom land and the roots have reached the water table. This is an unusually good special situation that provides this grower with an economic advantage.

Another special situation exists with a dairyman who is using waste washdown water from his milk sheds to both irrigate and fertilize with what was previously a problem waste product. He has utilized non-agricultural alluvial slopes at the base of a mountain.

Fertilizer Practices

No research data on fertilization for Eucalyptus in southern California is available. Within 3 years some useful data will be obtained from the U.C. Moreno experiment. Current recommendations are based on observation.

Turnbull and Pryor state that many Eucalyptus have the capacity to respond to higher levels of nitrogen and phosphorus but give no further information regarding species or fertilizer levels exhibiting favorable responses.

They also state that in Tasmania, E. delegatensis has not shown a significant response to various nitrogen/phosphorus/potassium fertilizers.

In Victoria, Australia there has been a good response to applications of nitrogen and phosphorus fertilizers by young trees of E. globulus. In Gippsland, superphosphate is applied shortly after planting, followed by nitrogen/phosphorus fertilizer 1 year later.

In Australia, the survival and early growth of E. nitens has been substantially increased by applications of magamp, a slow release fertilizer, at planting time.

Cremer et al have written that field trials in Victoria and West Australia showed responses to nitrogen and phosphorus. In Papua, New Guinae, E. deglupta responded to nitrogen but not to phosphorus or potassium. E. globulus fertilized with a total of 202 Kg/ha and 90 Kg of phosphorus in the first months after planting yielded a total above-ground biomass at 4 years of age of 30.4 tons/ha. The unfertilized control yielded only 6.3 tons/ha.

Geary, in unpublished data, reported increased growth by 3.5-year-old E. grandis on Florida's acid palmetto prairie land to pre-plant incorporation of 1120 Kg/ha of ground phosphate rock. E. robusta and E. viminalis responded to a lesser extent to applications of 560 and 1120 Kg/ha.

In most California locations it is unlikely that Eucalyptus would respond to either phosphorus or potassium fertilizer. Most of southern California soils are amply supplied with both macro-nutrients but are deficient in nitrogen. However there are exceptions.

Some of the Ramona soils in foothill locations, the Aiken series in the Sierra Foothills and the Altamonts around Northwest San Diego County are known to be low in phosphorus. Citrus in these areas has responded to phosphorus applications but no data has ever been collected for Eucalyptus.

Imperial Valley soils are also deficient in phosphorus and some of the soils of Coachella Valley are borderline.

Most of the valley floor soils throughout the remainder of southern California are amply supplied and no response to additional applications would be anticipated.

In as much as we are dealing with a new crop some plantings of which may come under intensive management practices, it appears prudent to take pre-plant soil analyses to determine the nutrient status of the soils at the planting site.

Leonard Tanner, a Eucalyptus nurseryman, cites responses to phosphorus by newly planted seedlings of E. grandis on certain soils in San Diego County.

This may indicate that newly planted trees of some species with limited root systems can respond to phosphorus. However, no indications of phosphorus deficiency have been observed by the author in Riverside and Imperial Counties. A small planting of E. camaldulensis in soil considered to be low in phosphorus has grown remarkedly well during the first year with no signs of nutrient deficiencies.

Most of the plantings which have been established since 1979 have received some nitrogen fertilizer. Typical practice under drip irrigation is to distribute soluble nitrogen through the drip system at the rate of approximately 32 pounds of actual nitrogen per acre every second irrigation. On an annual basis, this amounts to approximately 100 pounds of N per acre per year.

Similar rates are applied to sprinkler and furrow irrigated plantings.

Generally speaking no fertilization has been used on the older wood lots in the State.

In summary, the nutritional requirements of Eucalyptus in California are not well enough known to make fertilizer recommendations nor can increases in yield from fertilization be predicted. Suggested fertilizer practices can only be inferred from known responses of other tree crops and observations on existing plantings.

Until actual requirements are developed from current research the following guidelines are offered for Eucalyptus groves under intensive cultivation:

1. For newly planted trees use slow release forms of complete fertilizers such as Sierra Chemical Companies Planting Tablets, Osmocote and Magamp. This will assure that all macronutrients are available for stimulating early growth. Placement should be to the side and below the root ball and in the amount of 1/2 to 1/1/2 ounces per tree.

2. Follow with annual applications of nitrogen fertilizers equivalent to 50 to 100 pounds per acre per year. These may be applied through the irrigation water, drilled, or broadcast. If drilled or broadcast during the growing season placement should be such that it is dissolved by the irrigation water and moved into the rootzone. Broadcasting the total amount before the end of the rainy season will also assure that rainfall will move the fertilizer into the rootzone.

3. Establish test areas in your plantings on which different amounts of nitrogen phosphorus and potassium are applied. No fertilizer should be one of the treatments. Measure the D.B.H. annually on several trees in each treatment and evaluate the responses.

4. Calculate cost benefits to determine if fertilization pays off.

Such testing is a part of good management and should be used as a tool to check on the economic benefits of any practice. It has the advantage of giving specific answers related to the immediate site and management practices.

REFERENCES

Cremer, K. W.; Cromer, R. N.; Florence, R. G. Stand establishment. In: Hillis, W. E.; Brown, A. G., eds. Eucalypts for wood production. Division of Building Research, CSIRO, Melbourne, Australia; 1978; 434 p.: Chapter 4.

Turnbull, J. W.; Pryor, L. D. Choice of species and seed sources. In: Hillis, W. E.; Brown, A. G., eds. Eucalypts for wood production. Division of Building Research, CSIRO, Melbourne, Australia; 1978; 434 p.: Chapter 2.

Managing a Coastal Bluegum (*Eucalyptus globulus*) Forest[1]

Ralph S. Osterling[2]

Abstract:

Eucalyptus was thought to be a replacement to oak and other hardwoods for many products. Thousands of acres have been planted and now are in need of management. Management techniques are discussed in context with a coastal stand of approximately 300 acres of mixed aged bluegum. Potential markets are explored.

HISTORY

In 1853 eucalyptus was introduced from Australia into California by Mr. Abbot McKinley[3]. At first, plantings were scattered over several areas on an expanded trial basis. Some fifty years later eucalyptus plantings experienced a boom. Grand scale plantings were made based on predictions of tremendous monetary profits.

The March and September 1909 issues of The Early Sunset (predecessor to the current Sunset) carried an article "Eucalyptus - Hickory's Younger Brother". The author, F.D. Cornell, portrays this genus as having specimens so large they rival the sky-piercing sequoias. The most common species, *Eucalyptus globulus* is noted for its rapid growth. In 1909 it was being utilized for farm implements and insulator pins. The article states that many species of eucalyptus will adapt to the hills and valleys of California, however, bluegum is the most promising for the coastal areas. The article continues to say that it is also used for pilings that will last up to 50% longer than any other species used on the West Coast. *Eucalyptus cladocalyx* (sugar gum) also shows great promise, especially for the southern California area. "In my judgment *E. cladocalyx* and *E. globulus* will replace oak, hickory, and ash in the manufacture of implements, vehicles and kindred products."

A few years ago (about 1909) the commercial culture of eucalyptus was not numbered among the great opportunities offered by California...[3] Advertisements in 1909 heralded, "A Fortune For You In Eucalyptus". Land with trees already planted near Willows sold for $250.00 an acre. "We expect an average diameter growth of 1½ inches per year. A 7-year-old tree averaging 10 inches in diameter is conservatively worth $6.00. Five acres growing 2500 trees would then be worth $15,000. Cut 1/7th each year and your annual income will be $2,000."[3]

During the 120-year history of eucalyptus in California, this species has probably been tested for more uses than any other species. Everything from handles, toys, charcoal, to paving blocks have been investigated. Some 3,000 were even felled for the movie, The Good Earth. Obviously, history has set the pace and has crossed many bridges and many potential products have been proven infeasible. The problem now is how to best manage the present crop. The real question now remains, "What are the best products for this timber crop?"

The property described in this paper is surmised to have been part of the early eucalyptus high-profit program, however, the harvesting and intensive management did not occur as suggested in 1909. In 1929 a catastrophic fire raced through the property. Newspaper accounts described the trees as exploding like shots during the conflagration. Following the 1929 fire the forest regenerated to a fully stocked condition; then in November 1946 a second fire burned much of the parcel. The only known management activity is in a small clear cut, probably for pulp logs during the mid 1950's. Again the forest regenerated until today it is a very dense uneven-aged stand with over 1,130 stems (average) per acre.

MARKETS

Contrary to the spectrum of uses suggested by the historical accounts, the present markets for eucalyptus are limited. Two primary markets exist, namely fuel materials and pulp chips. Other minor products include bumper logs, poles and some pilings. Fuel materials include fire-wood for the consumer market and hog-fuel or biomass fuel for industrial boiler applications. The consumer fuel wood market has increased dramatically with the increased cost of heating oil and natural gas. The popularity of fire place inserts and other wood burning heating

---

[1]Presented at the Workshop on Eucalyptus in California, June 14 - 16, 1983, Sacramento, California.

[2]Registered Professional Forester, State of California; ACF; Private Forestry Consultant, 851 Burlway Road, Burlingame, California 94010

[3]Cornell, F.D. "Eucalyptus - Hickory's Younger Brother", Sunset Magazine, March and September, 1909.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

devices has increased many fold in the past few years. The demand for wood has likewise jumped. It is difficult to accurately access the total demand due to the large number of firewood operators. The author made a brief survey which resulted in confirmation of the doubtful results. Some operators tend to boost sales figures while others hedge or just "don't know". Eucalyptus pulp chips have a specialized and rather limited market due to their fiber characteristics and the limited number of pulp mills within an economic haul radius. Unfortunately, from the San Mateo County coast, any chip trucking operation must cross the entire Bay Area traffic pattern to deliver the chips to the nearest pulp mill located in Antioch.

MANAGEMENT

The goals of forest management are often product oriented. The product might be sawlogs, pulp wood or one of several other forest products. Within the unmanaged eucalyptus forest, product identification is often difficult. Past management activities of many eucalyptus stands have been extensive or nonexistent. Trees have been allowed to grow and reproduce in many stands for more than sixty years. Considering the dynamics of the species, this time frame is equal to perhaps 150 or more years for a western softwood plantation. The eucalyptus forest may well be in a condition to produce a desired product, but probably not in a condition to optimally benefit from a given management practice. The question remains where do we go now? Management of the forest should require maximum utilization of the resource into the desired product or products. Consumer firewood was chosen as our goal because of the adjacent Bay Area population and a less favorable chip market.

Paramount to a harvest operation is the development of a transportation system through the forested area. The forested area of this property was basically unroaded at the time of management planning. A network of roads was engineered to provide close road spacing and numerous landings where logs could be marshalled and wood processed. Benefits secondary to the harvest activities include management access, future harvest and perhaps most importantly fire control access. On this property adequate fire access is paramount due to fuel loading, winds, and the immediately adjacent residential neighborhood.

Topography of the eucalyptus forest consists of a primary ridge line running generally north-south in direction located at the easterly edge of the timbered area. Running nearly perpendicular to that main ridgeline are several spur ridges and drainages that form a watershed with a westerly aspect. Slope steepness ranges from nearly flat to isolated small areas of 70% side slope. The proposed road spacing is engineered to be approximately 300-foot spacings between interconnected contour roads.

SILVICULTURE

Silvicultural application in this dense forest is very difficult due to the extreme amount of knock down and breakage damage that occurs with harvesting. Clear cutting would allow for a more complete utilization, however, adjacent to Highway 1 and the close proximity to the residential area, clear cutting is politically impossible. Stand density creates a relatively high damage level to the residual stand.

For clarity, average spacing of the trees is shown below:

Table 1

DBH	Count (per acre)	Average Spacing
All	1,131	6.2 feet
6 in. +	314	11.8
12 in. +	226	13.9
18 in. +	92	21.8

The trees ten inches and larger average 110 to 245 feet in height. The combination of over stocking, heights and the visual sensitivity create a unique situation where careful harvesting and close supervision are paramount.

HARVEST

Proposed harvesting operations will be a selective thinning utilizing staged falling procedures and other techniques to minimize damage to the residual stand. Following large log removal, the clean-up operation will include added harvest of firewood size chunks, branches and the smaller damaged trees. The secondary fuelwood removal is very beneficial for it will reduce the logging debris and decrease the fire hazard while producing added product.

Skidding will be accomplished with a combination of crawler tractors and rubber tire skidders. Many of the slopes are too steep for rubber tire skidder operation, however, the roads may be used as skidways on which the rubber tire equipment can effectively operate.

POST-HARVEST

Post- harvest management includes road maintenance, erosion control and coppice management. Coppice management is now being researched in cooperation with UCCE; no conclusions have been drawn at the time of this writing. We are optimistic that through prudent coppice management, the yields will be increased, cash returns will be increased and a shorter rotation will be realized. Intermediate crops may also result.

Harvesting to Get a *Eucalyptus* Coppice Crop[1]

Thomas F. Geary[2]

Abstract: Coppicing of eucalypts saves replanting after harvesting, but plan for coppice before planting seedlings. Select a species that coppices in the planned season of harvest; plan spacing and harvesting methods so that harvesting will not damage stumps; plan coppice management. Best coppice is produced by spring harvest with chain saws, low stumps, no bark or root damage, and no debris left on stumps. Problems are fire hazard, regeneration from seeds, coppice reduction, and killing an unwanted coppice crop.

When eucalyptus trees are felled, new stems often grow from the stumps to produce another crop of trees. This new crop is called the coppice crop to distinguish it from the seedling crop. Coppice crops can be important in growing eucalypts profitably. Replanting costs are saved and coppice crop rotations are usually shorter than those of seedling crops, because coppice stems grow faster than seedlings. Several successive coppice crops are possible, but getting a coppice crop depends on planting the right species in the right environment and harvesting with the right method.

PLAN FOR COPPICE

The time to plan for a coppice crop is before planting the seedling crop. Not all eucalyptus species coppice. Choose a species that coppices vigorously and predictably, that grows well, and has the desired wood qualities. Eucalypts For Planting (FAO 1979) describes coppicing ability of species commonly used for wood production. However, relying on a species' reputation for good coppicing is risky, because it might not coppice reliably everywhere. Also, the species may coppice well on average, but some seed sources may not. Before planting a new species in a new environment on a large scale, establish enough experimental plantings to determine coppicing ability at different seasons and ages by periodic fellings.

Spacing and harvesting methods need to be carefully considered in developing a coppicing system. The spacing pattern must allow harvesting equipment to move about without damaging stumps. In irrigated plantations the harvesting plan must include protection of the irrigation system.

Seasons of harvest and rotation age should be planned too. Will coppicing occur in the months in which harvesting must be done? The power to coppice decreases as trees age. Will the trees coppice at the end of the planned rotation? Typically, eucalyptus plantations with rotations up to 12 years are regenerated by coppice, while plantations with rotations longer than 20 years are regenerated by replanting.

THE DO'S AND DON'TS OF HARVESTING

Make A Low Stump

The higher on the bole that a tree is cut, the more likely it is to coppice and to produce many coppice stems. The absurd extension of this principle is to lop off branches, so that the bole becomes covered with shoots. Low cuts rather than high cuts are standard in eucalyptus plantations for at least three reasons. Firstly, the height at which coppice stems are felled is usually above the height used for felling seedling stems, to avoid cutting the ever-thickening stump. The cutting height progressively raises with each coppice crop. If a high cut were used initially, then the cutting height of later coppice crops could become too high. Secondly, stems produced on high stumps are reputedly less wind firm than stems on low stumps. Finally, harvesting equipment may not be able to pass over high stumps.

A stump height of 10 to 12 cm above ground is common. A slanted, smooth cut, which allows water to run-off the stump's surface is preferred.

Do Not Damage The Stump's Bark

Buds in the stump's bark or in underground lignotubers produce coppice shoots. Coppice in plantations usually comes from bark buds. Lignotubers are a reserve source of coppice and some species do not have lignotubers. Therefore, the bark needs to be kept intact and tight to the stump. A stump can coppice

---

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Asia Coordinator, Forestry Support Program, Forest Service, U.S. Department of Agriculture, Washington, D.C.

[3]T.F. Geary studied eucalyptus coppicing in Florida for the Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture.

if some of the bark is damaged, but the more bark damaged, the more likely the stump will not coppice, even though stumps occasionally develop coppice shoots on a barkless area.

Do Not Damage The Stump's Roots

Coppice grows rapidly because the new stems feed from the root system of the seedling stem. Therefore, roots should not be damaged during harvesting. Root damage apparently has not been studied, perhaps because much of the world's eucalyptus plantations are harvested with light-weight equipment. Eucalyptus roots are concentrated in the top few inches of soil. In the United States there is a tendency to use very heavy equipment in forestry, and this equipment can compact soil and break roots, especially if harvesting is done in wet weather, so that ruts are deep.

Remove Debris From Stumps

Remove logging debris from stumps, because coppice shoots are deformed if they must snake their way through debris.

Harvest At The Right Season

Eucalyptus grandis Hill ex Maid. illustrates the variation in coppicing that can occur in different seasons depending on where the trees are grown. In the Republic of South Africa, *E. grandis* is grown extensively and adequate coppicing occurs no matter when young plantations are felled. In Florida, coppicing decreases drastically in summer. Often no stumps coppice following August harvesting. In its native New South Wales, Australia, *E. grandis* coppices poorly in fall and winter.

Season of harvest affects coppicing of *Eucalyptus camaldulensis* Dehnh. in Israel (Heth and others, 1982). Trees felled in winter do not coppice until spring. Trees felled in spring coppice soon after felling, while trees felled in the rest of the year coppice sporadically over several months. Prolonged coppicing causes a great variation in stem sizes in a stand, which complicates management. However, in contrast to experience with *E. grandis* elsewhere, the percentage of stumps that coppice is the same no matter when harvesting is done.

Other seasonal effects must be guarded against. Bark on stumps can crack if trees are felled during a drought, or if freezing weather occurs. Season affects the number of coppice shoots produced, for example, on *E. camaldulensis* in Israel. It seems likely that coppice vigor might be affected by when trees are felled. After considering all factors, it seems that spring felling usually makes the best coppice.

Choose The Right Harvesting Equipment

Felling

Eucalypts felled with axes coppice satisfactorily in the few places where ax felling is still done. However, felling with chain saws results in consistently better coppicing then ax felling. Bow and other kinds of manual saws are very effective in making cuts that favor coppicing, but are rarely used.

A chain saw is the common tool used for felling eucalypts. It has the advantages of making a clean cut that can be slanted and bark damage is rare. In Florida, eucalypts have been cleanly felled by Georgia-Pacific Corp. with chain-saw heads attached to a grapple-skidder.

Anvil-shears are commonly available for harvesting in many parts of the U.S.A. Anvils squeeze the tree as they sever it and this may damage the stump's bark. In Florida harvesting with anvil-shears was compared to harvesting with chain-saws. Although the test was not conclusive, anvil-shears appeared to give coppicing comparable to that of chain saws, if the shears were sharp and the stumps were not struck with the machine's wheels. Dull shears badly damaged bark, split stumps, and even pulled stumps out of the ground. Damage to roots by vehicles mounted with either chain-saw heads or anvil-shears needs study.

Extraction

Felled trees can be bucked into short lengths in the stand, or removed as whole trees. Either option can damage stumps if not done carefully. Bucked trees are commonly extracted from eucalyptus plantations with light-weight equipment, such as agricultural tractors, or even with animals and by hand. Cable removal is common on slopes. During extraction care must be taken not to strike the stumps, although in Portugal racks of logs on slopes are rolled by cable over stumps without damaging stumps significantly. Root damage by different extraction systems has not been studied, but some damage must occur, and it could be appreciable with heavy equipment or the skidding of heavy loads.

Extracting trees whole, including the crown, eliminates a debris problem, and decreases seedling regeneration from seeds stored on the trees. Skidding whole trees has potential for damaging many stumps unless extraction is well planned and the plantation is designed for it.

PROBLEMS AFTER HARVESTING

Fire

The debris left in the plantation is a fire hazard. Information on fire effects in recently harvested stands of eucalypts is scarce. A light fire that occurs before coppice shoots erupt from the bark might not do any damage. After shoots erupt, a hot fire will surely kill young coppice, but if the bark is not badly damaged the stumps might coppice again.

Regeneration From Seeds

Many eucalyptus species store massive amounts of seeds in capsules in their crowns. If crowns are left on the site, the seeds are released. If soil and weather conditions are suitable, germination occurs and a thick stand of seedlings arises. These seedlings usually are suppressed by coppice, but if spacing is wide some seedlings develop into large stems. In plantations established with genetically improved seeds or clonal plants, the seedlings from natural regeneration are of poorer genetic quality than the parent stand. Thickets of seedlings are a nuisance because they complicate coppice reduction.

Coppice Reduction

A stump that has recently coppiced is frequently covered with clusters of shoots. Only one shoot usually survives the competition in a cluster. This still can leave many shoots. Within a few years competition among the remaining shoots reduces their numbers, but that number may still be more than may be wanted for management purposes. The more stems on the stumps in a plantation the more wood produced in short rotations. But as number of stems increases, stem diameter decreases. Too many stems may produce wood too small in diameter for its intended end-use and may increase harvesting costs.

In eucalyptus plantations outside the United States, hand labor reduces the number of stems on a stump to one to three, depending on product goals. A mechanical method for reducing coppice does not exist. Before planting eucalypts with the intention of producing coppice crops, determine if coppice reduction will be necessary and, if so, if it can be afforded. The references FAO (1979), Poynton (1981), and Wattle Research Institute (1972) are good sources of information on reducing coppice.

Killing An Unwanted Coppice Crop

A number of reasons exist for wanting to kill the living stumps. Growing eucalypts may no longer be desired. Other reasons are more common. Some stumps die after each harvest. Eventually too few living stumps remain to produce a well stocked stand, so a new seedling crop would be more productive. Genetically improved seeds or another species may have become available since the original planting, and it may be more productive to replace the existing trees with superior ones.

Understocked coppice stands are not commonly planted with new seedlings without killing stumps, because mixed stands of seedlings and coppice are not uniform, which complicates management. However, understocked eucalyptus plantations can be interplanted (Wattle Research Institute 1972).

A way to kill stumps is to remove them and this is done where there are markets for stump wood. More commonly the stumps are debarked, poisoned with herbicides, or covered with soil. Another alternative is to break off coppice shoots repeatedly until the stump runs out of food reserves or buds, and stops producing shoots.

REFERENCES

FAO. Eucalypts for planting. FAO Forestry Series No. 11. Rome, Italy: Food and Agricultural Organization of the United Nations; 1979. 677 p.

Heth, D.M.; Reuveni, O.; Fanger, L.J. Vegetative propagation of selected clones of Eucalyptus camaldulensis Dehnh. Second Annual Technical Progress Report for research supported by a grant from the United States-Israel Binational Agricultural Research and Development Fund-BARD. Bet-Dagan, Israel: 1982.

Poynton, R.J. The silvicultural treatment of eucalypt plantations in southern Africa. South African Forestry Journal 116:11-16; 1981.

Wattle Research Institute. Handbook on eucalypt growing. Notes on the management of eucalypt plantations in the wattle-growing regions of South Africa. Pietermaritzburg, Natal, South Africa: Wattle Research Institute; 1972. 173 p.

Propagation and Planting of Containerized *Eucalyptus* Seedlings in Hawaii[1]

Gerald A. Walters[2]

Abstract: A container reforestation system has been researched and developed in Hawaii which results in consistently high survival and growth rates for eucalyptus seedlings. Mean survival of containerized saligna eucalyptus (Eucalyptus saligna Smith) seedlings is 90 percent with a standard deviation of 4. Because transplant shock is minimal, seedlings begin to grow quickly. Mean survival of bare-root saligna eucalyptus seedlings was only 56 percent with a standard deviation of 32, and about 70 percent of the seedlings suffered stem dieback. The containerized system includes the nursery, transport, and field phases of reforestation.

Eucalyptus seedlings are propagated and planted in Hawaii through a container reforestation system. The dibble-tube system, which was researched and developed by the Forest Service, U.S. Department of Agriculture, and the Hawaii Division of Forestry, has increased seedling survival and growth rates over those obtained with the old bare-root system (Walters 1981b, Walters and Horiuchi 1979).

The basis of the system is the Hawaii dibble tube (fig. 1)--a specially designed plant container of high-density polyethylene. Its size, about 5 inches deep and 1 1/8 inches in diameter at the top, represents a trade-off between biologic and economic considerations. The dibble tube is large enough for adequate seedling development but small enough for economical handling. The tube has four ridges on the inside that extend from top to bottom. These ridges prevent the lateral roots from spiraling within the container.

The tubes and their racks reduce the number of biological and mechanical variables involved in growing, transporting, and planting seedlings. The dimensional uniformity of the tubes and racks provides potentially the same rooting and aerial volume for each seedling and allows mechanization of nursery and planting operations.

This paper describes the specialized equipment and procedures used in Hawaii to propagate and plant containerized eucalyptus seedlings.

Figure 1--Eucalyptus saligna seedlings growing in the dibbling tubes. A rack holds 100 seedlings.

DIBBLE-TUBE SYSTEM

The dibble-tube system closely links the nursery, transport, and field phases of reforestation (fig. 2). Sufficient technology has been developed or borrowed to allow for a smooth progression from processing seed in the nursery to planting seedlings in the forest.

Nursery Phase

The nursery phase includes headhouse operations and seedling culture. The headhouse is divided into storage and work areas. Sufficient tubes, racks, rooting medium, and gravel (seed cover) are stored to produce about 500,000 seedlings. The work area is designed so that tubes are put into racks, cleaned, filled, seeded, covered, and transported to the seedling culture area in one continuous flow (fig. 3). Eight people can process 100,000 tubes per day.

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Research forester, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Redding, Calif.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

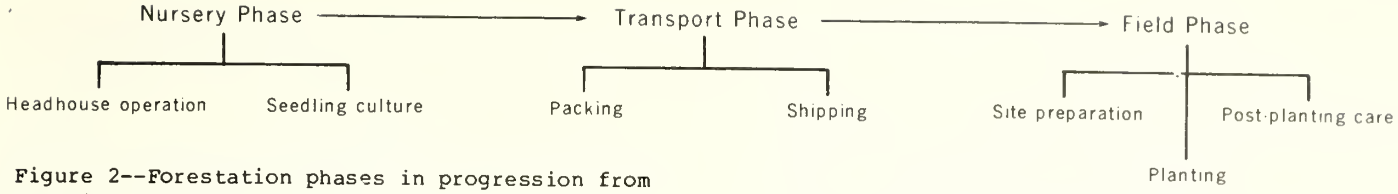


Figure 2--Forestation phases in progression from seed in the nursery to established tree in the forest.

Preparing Tubes and Rooting Medium

Tubes and racks are cleaned and chlorine-rinsed in a commercial dishwasher with a water-saving system at a rate of 8000 tubes per hour. A more automated dishwasher could increase the rate.

The rooting medium--a 2:1 by volume mix of sphagnum peat and vermiculite--is prepared in a self-cleaning soil mixer with 1-yd^3 capacity. Bales of peat and vermiculite are placed in the mixer and then their covers are slit and removed. This loading method reduces the dust problem. Mycorrhizae spores or mycelium are added if available. To ensure that each batch of medium has the same moisture content, a recycling timer allows a specified amount of water to be added during mixing from nozzles on the mixer lid. The mixed rooting medium falls through the bottom hatch of the mixer onto a conveyor, which carries the medium to a hopper over the tube-filling machine.

Three racks (300 tubes) are filled with rooting medium at one time in an automatic impact loader. The impact loader raises the racks then lets them drop; the sudden stop at the bottom forces the rooting medium into the tubes. Filled tubes are carried on a dead-roller conveyor to a simple revolving drum press, which compresses the medium to make room for seeds. The press can be adjusted for compaction to different depths, depending on the size of the seeds to be sown.

Sowing Seeds

Eucalyptus seed is cleaned using sieves and a blower, and then is pelletized by a commercial company. Pelletized seeds are about 1/16 inch in diameter and can be sown accurately and precisely with a simple manual seeder (Walters and Goo 1980).

The seeder consists of three plates with holes held by a frame (fig. 4) so that the holes in the top and bottom plates do not line up; the middle plate slides between the top and bottom plates. Seeds are put on the top plate. The middle plate is positioned so that the holes in

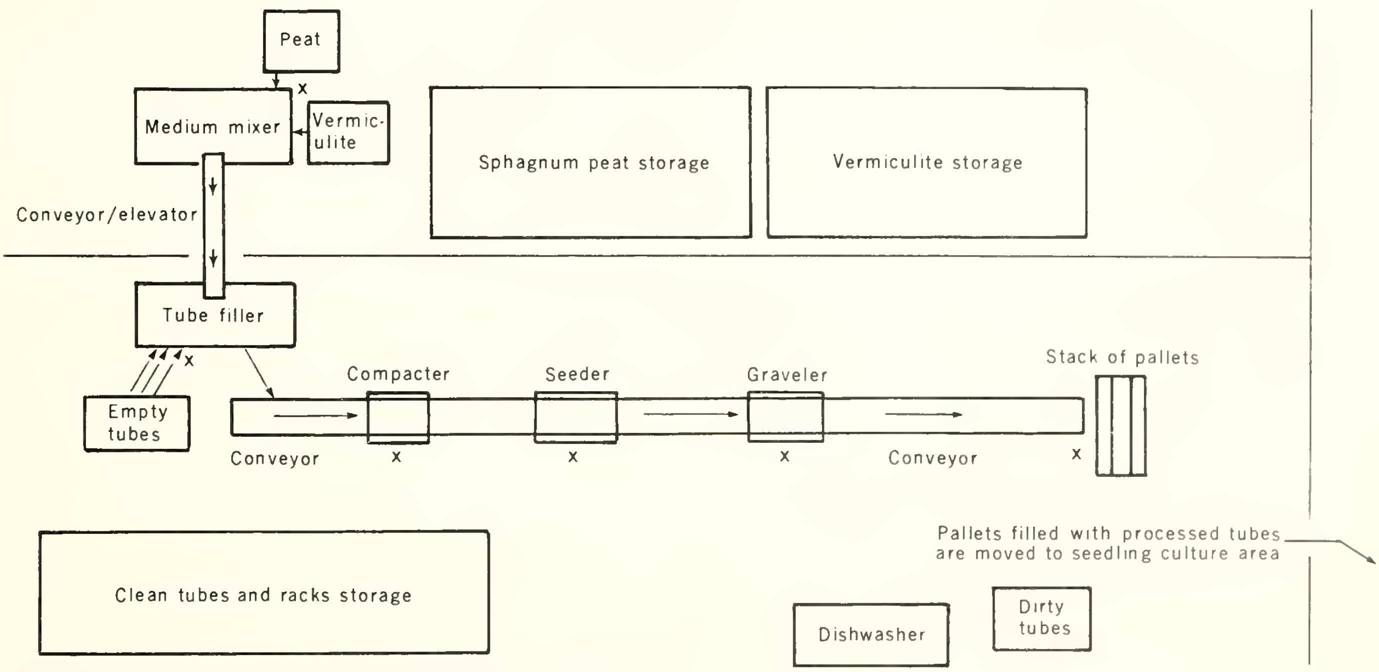


Figure 3--Layout of headhouse showing storage areas and processing equipment for tubes and racks.

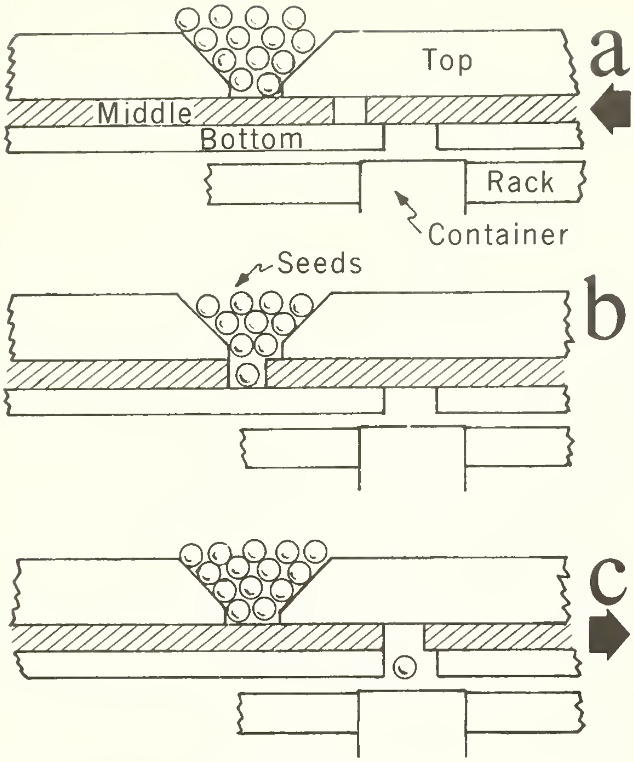


Figure 4--How the manual seeder works: (A) A hole in the top plate is filled with seeds; (B) the middle plate is moved so the hole in it lines up with the hole in the top plate, and a seed drops into the hole; and (C) a seed falls into the container as the middle plate is moved so the hole in it lines up with the hole in the bottom plate.

it line up with the holes in the top plate, and seeds fall into the holes in the middle plate. Then the middle plate is moved so that the holes in it line up with the holes in the bottom plate, and the seeds fall through into tubes. A number of seeds can be sown in each tube by moving the middle plate back and forth as many times as the number of seeds desired per tube, as determined on the basis of germination tests.

Seeds are covered with a 5-millimeter layer of crushed basalt by a device similar to the manual seeder (Walters 1981a). Gravel prevents the seeds from being washed away during irrigation and prevents the buildup of moss and algae on the top of the soil.

Transfer of Tubes and Racks to Seedling Culture Area

A stack of specially designed pallets is placed at the end of the conveyor. When a rack of tubes is complete, it is placed on a pallet. When the pallet is filled with 12 racks (1200 tubes), a forklift picks up the load and moves it to the plant shelter. The next pallet in the stack is there to receive more racks. In the plant shelter, a pallet is set on four cement blocks so that it forms a bench top.

Seedling Culture

In the plant shelter, pallets are supported several feet off the ground to prevent disease organisms from being splashed up to the roots, to provide air space so air pruning of the root systems occurs, and to provide a convenient height for workers to weed and thin the seedlings. During germination and early seedling growth, light intensity is kept at about 50 percent sunlight with plastic screens. An overhead irrigation system applies water daily. When the seedlings have several true leaves, nutrients are applied twice a week through the irrigation system at a rate of 75 to 100 parts per million (nitrogen basis) of a 12.5-25-25 commerical formulation. Pesticides are applied as necessary.

After about 6 weeks or when the seedlings are several inches tall, they are moved outside. There, only watering and feeding can be controlled. Water is applied daily through impact irrigation heads. The system provides about 120 percent overlap, which is necessary because of the frequent winds that often reach 20 mi/h at the nursery site. Nutrients are injected through the irrigation system twice a week. The nutrient solution initially is about 75 parts per million (nitrogen basis) of 20-20-20. After several weeks, the concentration is increased to 250 parts per million (nitrogen basis). When seedlings are about 10 inches tall, the formulation and rate are changed to 75 parts per million (nitrogen basis) of 12.5-25-25.

Transport Phase

When seedlings are 12 to 14 inches tall, they are shipped to the field for planting. The roots and rooting medium form a mass that holds together during handling. In the packing area seedlings are removed from the tubes and packed horizontally in wax-lined cardboard boxes so the roots face toward the box ends and the tops overlap. Box flaps are held closed with string instead of staples or tape. These boxes, even when stacked on pallets, protect the 200 seedlings inside and fulfill government regulations for shipping plant material between islands. Pallets of boxed seedlings are transported to the planting site by trucks, or to other islands by air freight.

Field Phase

Planting sites are generally prepared by clearing or crushing weeds and slash with a bulldozer.

Figure 5--A seedling packing box is easily converted to a carrying box. This is done by: (A) cutting along lines marked on three sides and (B) folding ends together. A precut handhold (C) makes the box simple to carry. When the box is empty, it is flattened and shipped back to the nursery. The cut section is taped for reuse.

Packing boxes are quickly converted to carrying boxes by making several cuts and folding the box (fig. 5) (Walters 1978, Walters and Goo 1978). Packing seedlings in one end of the box before packing the other end will allow the tops to separate easily when the box is cut and folded into a carrying box in the field. When the box is empty, the strings are cut allowing the box to be flattened. Boxes are shipped back to the nursery. When the box is needed again, the cut section is taped and the box is reused.

Seedlings can be planted by hand or by machine. For hand planting, a dibble is used to make planting holes the same size and shape as the seedling root mass. A worker places the root mass into the hole and presses it down to ensure maximum contact between roots and soil, then puts soil over the root system. Dibble planting works well in clay soils and in lava rocklands. Using this method, one worker can plant 750 to 1000 seedlings in 8 hours. In the same time, a single-row planting machine on a clay or loam soil can plant 3000 to 7000 seedlings, depending on spacing and terrain.

Forest plantings are not irrigated, but are commonly fertilized with 1 to 2 ounces of 10-30-10 fertilizer at the time of planting. The fertilizer is poured into a hole made about 3 inches from the seedling root system. The fertilizer stimulates growth enough to reduce the need for weeding (Walters 1982).

SEEDLING SURVIVAL AND GROWTH

Sufficient biological data have been collected to allow seedlings to be grown in the nursery that have a high survival and growth potential in the field. Mean survival for forestry plantings of containerized saligna eucalyptus is 90 percent with a standard deviation of about 4. Under the old bare-root system, mean survival was 56 percent with a standard deviation of 32, and about 70 percent of the seedlings suffered stem dieback. When stem dieback was severe, 3 months or more were often required for the seedling to attain its original height. Under the new system, seedlings grow quickly because transplant shock is minimal.

REFERENCES

Walters, Gerald A. Seedling packing box easily converts into seedling carrying box. Tree Planters' Notes 29(1):27-29; 1978 Winter.

Walters, Gerald A. Manual gravel spreader for covering seeds in containers. Tree Planters' Notes 32(4):15-16; 1981a Fall.

Walters, Gerald A. Why Hawaii is changing to the dibble-tube system of forestation. J. For. 79(11):743-745; 1981b November.

Walters, Gerald A. Influence of fertilizer on early growth of saligna eucalyptus in Hawaii. Tree Planters' Notes 33(2):3-7; 1982 Spring.

Walters, Gerald A.; Goo, Donovan. Field performance of container-grown saligna eucalyptus seedlings not affected by packing/storage treatment. Tree Planters' Notes 29(1):30-31; 1978 Winter.

Walters, Gerald A.; Goo, Donovan. A new manual seeder for round seeds. Tree Planters' Notes 31(2):23-24; 1980 Spring.

Walters, Gerald A.; Horiucni, Howard. Containerized seedlings: Key to forestation in Hawaii. Proceedings of the Intermountain nurserymen's association meeting; 1979 August 13-16; Aspen, CO; 1979; 87-92.

Micropropagation of Frost-Resistant *Eucalyptus*[1]

Michel Boulay[2]

Abstract: A method for the in vitro propagation of frost resistant eucalyptus is presented. It was used for the propagation of 2-30 years old trees. This method is presently used for the fast production of mother trees from selected trees.

For 10 years now, AFOCEL has inscribed micropropagation of forest trees into its research and development program of intensive silviculture.

Eucalypt is a genus which is studied for 6 years. After research on micropropagation of very juvenile trees (seedlings) our association has tried to develop the method for mature trees selected in nursery, experimental plots or plantations.

Numerous workers have shown that vegetative propagation of eucalypt was possible at the industrial level using physiologically and ontogenetically mature plants. This kind of propagation needs the use of rejuvenated shoots which can be obtained by intense pruning, grafting and successive graftings (with a great attention to take cutting or graft on the precedent generation as soon as possible) or cutting back. HARTNEY published a detailed review on this topic.

Under french climate, the use of such methods as cutting back (which is very efficient in Congo or Brazil) has numerous drawbacks :

- important variability (even for small climatic variations) in a few days of the rooting ability of the cuttings which have been obtained from sprouts, pruned trees or cuttings from the preceding generation. Such phenomena involve a number of complications in the organization of the supply of cuttings even if cuttings from the preceding generation are used ;

- low productivity by unit area of mother tree orchards in cuttings of good quality which increases the cost of cuttings ;

- important difficulties to overcome problems linked with rejuvenation by successive graftings ;

- very low multiplication coefficient of vegetative propagation on such material which involves a long period between the selection of the tree and the disponibility of the genotype for reforestation.

Such difficulties always present in our two nurseries which are involved in vegetative propagation are the main reason for our interest in developing an in vitro method for supplying reforestation plots or industrial nurseries.

Micropropagation of eucalypts is not new. After the first pioneer works of DURAND-CRESSWELL, numerous researchers, de FOSSARD, HARTNEY, LAKSHMI et al, developed and applied the method to different species. A recent paper by DURAND-CRESSWELL et al gives all indications on the question.

At AFOCEL, research has begun in 1976 and several communications, have been done : LODEON, FRANCLET and BOULAY, DEPOMMIER. In this paper we will present the more recent results which have been obtained on in vitro cloning of selected trees two years old or older.

PLANT MATERIAL

Taxonomic entities of eucalypts which can resist to frost to minus 18°C or 20°C or to late spring frost in France are very rare. They are essentially species from tasmanian mountains, as Eucalyptus gunnii and Eucalyptus coccifera or from australian south eastern mountains as Eucalyptus pauciflora (Eucalyptus niphophila). Species from good forest value like Eucalyptus dalrympleana or Eucalyptus delegatensis have shown in trials which have been planted earlier in France irregular success.

Actually, we have now in France three kinds of plant material :

- category A : trees of good forest value which have resisted the "historic frosts" from 1956 and 1963. These trees are over 20 years old ;

- category B : trees from 5 to 15 years old which have been planted in AFOCEL or INRA[3] collections. These collections are provenance trials with Eucalyptus dalrympleana or Eucalyptus delegatensis or progeny tests with off springs from category A trees. Many hybrids have been observed among these progenies. This lets us assume that the mothers may be hybrids.

[1] Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2] Head of the in vitro lab, AFOCEL, Nangis, France.

[3] National Institute of Agronomic Research

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

- category C : young vigorous seedlings selected in progeny or provenance trials and raised in big containers. This kind of culture allows to submit them to natural frosts for selection purpose, according to a method imagined by LACAZE and realizedby DESTREMAU and CAUVIN and MARIEN. This selection for two criteria (juvenile growth and frost resistance) on seedlings 2 or 3 years old, give clones from which scions or sprouts can be taken after cutting back. Later with progress in artificial hybridization such seedlings will be replaced by controled hybrids of the same age and selected in the same way.

For most of these selected trees, it is difficult to undertake vegetative propagation without rejuvenation. For this reason, mobilization of the selected genotype by graft or cutting (from sprout or from graft) is necessary.

Rejuvenation can be obtained totally or partically in vivo by the means of successive graftings onto young seedlings. In any cases, the in vitro primary cultivation is possible only with this king of material (cuttings, sprouts and more frequently grafts). The mother trees obtained can be cultivated under good nutrient conditions and a great attention is paid to the sanitary status of the plant (spraying with systemic fungicides every two days specially the week before primary culture). When sprouts are used (category C), they are also treated with fungicides. In vivo and in vitro introduction is done very soon after cutting the sprouts.

IN VITRO MICROPROPAGATION

General conditions

Culture media which are used, have been established by de FOSSARD, DURAND-CRESSWELL et al, LODEON, FRANCLET and BOULAY and DEPOMMIER.

Three kinds of medium are commonly used :

- multiplication medium .... : M
- root induction medium .... : RI
- root and stem elongation medium : RA

For all these media the pH is 5,5 - 5,6 before sterilization. The agar concentration is 7 gl^{-1}. The sterilization occurs at 115°C-116°C during 25 minutes. After plantation, cultures are put under controlled environment with the following conditions :

- photoperiod ; long day D : 16 h ; N : 8 h
- thermoperiod ; D : 24°C-25°C ; N : 18°C-20°C

Primary culture

After severance, the shoots are sealed at both ends with paraffin and treated with a disinfectant. Calcium hypochloride is commonly used (filtration of a mix containing 10 percent solid solution) but a two fold dilution of a commercial solution of sodium hypochloride is also efficient.

Once planted on agar medium, cultures (nodes + petiole + piece of leaf) are put one week in the dark. This operation is done to limit the formation of brownish compounds in the culture medium.

If we start with sprouts (explants from category C of plant material) a 30 to 40 percent infection is generally obtained with primary culture. With plant material coming from greenhouse conditions (mobilization or successive grafts or cuttings it is necessary to decrease the time of disinfection (3 to 5 minutes instead of 8). Under such conditions, the percentage of infection varies from 10 to 50 percent.

The primary culture medium is comparable to the multiplication medium M. The composition is the following : half concentration of macronutrients of Murashige and Skoog medium and vitamins from de Fossard. The sugar is sucrose at 30 gl^{-1}.

The difference with M medium is only at the level of cytokinin concentration. B A (benzyl adenin is used at a concentration varying from 0,1 mgl^{-1} to 1 mgl^{-1}, depending upon clone, season of cutting and lignification of stems. In every case, auxin concentration (N A A : naphtalen acetic acid) is alway 10^{-2} mgl^{-1}. Other medium have also been used for this first culture, some with activated charcoal for example, give also good results.

The experimentation on primary culture with more than 25 clones, has shown that several problems arise.

- There is a very small percentage of explants which are able to react (reaction means in vitro development of the axillary buds which are present at the basis of petiole) with regard to the number of introduced uninfected explants (about 2 to 40 percent of living explants react). So, the "vitro-plants" obtained from in vitro culture are coming from a very small number of cultures (Table 1).

The limitation of experimentation at this level is due to the small number of rejuvenated explants obtained after mobilization or successive graftings or cuttings for each genotype (20 to 30 nodes are often available for this stage of culture).

- A large number of explants show also a friable brownish callusing place of budding reaction. To solve this problem frequent subculturing every 15 days from the first 2 to 3 transfers are needed.

- Hyperhydric transformation (water logging) can also occur at this level of culture on the axillary bud developed in vitro.

These different problems are presently partially solved by frequent subculturing, decreasing cytokinin dosis, use of activated charcoal and adjustment of the time of disinfection.

Subculture and in vitro cloning

The primary culture leads when the explant reacts to elongated axillary buds. Two to four axillary buds can be obtained by reacted nodes. The separation of these axillary buds developed in vitro from the initial explant occurs progressively. Hormons (cytokinin and auxin) are necessary to obtain axillary budding. The best balance is : B A 0,2 mgl^{-1}, N A A 0,01 mgl^{-1}.

The propagation process is comparable to that of de FOSSARD et al. Cluster of buds are obtained by axillary budding. Multiplication is obtained by cutting these bushy explants in smaller pieces every three to four weeks. The time between two subcultures is a very important parameter. For maintaining a very active culture, four weeks is a maximum delay.

In subculture, during the first transfer, all clones do not react in the same way at the multiplication level.

Figure 1 shows the evolution of six clones after five transfers. They are among the first selected clones introduced in vitro.

In transfer five, some of the clones have multiplied by 49 the initial number of introduced cultures (clone 041), some others show no evolution but stay living (clones 032, 039). With these last clones, we can obtain after eight to twelve transfers, a multiplication coefficient comparable to the first one. Depending upon the clone, there is different responses to the medium M, but this difference disappears progressively with subculturing once primary culture is successful.

An example of the delay to obtain exponantial multiplication is given by the clone 16. This clone comes from a 30 year old selected mother tree. It has been introduced in vitro by taking an explant from the fourth successive grafting. On figure 2, we can see that this clone has been maintained just living to the eighth transfer. The number of copies from the ninth subculture onward from this clone is increasing, exponential multiplication is obtained for transfer 12.

We don't know actually what are the reasons responsible of such a phenomenon : stem selection for their sanitary qualities, modification of endogenous hormonal equilibrium, habituation to the medium, none of the experiments we conducted could permit us to choose between these various hypotheses (which are not necessarily exclusive).

Under exponential multiplication conditions, with our method, the multiplication rate amounts to about 4 to 5 for each subculture and every three weeks.

Rhizogenesis, root and stem elongation, acclimatization

With the propagation medium M, we obtain stems 10 to 20 mm in height which are rooted and grown in two steps :

- root induction on R I auxin containing medium ;

- root and stem elongation on R A medium with activated charcoal and no auxin.

Using an elongation medium after propagation as first recommended was leaved for the above described method.

Rhizogenesis induction

The culture medium used is the Knop medium full strengh for macronutrients, micronutrients and vitamins are similar to that of M medium except I K and riboflavine which are eliminated from the medium. Sugar (sucrose) is often used at 15 gl^{-1}. Two parameters are modified according to the clone : lenght of dark period and auxin concentration of the medium (I B A).

A dark period is used during root initiation because it has a positive effect on root primordia formation (DRUART et al).

Just after subculturing on R I medium cultures are put for 10 to 20 days in the dark. Concerning the rhizogenesis hormone, we use I B A (indol butiric acid) added to the medium at 1,5 mgl^{-1} or 3 mgl^{-1}. The best combinations which are used for different clones (i.e. hormone concentration, sucrose dosis, lengh of dark period) are indicated in table 2. The rooting percentage often exceeds 60 percent. The time on multiplication medium M before rhizogenesis has a great influence on rooting success. Stems put in induction must be taken after no more than 3 to 4 weeks in culture on medium M to get a good rooting percentage andfew apical necrosis.

Figure 3 shows the rooting cinetic for the clone 047 (hybrid between gunnii and globulus). After 25 days on R I medium, about 80 percent of plants are rooted.

Root and stem elongation, acclimatization

Once stems are been induced, or when root primordia develop, rooted stems are cultivated on R A medium which has the same composition than R I but with activated charcoal added and without auxin. The sucrose concentration is increased to 30 gl^{-1}.

Subculturing on R A medium favours the development of roots which were induced on R I medium. Within 2 to 5 days, roots reach the bottom of the test tubes. 10 to 20 days later, ramifications and secondary roots appear. After root elongation, herbaceous stems begin to grow (15 to 30 days after transplanting) and the rooted stems develop leaves and nodes which are quite similar to those of seedlings. Rooted stems at this moment can be let during 4 to 6 weeks on this R A medium.

The medium R A has several advantages :

- At the production level, it allows the nurseryman to group the transplanting operation which he carries out once a week.

- The media allows also the regeneration of the herbaceous stem after necrosis. Such neoformed stem growsfrom basal axillary buds of the explant after death of the stem put in rhizogenesis induction.

- The morphology of the rooted stem obtained in vitro on R A medium makes also acclimatization easier.

- Acclimatization takes place when rooted stems have a height compatible with culture in MELFERT[4] containers. It means 30 to 50 mm. After transfer in such containers during 10 or 30 days depending upon the season (10 days in spring or summer, 30 days in winter), the young plantlets are put under plastic film confinment. When roots appears on the side of the containers, confinment is progressively removed and plantlets are placed in greenhouse for cultivation. Percentage of success in acclimatization are variable from 30 to 100 percent depending upon clone and season.

DISCUSSION AND PROBLEM OCCURING WITH THIS METHOD

The scheme of this method is given in figure 4. We can see four phasis and a preparatory one which is the following :

Preparatory phasis : tree selection, and collection from this one of cuttings, sprouts and grafts after mobilization or successive grafts (rejuvenation). Cultivation of this material under greenhouse conditions.

Phase I : obtention of axillary budding in vitro ;
Ia : primary culture ;
Ib : obtention of a reactive culture with experimental multiplication by axillary budding ;

Phase II : in vitro cloning ;

Phase III : obtention of rooted plantlets ;
IIIa : rhizogenesis induction ;
IIIb : root and stem elongation ;

Phase IV : acclimatization of in vitro rooted plantlets.

[4]Melfert : patented containers Fertil Pot Tour Maine Montparnasse 75755 PARIS Cedex 15

The preparatory phasis is very important for the success of culture and specially for reducing the delay to obtain exponential multiplication and in vitro cloning. For all the plant material we selected, no success was obtained with material collected on the tree and introduced directly in vitro. This failure is often due to infection and difficulties encountered in disinfecting the plant material without killing the explant. Successive grafting and rejuvenation seems to be a need for mature plant material. In this way, the number of subcultures needed for obtaining a reactive cluster (exponantial multiplication) is reduced.

Many problems occur in vitro specially when we started the development of the method at the industrial level.

Bacterial pollution can appear after 7 or 8 transfers, later after primary culture on selection of clean culture. ZIMMERMANN wrote about such contamination in micropropagation of fruit trees species. This problem shows that a particular attention must be paid during the phasis Ia and for industrial micropropagation. Indexation of culture must be done at the end of phasis Ib, before in vitro cloning. Indexation of culture can be done by addition of malt extract or peptone (10-100 mgl^{-1}) to the multiplication medium.

The small number of reactive cultures in phasis Ia can be bound to the disinfection method or hormonal endogenous gradients along the stem of cuttings. To obtain a clone under sterile conditions it is therefore necessary to have a suffisient number of nodes for conducting factorials trials with combination of time of disinfection and cytokinin concentration.

Callus and brownish compounds released in the medium present also a problem at this point of the culture (phasis I) and we indicated earlier a method to decrease or avoid such problems.

During phasis II, waterlogging (hyperhydric transformation) and a too small elongation of the axillary bud are the two main problems.

Waterlogging often occcurs in in vitro culture and the causes of this phenomenon have been investigated. When it occurs in our subcultures (phasis II) it is often confined to one or few buds and does not necessarily extend to the whole of the explant. Transferring the culture to medium A (elongation medium, i.e. medium M with activated charcoal added at the rate of 15 gl^{-1}) promotes the development of untransformed buds which may then be taken off for a new multiplication process. This type of activated charcoal containing medium, can also be used for the selection of stems, without callus on leaves or buds (clone 16), which can sometimes occur on multiplication medium.

A too small elongation of axillary buds is often a limitation to the obtention of a large number of stems which could be transferred on R I medium. Often, 2 to 4 buds only by culture, present the appropriate height of 10 to 20 mm. On a defined cytokinin concentration there is often a clonal response for elongation, even when decreasing the cytokinin concentration of M medium, some clones show a very small elongation. NKANKA has decribed similar problems with Eucalyptus rudis and he recommends to use vitamin E (D-L Tocopherol) to promote the elongation. Now, with this compound no or low improvement of elongation was observed in our cultures. Research to solve this problem should be oriented toward the mineral composition of the medium and also on the size of the explant in transfer. Using too small explants in transfer increase the budding but gives no elongation of the developed buds.

In phasis III, the main problems are formation of callus at the basis of the stem on R I medium and sometimes rooting of leaves in contact with the medium and also necrosis of the main stem.

Some hybrids as gunnii x globulus, root easily but with a very big and hard callus and a poor root system develops from this structure. Such callus is a problem for acclimatization because it is a source of root rot.

Decreasing sucrose concentration just limits the phenomenon but it is always present. A better definition of optimum mineral medium and the use of smaller concentration of auxins must be investigated to avoid such callus.

The ability of leaves to induce roots when they are in contact with an auxin containing medium necessitates the complete elimination of leaves at the basal part of explant before planting on R I medium. This operation is time consuming.

For necrosis of main axis at the end of rhizogenesis induction, it is possible that dark period is partially responsible for the phenomenon. R A medium corrects partially this drawback but attention must be paid to the growing time on medium M before root induction and works should be conducted to try to suppress this dark period without decreasing the rooting percentage. The subtitution of agar for rockwool which gives a better aeration of the medium has begun with encouraging results.

CONCLUSION

The method presented in this paper allowed to produce about 20,000 plants from 10 to 12 clones. Most of these in vitro plantlets are used as mother trees for cuttings. But the cost of the plantlets do not yet allow to use it for reforestation. Nevertheless, the use of in vitro plantlets as mother trees for the production of cuttings is interesting and the rooting ability of cuttings taken from such plants is better than this of cuttings taken from scions or in vivo cuttings. The transfer on cytokinin medium for a long time increases the rooting potentiality. This is well demonstrated by clone 16 (old selected tree).

Another advantage of this method is to maintain the rooting ability of the clone. Some of our clones have been introduced in vitro for 3 years now and they kept their rooting potential.

Most of the problems we described must be solved for "mass propagation of eucalypts" at a reasonable cost, but presently we can easily produce good mother trees, even from mature material.

It is also very interesting to see that the multiplication medium M can be used with some minor adaptation (cytokinin concentration) for various clones, species and hybrids.

We think that for obtaining the mass propagation of eucalypts by axillary budding under in vitro conditions, research should be conducted on the mechanization of the process.

The major part of the costs of a plant is labor. Some other ways must also be investigated, as somatic embryogenesis. But with this method, attention must be paid to the genetic conformity of the production.

LITERATURE

CAUVIN B., MARIEN J.N. La multiplication végétative des eucalyptus en France. Ann. Rech. Sylvicoles. 1977 : 141-175.

CHAPERON H., QUILLET G. Resultats des travaux sur le bouturage des eucalyptus au Congo Brazzaville. FAO Third World Consultation on Forest Breeding, Canberra, Australia, 1977 : 835-856.

CRESSWELL R.J. The vegetative propagation of eucalyptus by organ culture. Honours Thesis UNE ARMIDALE.

DEBERGH P., HARBAOUI Y., LEMEUR R. Mass propagation of globe artichoke (Cynara scolymus). Evaluation of different hypothesis to overcome vitrification with special reference to water potential. Physiol. Plant 53, 1981, 181-187

DEPOMMIER D. Culture in vitro d'eucalyptus resistants au froid. Influence de quelques facteurs sur l'allongement et l'enracinement des plantules. DEA Biologie Végétale Fondamentale et Appliquée Pédologie Biologiques et Sciences Forestières, Université de Nancy I, 1981, 59 p.

DEPOMMIER D. Micropropagation d'eucaluptus résistants au froid. IUFRO International Symposium on in vitro cultivation of forest trees. Fontainebleau 1982, AFOCEL ed., 127-132.

DESTREMAU D.X. Culture de biomasse ligneuse : taillis à courte rotation. AFOCEL ed. 1982, 212 p.

DRUART Ph. KEVERS C.L., BOXUS Ph. GASPAR T.H. In vitro promotion of root formation by apple shoots through darkness effect in endogenous phenol and peroxidasis. Z Pflanzenphysiol 108, 1982, 429-436

DURAND-CRESSWELL R. The vegetative propagation of eucalypts by organ culture. Ph D Thesis University of New England, N.S.W. Australia, 1977.

DURAND R., BOUDET M. Le bouturage in vitro de l'eucalyptus. Micropropagation des arbres forestiers, AFOCEL Etudes et Recherches n° 12, 1979, 57-66.

DURAND-CRESSWELL R.J., BOULAY M., FRANCLET A. Vegetative propagation of eucalyptus. in Tissue Culture in Forestry ; BONGA J.M., DURZAN D.J. ed, MARTINUS NIJHOFF, Dr W. JUNK Publishers, 1982, 150-181.
DE FOSSARD R.A., BOURNE R.A. Vegetative propagation of Eucalyptus ficifolia R. Muell. by nodal culture in vitro. Internat. Plant. Propagator's Soc. Combined Proc. 26, 1976, 373-378.
DE FOSSARD R.A. Tissue culture propagation of Eucalyptus ficifolia F. Muell. Proceedings of a Symposium on Plant Tissue Culture. Sciences Press. Peking, 1978, 425-438.
FRANCLET A. Premiers travaux d'amélioration génétiques des eucalyptus. Ann. Rech. For. Rabat Maroc, 1956, 65-89.
FRANCLET A., BOULAY M. Micropropagation of frost resistant eucalypt clones. in proceedings XIIIth International Botanical Congress, 21-28 august 1980, Sydney Australia
HARTNEY V.J. Vegetative propagation of the eucalypts. Aust. For. Res. 1980, 10(3), 191-211
IKEMORI Y.K. Resultados preliminarios sobre enraizmento de estacas de eucalyptos. Aracruz, note techn. n° 1, 1975.
LACAZE J.F. La résistance au froid des eucalyptus. Compte rendu d'un test précoce sur E. gunnii (Hook) et E. cinerea (FvM). Revue Forestière Française, 14(5), 1962, 422-429.
LAKSHMI SITA G., VAIDYANATHAN C.S. Rapid multiplication of eucalyptus by multiple shoot production. Curr. Sci. (Bangalore) 48, 1979, 350-352.
LODEON C. Expériences préliminaires relatives à la multiplication végétative de l'eucalyptus. Rapport de stage 2e année, 3 cycle d'Horticulture ENSH, 1977.
MARTIN B., QUILLET G. Bouturage des arbres forestiers au Congo. Bois For. Trop. 154, 1974, 155-157.
METRO A. Possibilité d'emploi des eucalyptus dans les reboisements en France. Ann. ENEF 12, 1950, 270-320.
MURASHIGE T., SKOOG F. A revised medium for rapid growth and bio-assays with tobacco tissue cultures. Physiol. Plant. 15, 1962, 473-497.
N'KANKA B. Influence de la vitamine E (d-1-Tocopherol) en tant qu'agent antioxydant et regulateur de croissance au cours de la multiplication végétative in vitro d'Eucalyptus rudis Endl., de Larix x eurolepis Henry et de Quercus borealis Michx. preprint to be published in Bulletin des Sciences agronomiques de Gembloux, Belgique.
ZIMMERMAN R.H. Apple tissue culture. Preprint to be published in Handbook of Plant Tissue Culture Edited by EVANS D.A., SHARP W.R., AMMIRATO P.V., YAMATA Y., Mc Millan Co, N.Y.

Clonal Propagation of *Eucalyptus* by Cuttings in France[1]

H. Chaperon[2]

Abstract : A.FO.CEL has developed a technique for mass propagation by cuttings of Eucalyptus in France. This technique is described from the selection of the ortet to the mass propagation of the clone for afforestation : the first stage is the mobilization of the ortet, the second stage is called pre-propagation which includes rejuvenating and rooting conditioning, the third stage is mass propagation. The mass propagation is realized from successive propagations of mother trees ; the number of which increases from generation to generation by including the new rooted cuttings. We give practical advices on atmosphere, treatments depending on the season which govern the success of the technique.

Genus Eucalyptus is so broad and so varied that one should avoid any generalization : However it seems possible to state that a revolution is setting on in afforestation thanks to the development of the technology of the horticultural propagation by cuttings.

This technology which has proved successfull on thousand hectares in tropical countries (Congo, Brasil) is now developed under very different climates as countries like France or Morocco have choosen to create or to regenerate their forests by cuttings. There is not doubt that this trend is going to increase in the near future and reach the most part of the afforestation not only with Eucalyptus but also with other species.

The advantage of the propagation by cuttings depends, for Eucalyptus, on several factors :

- It is a genus heavily employed as an exotic in afforestation with as main objective a strong biomass production from short rotation coppice. The stands are planted at final spacing : It will not be possible to improve the quality of the stand by sylvicultural interventions so it is important to start from an homogeneous and high quality vegetal stock.
- The exotic characteristic implies that many afforestations are set up in zones where it is difficult to find both adapted and productive species. The possibility to hybridize adapted species with productive species allows the synthesis of high performance hybrids on marginal sites : afforestation of poor savannahs in Congo, dry sites in Morocco, cold sites in France.
The mass propagation of these hybrids is only possible by cuttings.
- The particularity of the flowering of Eucalyptus induces a proportion of inbreds in the progenies which may be important. These trees, supply of heterogeneity and of lack of production, cannot be detected in the nursery, the propagation by cuttings will allow to exclude them.
- It exists, in this genus, species or hybrids with a good rooting ability in rather simple conditions for allowing to develop the technique into economical conditions.

The consequences of the use of this type of propagation must be well understood : we will have to adapt an accurate and intensive silviculture to the clonal stands which will have to be at the level of the quality of the vegetal stock.

This evolution will change the aspect of the forest investment : its often weak considered rentability can reach a very attractive level while the lowering of the rotation is a favourable agent for the research of investment. At the wood product level, the industrial will profit by a rigorous homogeneous and well fitted material.

SELECTION OF VEGETAL STOCK

The exact copy of clones by cutting propagation assure the best valorization of a breeding program.

From the ortet selection to the mass propagation of the clone one can distinguish three successive stages :

- The "mobilization" or first propagation allows to obtain the first vegetative copies and to assure the transfer of the clone to the nursery.
- The "pre-propagation" is the stage during which the first copies are handled so as to obtain new juvenile and more reactive copies suited to the conform mass propagation.
- The mass propagation is the final stage which allows to use the clone in afforestation.

Mobilization

Ortets are selected at a stage which permit them to express their qualities ; at this stage the vegetal has lost its rooting ability (this one disappears between two months to one year old according to the species).

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Director of Association Forêt Cellulose for the South West of France, Bordeaux, France.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

One can choose between two ways to mobilize the clone :

Grafting

This way has the advantage to conserve the entirety of the ortet. The scions are taken off during the winter on a part of the tree in potential active growth.

The root-stock grown in a green house is cut at the level where the section of its stem corresponds to the section of the scion.

We use the cleft grafting by effecting an incision at the top of the rootstock in which we introduce the bevelled scion.

The good contact between the root-stock and the scion is secured by a tying with a cellophan bound.

The grafted plant is put in a warm green house and confined under a plastic cover ; the union between the root-stock and the scion is effective during the fortnight after the grafting operation, the growth of the grafted plant will occur one month after grafting.

The scion, which showed an adult morphology, can return during a short period to a juvenile stage (rejuvenating action of the root-stock) but will quickly show again senile features.

The rejuvenating effect of the root-stock is the more lasting as the level of the graft is the lower.

Felling down the ortet

It is a more destructive technique which presents advantages to simplify the "pre-propagation" stage.

The ortet is cut down at the end of the winter or at the beginning of the spring (March) at fifteen centimeters high. Sprouts will develop on the stump and will be cropped on june. The shoots are removed as soon as the rooting ability is get, each removing allows the departure of new shoots.

We have stated that the first emission of sprouts generally have a lesser rooting ability than the following ones. Sprouts can be cropped as soon as the foliage get a good chlorophyllian pigmentation ; the emergence of axillary shoots on the sprouts is often the sign of a decreasing rooting ability.

Cuttings correspond with the lower part of the shoot from which we can prepare a four leaves cutting. The less coloured and hard to root upper part of the sprout is not used.

The cuttings prepared in this way have a good rooting ability and one can obtain as early as the mobilization stage juvenile and exact copies of the ortet.

Pre-propagation

This stage presents two different aspects according to whether the clone was mobilized by grafting or by felling down the ortet.

Pre-propagation after grafting

The clone is now represented by some grafted copies which can have shown a fugitive juvenile stage. The cuttings that one could crop on the grafts are unfitted for rooting : the clone must be rejuvenated.

The rejuvenation can be realized in two different ways :

- Successive grafting : if we take off a scion on the first graft during the juvenile stage and if we make a new graft (as low as possible), we notice that this new graft exhibits a more lasting juvenile stage followed by a new reversion to adult stage. By taking again a new scion on this second graft in its juvenile stage, we will obtain a new progress in juvenility. At the fourth or fifth successive grafting, we can generally obtain a sufficient juvenility for considering the rooting of the cuttings taken off from the graft. This method is relatively long and costly.
- Felling down of the initial grafted plant, followed by the rooting of the new shoots initiated on the scion : instead of realizing successive grafting, one can prefer to let the grafted plant develop during one year or two years. The graft will be cut on march fifteen centimeters upon the grafting point in order to initiate new shoots. If the grafting level is sufficiently low, the rejuvenating influence of the root-stock allow to root the lower part of the new shoots.

In these two pre-propagation ways the rejuvenating of the clone is not complete : the rooting is possible but difficult and the rooted cuttings do not have a satisfactory growth.

A complete rejuvenating will occur by the complementary use of in vitro propagation or by successive horticultural propagation by cuttings : we have stated that in vitro propagation leads more quickly and surely to juvenile and reactive mother trees suited for mass propagation.

Pre-propagation after felling down the ortet

The rooting of the sprouts of stump allows to obtain exact and juvenile copies of the ortet. These copies have a good rooting ability and will be used as mother trees for a successive cutting propagation. The rooting ability is increasing from a generation to the following generation of cuttings, showing the improved reactivity of the mother trees. It seems that the best rooting is obtained after an in vitro propagation cycle which allows to obtain mother trees the quality (homogeneity and reactivity) of which answers the requirements of a mass propagation by successive cuttings.

The propagation by successive cuttings can lead to the same result if we take care to select at each generation of cuttings the mother trees of best quality.

Mass propagation

It is the final stage during which a mobilized, rejuvenated and rooting conditioned clone is commercially propagated. The set up technique is the horticultural successive propagation by cuttings which is explained in the following developments.

The easiest way to reach this stage consists in cutting down the ortet then to root the shoots. The safest way for pre-propagation is the preparation of the clone by in vitro technology.

SUCCESSIVE PROPAGATION BY CUTTINGS

The mother trees

Origin

They originated from the pre-propagation stage which must give exact, juvenile and rooting conditioned mother trees.

These mother trees will be propagated by cuttings and give rooted cuttings which will be used as mother trees in their turns.

During the successive generations of cuttings, one will notice the apparition of a certain proportion of cuttings with a weak root system : it is important to avoid the propagation of this type of plants if we want to avoid to create, inside the clone, bad rooting ability lines.

The keeping of the quality and of the homogeneity of a clone during the successive generations of cuttingssupposes either to be conspicuous to quality of the mother tree or to plan a periodical replacement of the mother trees (once a year) for mother trees produced by in vitro propagation.

The cycle of the successive propagation by cuttings is described in the diagram n° 1.

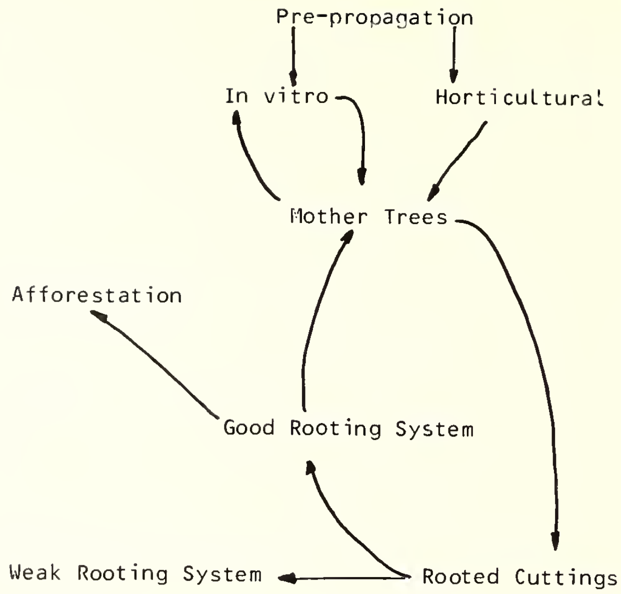


Diagram 1--Successive propagations by cuttings.

As we can see in the diagram, a light proportion of weak rooting system cuttings are eliminated from the cutting cycle. These cuttings can create a new convenient rooting system during the nursery breeding ; if it is the case one will send them for afforestation.

We use to make direct cuttings in the container used in afforestation (containers with roots permeable walls) because the advantage of the technique lies in not distinguishing the mother trees from the cuttings for afforestation. These mother trees are periodically cropped as soon as the shoots reach the size and the development level corresponding to the best rooting ability. When we obtained a sufficient number of cuttings (including the mother trees) corresponding to the afforestation program, we let the mother trees grow in order to reach the required size for afforestation.

The diagram 2 allows a better understanding of the successive propagations by cuttings.

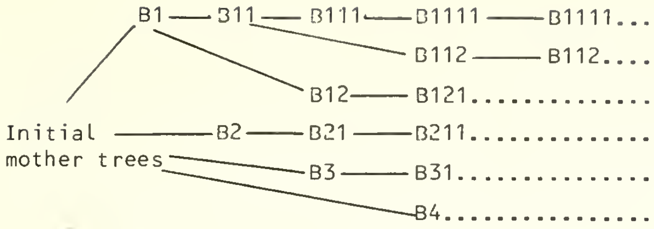


Diagram 2

The advantage of this system lives in its great flexibility :

- The successive propagation by cuttings permits to quickly obtain a great number of copies from a limited number of initial mother trees (multiplication rate superior to one hundred during a year).
- We can change the composition of the multiclonal variety at every moment without financial losses because there is no immobilization in mother trees bank in the field. If a clone becomes obsolete all the mother trees can be used for afforestation before the mass propagation of a new clone.

Growing atmosphere

The growth conditions of the mother tree are essential for the rooting success : the mother tree must have a vigorous growth (appropriate level of water, light, warmness, fertilization) and it is recommended to avoid to multiply mother trees exhausted by too many crops.

The growing atmosphere of the mother tree is determined by the season and the rooting atmosphere : from a general point of view, the mother trees must grow in the same atmosphere used for rooting.

In winter, the mother trees are grown in green houses with a soil heating (substratum temperature 18°) and under a plastic cover (confined atmosphere). In Spring, mother trees are grown in greenhouses without soil heating and extra plastic cover, in Summer the mother trees are grown in the open air.

We will see later that these conditions correspond to the rooting atmosphere.

Rotation of crops of mother trees

The rotation on mother trees should be as short as possible : the shoots are cropped as soon as they reach a development level compatible with the propagation by cuttings.

In practice the rotation is fifteen days long and we can prepare on average one and half cuttings per mother tree.

It is important to know that mother trees are weaker in winter than in summer : their growth conditions should be more precise, the removal of cuttings should be made carefully and the number of crops restricted in order to avoid to exhaust them.

Crop of the cuttings

The decision of cropping the cuttings on a mother tree is governed by a certain number of parameters which determine the rooting ability :

- The minimal size of the cuttings allowing its handling is near five centimeters,
- The minimal number of well coloured and developed leaves is fixed to four (without counting the bad coloured and young leaves).
- The rooting ability decreases quickly as soon as ramifications appear on the shoots : one must imperatively propagate by cuttings before this stage.

The morphology of the shoots moves according to the season : in winter the internodes are short, the leaves small and well coloured ; from spring to summer the internodes grow longer, the size of leaves increases and they take their coloration more slowly.

The shoots are cut off just above the leaves of the lower part in order to initiate two new shoots at this level.

For avoiding a too great ramification of the mother tree which would lead to the production of shoots unsuited to rooting, the level of the size is lowered from time to time.

The cuttings are immediately placed in a water filled up vessel to avoid their fading.

Cuttings preparation

In winter the cutting is constituted by the whole shoot cropped on the mother tree. There is no special preparation unless the ablation of the leaves of the lower part when they impede the insertion of the cuttings in the substratum. The cutting corresponds generally to a four to eight leaves shoot.

In summer the cutting corresponds to the lower part of the shoot (we remove the bad coloured upper part). The cutting has generally four leaves.

The cuttings are dipped in a fungicide solution (six grams Benlate per ten liters water) then drained before hormonal treatment. This treatement is essential : the lower part of the cuttings is dipped in a commercial powder which contains one per cent Indol butyric Acid. Then the base of the cutting is inserted in the rooting medium after we made a hole in order to avoid to wound the herbaceous stem or to remove the hormone.

Cutting environment

The environment for the propagation by cuttings varies depending on the season for fitting the needs of the plant in water, warmness and light.

We can discern the following periods :
- From January to March : Winter cuttings,
- From April to Mai : Spring cuttings,
- From June to the 15th of August : Summer cuttings,
- From the 15th of August to October : Fall cuttings.

In November and December, the natural conditions are very bad for the growth of the mother trees and the rooting of cuttings : we have to bring a great quantity of additionnal heat and light to obtain weak results. So we recommend to stop to propagate at this time.

Winter cuttings

The cuttings are put in an enclosed atmosphere by covering them with a polyethylene film just over the leaves.

This plastic cover keeps a good atmosphere humidity. Substratum humidity is weekly controlled when we do the phytosanitary treatments : the rooting medium must be always humid without excess (obligatory draining), the humidity is increased from January to March.

Rooting medium temperature is maintained at twenty degrees at the base of the cuttings : a too high temperature increases the risks of rooting, a too weak temperature inhibits the rotting.

Atmospheric temperature is not controlled.

Light is very important for rooting : we verify that the rooting percentage is directly proportion to the insolation duration. The minimal insolation duration is estimated to one hundred hours per month to obtain good results. This minimum is generally reached in the South West of France from January. Below this point we have to foresee an additional artificial illumination. From February we are obliged to reduce the natural light by a whitening of greenhouses in order to avoid the sun burn or an excessive temperature rising.

Spring or fall cuttings

The propagation by cuttings is realized in a greenhouse under a mist system. The mist is started by a clock fifteen seconds every ten minutes at the warm hours of the day in order to always maintain an humid film on the leaves.

The temperature of the greenhouse is controlled by aeration and whitening. We have to avoid the sun burn on the cutting leaves by arranging just above them a plastic shade (fifty per cent shade).

The overheating of the greenhouse (temperature superior to 30°) risks to lead at first to a too high substratum temperature (rotting) then necrosis of the aerial part.

The temperature and the humidity of the substratum are not specially controlled.

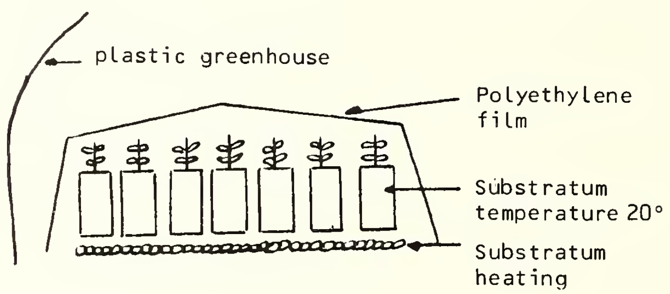
Summer cuttings

From June the increasing of the mean mensual temperature (20°) allows to propagate by cuttings in the open under a mist started by a clock at the warm hours of the day. This mist falls on a shade (fifty per cent) spread nearby the cuttings and which appears to have a double action :
- to avoid sun burns which induce the depigmentation of the Eucalyptus leaves,
- to maintain a humid atmosphere near the cuttings.

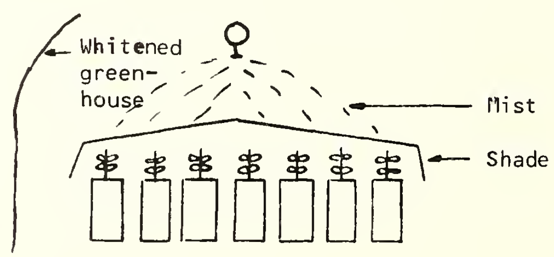
Rooting medium temperature and humidity are not specially controlled.

The three cuttings environments are described in the diagram n° 3.

Rooting percentages are good in each of this three environments but we have noticed that simplicity and cost of the propagation become better from winter to summer.

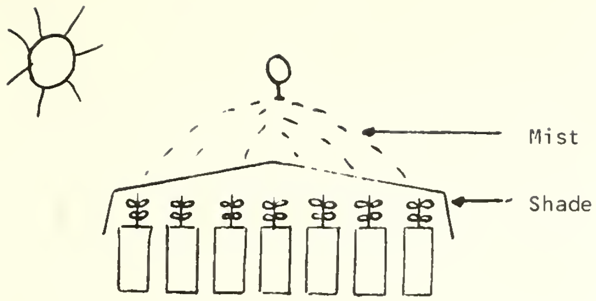


Winter cuttings



Spring cuttings

Diagram 3--



Summer cuttings

Diagram 3--(continued)

Rooting medium - Container

Rooting medium composition may change into large proportions without damage on rooting.

We have to watch over the rooting medium possesses the following qualities :
- intermediate granulometry assessing a good draining, a good aeration and sufficient water retention. The granulometry will be also of importance on the architecture of the new root system,
- organic matter contents rather poor (rotting risks),
- free of pathogen elements or adventicious seed (desirable desinfection).

We obtained good results with a medium containing seventy five per cent crushed and composted bark, twenty five per cent Perlite and five kilograms Osmocote per cubic meter.

When the rooting mean percentage exceeds seventy per cent one can consider to propagate by cuttings directly in the container in order to avoid transplanting which is a costly and damaging operation.

The propagation by cuttings has no particular influence on the choice of the container. That may be :
- a rigid walled container with a special design to avoid root deformations,
- a permeable root walled container (nonwoven material).

The successive propagation by cuttings supposes a prolonged keeping in the nursery (to six months) : the container volume should be big enough to assure a good growth to the cutting during this period. For the same reasons, we have to study carefully the medium fertilization during this period.

Rooting

Time for rooting is depending on the vegetative conditions of the mother tree and on the rooting atmosphere : this time varies from ten days in good conditions to three weeks in bad conditions. It decreases from January to July then increases from July to October.

Hardening-off

The hardening corresponds to the period between the acquisition by the cutting of a functional root system and the recovery of an active aerial growth. This duration varies between three weeks and one month.

The hardening atmosphere is as near as possible of the rooting atmosphere :
- In winter, the hardening consists to move away the plastic sheet from the contact of leaves (rooting atmosphere) to a certain distance (growing atmosphere). This modification is very light and can be done without any particular care.
- In spring and summer, we shall wait the aerial start of the cutting to suppress first the shade then for lessening the ON periods of the misting system.

The end of the hardening takes generally place two months after the insertion of the cutting in the rooting medium. At the end of this period the rooted cuttings is enough developped to consider to crop cuttings.

We can estimate that :
- the duration between the insertion of the cutting and the first crop on the new mother tree is two months,
- the duration between the insertion of the cutting and its possible dispatch for afforestation (fifteen to twenty centimeters high) is two months and a half.

Diagram 4 indicates the time necessary for each stage :

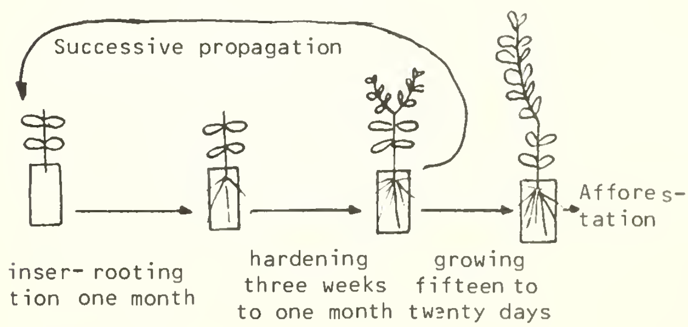


Diagram 4--

Results

Results of the propagation of Eucalyptus by cuttings depend on :
- the selection level : it is important to select on the rooting ability which varies in

any great extent from one clone to another inside the same species : in Eucalyptus gunnii, the mean rooting success is near fifty per cent and the rooting success of the best clones is near ninety per cent,

- the rooting conditioning of clones : rooting ability of a clone increases after an in vitro propagation cycle or after several successive propagations followed by a selection of reactive mother trees. This "conditioning" of clones allows to increase very obviously the rooting success especially when the first copies of the ortets are not completely juvenile,

- the rooting season : therooting in the open in June and July gives the better results.

In the best conditions, we reach a mean rooting percentage of eighty per cent for the selected clones in E. gunnii and E. hybrid gunnii x dalrympleana.

CONCLUSION

Research and development of the mass propagation by cutting of Eucalyptus have led to precise a technique of forest plant production which satisfies the economical requirements of afforestation and secure the mass propagation of clones selected for precise purposes.

The success depends on the conjunction of propitious factors :

- Selection of the clone not only on production or resistance criteria but also on rooting ability,
- Conditioning the mother trees for the supplying of high rooting potential cuttings,
- Choice of the cutting environment adapted to the season.

The keeping of every factor at the optimal level governs the success of the technique but it is certainly the management of the mother trees which consitutes the more critical point : the propagator must have the perpetual care to keep the quality and the homogeneity of the mother trees by the elimination of the degenerating ones. The cyclic return to mother trees produced by in vitro propagation allows to avoid every risk of degeneration.

REFERENCES

Bigot C. Reproduction végétative. Ecole Nationale Supérieure d'Horticulture de Versailles ; 1977

Boulay M. ; Chaperon H. ; David A. ; David H. ; Faye M. ; Isemukali K. ; Durand R. ; Boudet A.M ; Franclet A. ; Rancillac M. Micropropagation d'arbres forestiers ; A.FO.CEL 1979

Burgers J.P. Vegetative propagation fo E. grandis. N.Z Jour Forestry 1974 (4) ; 2. 181-184

Chaperon H. ; Quillet G. Résultats des travaux sur le bouturage d'Eucalyptus au Congo Brazzaville ; 3rd TWFTB Canberra 77 ; IUFRO

Cresswell R. ; Nitzch C. Organ culture of Eucalyptus grandis. Planta 125 87-90 ; 1975

Davidson J. Reproduction of E. deglupta by cuttings N.Z. Jour Forestry 1974 (4) ; 2. 191-203

Franclet A. Premiers travaux d'amélioration génétique des Eucalyptus. Rapport annuel Station de Recherches Forestières Rabat 1956 ; 64-90

Franclet A. Techniques de bouturage de E. camaldulensis. FAO Note Technique N° 12. IRT Tunis ; 1970

Franclet A. Manipulation des pieds-mères et amélioration de la qualité des boutures. A.FO.CEL Etudes et Recherches n° 8 ; 12/77

Hartmann H.T ; Kester D.E Plant propagation. Principle and practices. Prentice Hall N.Y. ; 1975 ; 662 p

Hartney V.J. Vegetative propagation of the Eucalyptus. Australian Forest Research, 1980 ; 10 (3) ; 191-211

Martin B. ; Quillet G. Le bouturage des arbres forestiers au Congo. Bois et Forêts des Tropiques n° 154 à 157. Mars à Octobre 1974 ; March-October

Paton D.M. Rooting of stem cuttings of Eucalyptus : a rooting inhibitor in adult tissues. Aust. J. Bot 1970 ; 18. 175-184

Pryor D.L ; Willing R.R. The vegetative propagation of Eucalyptus. An account of progress. Aust. Forest 27 ; 52-62 ; 1963

Part 7. Breeding Programs

Eucalypt Improvement for California: Progress and Plans[1]

F. Thomas Ledig[2]

Abstract: Six promising eucalypt species, suitable for fiber or biomass production, have been identified with some confidence: Eucalyptus camaldulensis, E. dalrympleana, E. viminalis, E. nitens, E. globulus, and E. grandis. The Forest Service's Institute of Forest Genetics has established provenance or seed source tests of E. camaldulensis, E. grandis, E. nitens, and the E. dalrympleana-E. viminalis complex. In E. camaldulensis, the Lake Albacutya source is outstandingly superior to any other, and can probably double yields previously achieved with this species in California. Growth among E. grandis provenances is more uniform, but gains of 32 percent may be made by seed source selection. Tests of other species are too young for firm conclusions. Once superior seed sources are identified, they should be used to fill planting demands in California. The next step is to begin selection and breeding within the most productive species.

California has a long history of flirtation with eucalypts, but little in the way of systematic programs to identify superior planting stock. Eucalypts (genus Eucalyptus) were introduced in California over 125 years ago and some have since become naturalized (Kirkpatrick 1977). Eucalypt windbreaks, road screens, and woodlots are so common that many laypeople believe eucalypts are native trees. But despite their familiarity, there have been few trials of eucalypts as timber trees. Most of our knowledge on their growth and adaptability is anecdotal, deriving from observations on scattered specimens (Metcalf 1924). Until recently there was little need of more intensive investigation because California has many fine conifers that are easily seasoned for construction lumber, while eucalypt timber is difficult to season. However, interest in eucalypts has increased because of their suitability for short-rotation fuel biomass plantations. Growers need a reliable source of rapidly growing planting stock, but development of eucalypt seed sources is not a small chore.

There are several stages in the development of any new crop. In the first stage, species trials are used to eliminate non-productive candidates and identify those with enough promise to justify further testing. However, even within a single species, the growth of one provenance (provenance = a population originating in a particular location, climate, and soil) may not be representative of the species. Therefore, species trials should include some minimum number of seed sources. Ideally, trials should be conducted on a number of sites to assure that results are not narrowly limited in application. Provenance testing is the primary objective in the second stage of introduction, to locate the best seed sources within the species. When yields are established for a range of provenances, the third stage can begin: intensive breeding methods are applied within the best adapted provenances to improve growth and economic value.

SPECIES TRIALS

Choice of species is the first consideration in growing eucalypts, but a complete survey of the genus would be a monumental undertaking. A recent compilation recognizes 550 eucalypt species (Chippendale and Wolf 1981). Of these, at least 70 are grown in California (McMinn and Shepherd 1973). Many are in arboreta and parks, and their range of adaptability or their potential as forest trees is unknown.

One of the most extensive trials of eucalypt species was undertaken by the University of California Cooperative Extension. The University tested 43 species and 18 sites, although not every species was represented at each site (Davis [1980?]). Plantings spanned a latitudinal range from Yuba County to San Diego. After 7 years, the species were given a subjective rating based on their value as landscape trees. Appearance was heavily weighted in the rating. The highest score was

---

[1]Presented at the Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, California.

[2]Project Leader, Institute of Forest Genetics, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley, Calif.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

Table 1--Survival and volume of eucalypt species from two plantings at Concord, California, 1977.

Species	1964 planting		1965 planting	
	Survival (pct)	Vol/tree (cu m)	Survival (pct)	Vol/tree (cu m)
E. camaldulensis	--[1]	--[1]	65	0.06
E. dalrympleana	65	0.29	60	0.02
E. ovata	29	0.28	24	0.10
E. grandis	13	0.20	91	0.07
E. nitens	54	0.19	94	0.13
E. viminalis	83	0.14	75	0.02
E. glaucescens	35	0.15	72	0.03

[1]Not planted in 1964

received by southern mahogany (*E. botryoides* Sm.), and it was followed by river red gum (*E. camaldulensis* Dehnh.). Actually, growth of river red gum was better than that of southern mahogany wherever they were planted together, but river red gum was not considered as suitable a landscape tree as southern mahogany. Because of the concentration on ornamental trees, many common timber trees were not included in the trials.

Species trials that focused primarily on timber trees were established at Concord, California, in 1964 and 1965 as a cooperative venture of the Navy Department and the Forest Service's Institute of Forest Genetics (King and Krugman 1980). Of 36 species, 6 or 7 were very promising (table 1), and if marketed for fuelwood or chips, would return at least 6.2 percent on investment (Standiford and Ledig, this volume).

PROVENANCE TESTS

The species trials of both the University of California and the Institute of Forest Genetics suffer from a common deficiency; neither took into account intraspecific genetic variation. Wide-ranging species are usually subdivided into populations adapted to the varying climatic and edaphic conditions in which they occur. While seeds from one area may produce rapidly growing trees under Californian conditions, seeds of the same species, but from other areas, may fail miserably. Species trials that only sample a single population may give misleading results. Species introductions should sample at least the extremes and center of the range.

A further problem is that neither the University nor the Institute included blue gum (*E. globulus* Labill.) in its species trials, so there is no direct comparison of California's most commonly planted eucalypt.

In 1975 a series of seed source, or provenance, tests were initiated to determine the range of genetic variation within species of greatest potential as indicated in the Institute's species trials. Provenances of five species are now under test. A provenance trial of blue gum is also planned because it often shows phenomenal growth in California, and its supremacy for biomass production is well established in world forestry.

River red gum

A seed source, or provenance, test of river red gum was begun in 1975. Seeds of 23 provenances were sown in June, the seedlings transplanted into Tinus containers, and then outplanted at Concord in February, 1976. Details of cultivation are reported by Emery and Ledig (in preparation). By the time the planting reached age 5.5 years, results were clear (table 2).

All the top six seed sources (A-F) come from the Murray and Darling River drainages and adjacent watersheds of Victoria, South Australia, and New South Wales. Statistical techniques that link areas of similar climate, tend to cluster these sources into one group (fig. 1). The area is characterized by relatively low rainfall, rather cool maximum temperatures, and a long season in which frost can occur (>120 days).

One seed source, from a dry lake bed, Lake Albacutya, Victoria, stood out. Its volume growth was 161 percent better than the average and 598 percent better than the worst seed source. Mean growth for the Lake Albacutya seed source was substantially better than growth of river red gum in the adjacent 1964-65 species trials. Diameter was 6.6 cm and height 6.2 m at 6 years in the species trial, but the Lake Albacutya source already exceeded that at 5.5 years: 9.5 cm and 7.2 m, respectively. We have

Table 2--Eucalyptus camaldulensis provenance means 5.5 years after planting.

Provenance	Volume[1] (cu m)	Height (m)	dbh (cm)	Straightness[2]
Lake Albacutya, Victoria	[3].0684 a	7.17 a	9.5 a	2.4 ghij
Hamilton, Victoria	.0570 ab	5.97 bc	8.9 ab	2.6 efghij
Nathalia, Victoria	.0463 abc	5.78 bcd	7.8 abc	2.9 cdefg
Angaston, South Australia	.0462 abc	5.85 bcd	8.5 ab	2.4 ghij
Darlington Point, New South Wales	.0421 bcd	6.32 ab	7.6 abcd	2.6 efghij
Forbes, New South Wales	.0297 cde	5.40 bcde	7.2 bcde	2.5 efghij
Port Lincoln, South Australia	.0270 cde	4.94 cdef	7.1 bcde	2.1 j
Petford, Queensland	.0253 cde	5.99 bc	6.2 cdef	3.2 bc
Mundiwindi, Western Australia	.0230 cde	4.98 cdef	6.0 cdef	3.4 ab
Agnew (AR), Western Australia	.0224 cde	4.85 def	6.1 cdef	3.0 bcdef
Alice Springs (I), Northern Territory	.0215 cde	4.54 ef	5.7 cdef	2.8 cdefgh
Onslow, Western Australia	.0201 de	4.36 ef	6.0 cdef	2.5 fghij
Quilpie, Queensland	.0200 de	5.19 cdef	5.8 cdef	3.1 bcd
Pentland, Queensland	.0194 de	4.85 def	5.8 cdef	2.6 efghi
Hughenden, Queensland	.0191 de	4.79 def	5.8 cdef	2.8 cdefgh
Wiluma, Western Australia	.0180 de	4.99 cdef	5.5 cdef	3.8 a
Alice Springs (H), Northern Territory	.0173 de	4.89 def	5.3 ef	3.0 bcde
Agnew (AO), Western Australia	.0170 de	4.82 def	5.5 def	2.9 cdef
Quilpie (P), Queensland	.0148 e	4.55 ef	5.5 def	2.2 ij
Thargomindah, Queensland	.0146 e	4.18 f	5.1 ef	2.3 hij
Three Springs, Western Australia	.0124 e	4.29 f	5.2 ef	2.7 defgh
Katherine, Northern Territory	.0107 e	4.36 ef	4.6 f	3.0 bcde
Newcastle Waters Creek, Northern Territory	.0098 e	4.14 f	4.3 f	2.7 defgh

[1]Estimated by dbh^2 x ht

[2]Scored from 1 = most crooked to 5 = straightest

[3]Means followed by the same letter do not differ significantly at the 5 percent probability level, according to Fisher's protected least-significant differences multiple range test

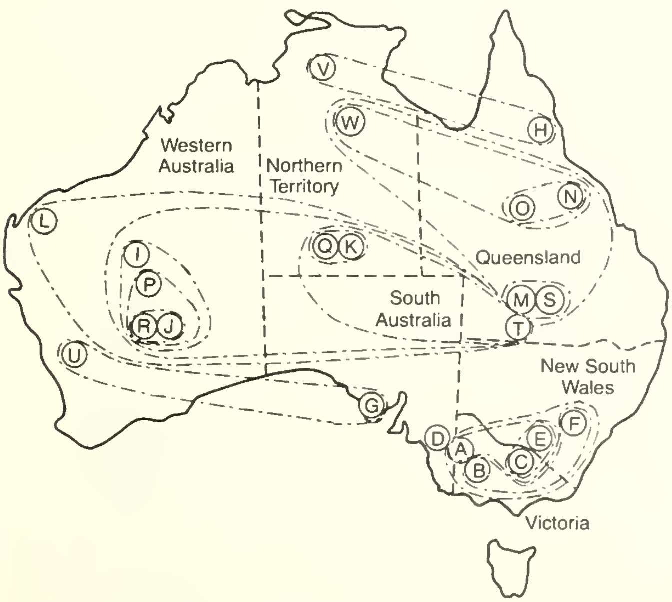


Figure 1--Location of Eucalyptus camaldulensis seed sources in Australia. Broken lines cluster seed sources of similar climate.

confidence in these results because the Lake Albacutya seed source has emerged superior wherever it was planted in a Mediterranean climate similar to California's; e.g., in Greece (Panetsos 1970), Israel (Karschon 1974; Moreshet 1981), Italy (Giordano 1974), Morocco (Destremau and others 1973), Rhodesia (Barrett and Carter 1976), Zambia, Spain, Algeria, and Portugal (Lacaze 1978). The Lake Albacutya source is also reported as highly salt tolerant (Sands 1981). It seems likely that this seed source will surpass any other previously planted in California. It should be able to withstand some cold and drought, as well as saline soils.

Flooded gum

Seed from 15 flooded gum sources (E. grandis Hill ex Maid.) was sown in September 1976, and outplanted at Concord in March 1978. Early results, at 3.25 years, show that there is less variation in flooded gum than in river red gum (table 3; Bailey and Ledig, in preparation). Nevertheless, the best seed source, Orara East in New South Wales, was 14 percent taller and had 32 percent greater volume than the plantation average.

Table 3--Eucalyptus grandis provenance means for relative volume, height, dbh, and straightness 3.4 years after planting.

Provenance	Volume (cu m)	Height (m)	dbh (cm)	Straightness[4]
Orara East	[3]0.041	[2]6.5 a	[3]7.5	[3]3.06
Tanban	0.039	6.4 ab	7.4	2.87
Newfoundland	0.037	6.3 ab	7.4	2.90
Tucker's Knob	0.041	6.1 abc	7.5	3.29
Pine Creek	0.033	6.1 abc	6.8	3.30
Orara West	0.032	6.0 abc	6.7	2.96
Yabbra	0.033	5.8 abcd	6.8	3.38
Newry	0.024	5.7 bcd	6.3	3.10
Wild Cattle Creek	0.035	5.4 cde	6.6	2.90
Lorne	0.026	5.3 cde	6.0	3.17
Nulla Five Day	0.021	5.1 de	5.5	3.14
Minmi	0.025	5.1 de	5.6	2.70
Queen's Lake	0.030	5.1 de	6.5	3.19
Brooloo	0.024	5.0 de	2.1	3.50
Bellinger River	0.019	4.8 e	5.1	2.61

[1]All provenances were from New South Wales except Brooloo, Queensland

[2]Means followed by the same letter do not differ significantly at the 5 percent level of probability, according to Fisher's protected least significant differences multiple range test

[3]Not statistically different among provenances

[4]Scored from 1 = most crooked to 5 = straightest

Despite the early age of the test, results can be viewed with some confidence. The same seed sources performed similarly in South African trials. The correlation between seed source height in South Africa and height in California was 0.72, and for dbh 0.79.

The relationships between climate at the seed source and growth in California were weak in flooded gum. There is a slight association of growth with longitude (r = 0.66), but it is of little help in indicating where to find superior provenances in Australia.

Shining gum

Shining gum (E. nitens Maid.) is not well-known in California. However, it grew well in the 1964-65 species trials at Concord and suffered almost no damage from the record freeze of 1972. Since it was first planted at Concord, provenance tests established in Australia (Pederick 1979) indicate that the seed source used in the Concord plantings is one of the most slow-growing, at least, under Australian conditions. By implication, the already excellent performance of shining gum at Concord can be improved upon with proper choice of seed source.

In 1982, 25 provenances of shining gum were planted at Concord. Similar tests were established near Ukiah in cooperation with Masonite Corporation. A third test near Santa Nella failed because it was planted late and did not receive necessary weed control or irrigation. It is much too early to draw any conclusions, but initial results after a year in the field suggest substantial differences among provenances (table 4).

Mountain gum and manna gum

The single most rapidly-growing eucalypt in the Concord species trial was mountain gum (E. dalrympleana Maid.). However, some of the trees in the test have leaves on basal sprouts that look more like manna gum (E. viminalis Labill.). It is possible that the seed supplied by the Commonwealth Scientific and Industrial Research Organization (CSIRO), Division of Forest Research in Australia was manna gum, a mixture of mountain and manna gum, or hybrids. The two species intergrade over an altitudinal gradient, and mountain gum could be merely the high elevational form of manna gum (Phillips and Reid 1980). We expect mountain gum to be more frost-hardy than manna gum because it occurs at higher elevations.

Because of the dubious taxonomic status of mountain and manna gums and the apparent ease with which they cross, it was decided

Table 4--*Eucalyptus nitens* provenance means for height and survival 1.3 years after planting.

Seed source and locality	Survival (pct)	Height (cm)
Rubicon, Victoria		
Tweed Spur	78	93.4
Snobs Creek	76	99.3
Barnewall Plain	78	81.5
Mt. Donna Buang	78	94.1
Toorongo, Victoria		
Toorongo Plateau	79	85.3
Upper Thomson	88	83.0
Marshall Spur	77	86.1
St. Gwinear	84	89.3
Mt. Erica	77	81.6
Mt. Toorongo	76	90.0
Tanjil Bren	68	94.6
Christmas Creek	75	81.9
Powelltown	92	90.7
Macalister, Victoria		
Mt. Skene	80	86.5
Connors Plain	85	86.9
Mt. Useful north	77	83.1
Mt. Useful south	85	90.8
Mt. Wellington	77	83.3
Errinundra, Victoria		
Errinundra north	84	102.4
Errinundra south	87	83.8
Goongerah	75	102.9
Southern New South Wales		
Nimmitabel	75	68.4
Tallaganda	83	70.2
Northern New South Wales		
Ebor	58	65.0

to include both forms in provenance trials. A trial of six provenances of mountain gum and two of manna gum was started earlier this year, 1983. Plantings were made at Concord, near Anderson in northern California, near Standard in the foothills of the Sierra Nevada, and at Santa Nella. It is much too early to tell whether these plantations will succeed, but the range of planting sites should provide a good test of adaptability. Subfreezing weather cannot be counted on at Concord each year; the Anderson and Standard sites will be more likely to provide a test of cold hardiness. The Santa Nella site will provide a test of tolerance for soil salinity.

Blue gum

Blue gum is a rapidly growing tree with some cold tolerance. However, the commonly planted ssp. *globulus* suffered badly during the freeze of 1972. Large trees in the Berkeley Hills were killed back to their base. Subspecies *maidenii* and *bicostata* are considered more cold-hardy than ssp. *globulus*. These subspecies, along with ssp. *pseudoglobulus*, were formerly considered separate species from blue gum (Kirkpatrick 1974). The Australian Division of Forest Research (CSIRO) provided seed of 35 provenances of blue gum, including all its subspecies, and these will be field planted in 1985.

Other considerations

For species already provenance tested, large plot tests of the best seed sources should be established in several locations to judge their breadth of adaptability and to develop data on growth and yield. Tests of container methods, planting time and technique, and spacing are also needed to develop more effective systems of production. Other eucalypts that may be provenance tested include tingiring gum (*E. glaucescens* Maid. and Blakeley) and swamp gum (*E. ovata* Labill.).

SELECTION AND BREEDING

To cover the wide variety of site and climatic conditions in California, it is likely that more than one eucalypt species will be used. Once superior provenances are identified, seed can be purchased from Australian seed dealers. But even greater growth and adaptability can be obtained by selecting and breeding eucalypts specifically for California. There is enough genetic variation within the commonly used species that we always find some outstanding individual trees even within the best provenances.

To capitalize on such variation requires selection of superior trees. The Institute of Forest Genetics has begun to select superior phenotypes in older plantations in California and in our own provenance tests at Concord. Trees in the older plantations have undergone one generation of selection under California conditions and have demonstrated their ability to withstand drought and cold. They constitute "land races." However, in an exotic species, there are limited possibilities for selection because the number of trees available is small.

Other eucalypt breeding programs, domestic and foreign, are another source of breeding material. The eucalypt breeding program in Florida has 40 clones of river red gum which should be tested in California. Perhaps even more valuable are selections of drought and saline tolerant eucalypts made by the Agricultural Research Organization, Israel and by agencies in India. The Institute of Forest Genetics is proposing collaborative projects with both Israeli and Indian tree breeders working with fuel biomass programs.

Once superior individuals are selected, there are two approaches to produce improved planting stock; i.e., through seed production in seed orchards or by mass production of rooted cuttings. In seed orchards, selected trees are brought together, as grafted or rooted clones, and allowed to cross-pollinate. Eucalypts flower at an early age so seed orchards will produce commercial quantities of seed in a very few years. If selection has been effective, the seed should produce superior progeny. The alternative is to clone the selected individuals and use them directly, perhaps as rooted cuttings. While clonal production is more expensive than seed production, it also offers the possibility of greater immediate gains. Techniques for vegetative propagation are discussed by Boulay and Chaperon in this volume. Whatever the approach, seedling or clonal, the next step in eucalypt culture in California is to establish sources for superior planting materials, and it is likely to require a cooperative commitment between growers and the State and Federal governments.

Acknowledgments: Thanks are due the Western Division, Naval Facilities Engineering Command, U.S. Navy and the Public Works Office, Concord Naval Weapons Station for supporting the establishment of eucalypt trials in California; to L. A. Pederick and CSIRO, Canberra, Australia for supplying seed of the many species and provenances; J. P. King for planning the provenance tests of river red gum and flooded gum; and C. W. Busche, R. A. Stutts, and other staff members of the Institute of Forest Genetics for their splendid work in establishing, maintaining, and measuring the tests.

REFERENCES

Barrett, R. L.; Carter, D. T. Eucalyptus camaldulensis provenance trials in Rhodesia. 2. Later results. Rhod. Bull. For. Res. 2 (pt.2): 1-39; 1976.

Bailey, D. B.; Ledig, F. T. Provenance variation in flooded gum (Eucalyptus grandis Hill ex Maid.). In preparation.

Chippendale, G. M.; Wolf, L. The natural distribution of Eucalyptus in Australia. Spec. Publ. 6. Canberra: Aust. Nat. Parks and Wildl. Serv.; 1981. 192 p.

Darrow, W. K.; Roeder, K. R. Provenance studies of Eucalyptus grandis (Hill) Maiden in South Africa. In: IUFRO symp. on fast growing species. In press.

Davis, W. B. Report on evaluation of several Eucalyptus species. Davis, CA: Univ. Calif. Cooperative Ext.; [1980?]. 34 p.

Destremau, D. X.; Jolly, H.; Korba, M. The results of a comparative trial of provenances of Eucalyptus camaldulensis of Sidi Slimane. Ann. Rech. For. Maroc 14: 121-154; 1973.

Emery, B. M.; Ledig, F. T. Provenance variation in river red gum (Eucalyptus camaldulensis Dehnh.) in California. In preparation.

Giordano, E. Observations on the provenance of Eucalyptus camaldulensis Dehnh. introduced in Italy. Inf. Bot. Ital. 6: 85-93; 1974.

Karschon, R. The relation of seed origin to growth of Eucalyptus camaldulensis Dehnh. and their significance. Aust. J. Bot. 19: 261-272; 1974.

King, J. P.; Krugman, S. L. Tests of 36 Eucalyptus species in northern California. Res. Pap. PSW-152. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 6 p.

Kirkpatrick, J. B. The numerical intraspecific taxonomy of Eucalyptus globulus Labill. (Myrtaceae). Bot. J. Linnean Soc. 69: 89-104; 1974.

Kirkpatrick, J. B. Eucalypt invasion in southern California. Aust. Geogr. 13: 387-393; 1977.

Lacaze, J. F. Etude de l'adaptation ecologique des eucalyptus; étude de provenances d'Eucalyptus camaldulensis. Projet FAO No. 6 In: Third World Consult. For. Tree Breeding, vol. 1. March 21-26, 1977, Canberra. Canberra: CSIRO; 1978; 393-409.

McMinn, H. E.; Shepherd, H. W. An illustrated manual of Pacific Coast trees. 2nd ed. Berkeley: Univ. Calif. Press; 1973. 301 p.

Metcalf, W. Growth of Eucalyptus in California plantations. Bull. 380. Berkeley, CA: Calif. Agr. Exp. Stn.; 1924. 380 p.

Moreshet, S. Physiological activity, in a semiarid environment, of Eucalyptus camaldulensis Dehnh. from two provenances. Aust. J. Bot. 29: 97-110; 1981.

Panetsos, C. P. Provenance test of Eucalyptus camaldulensis Dehnh. in Greece. Dasos 49-50-51/70; 1-8; 1970.

Pederick, L. A. Natural variation in shining gum (Eucalyptus nitens). Aust. For. Res. 9: 41-63; 1979.

Phillips, R. L.; Reid, J. B. Clinal variation between Eucalyptus viminalis Labill. and E. dalrympleana Maid. Aust. J. Bot. 28: 329-342; 1980.

Sands, R. Salt resistance in Eucalyptus camaldulensis Dehnh. from three different seed sources. Aust. For. Res. 11: 93-100; 1981.

Realized Gain from Breeding *Eucalyptus grandis* in Florida[1]

George Meskimen[2]

Abstract: E. grandis is in the fourth generation of selection in southwest Florida. The breeding strategy combines a provenance trial, genetic base population, seedling seed orchard, and progeny test in a single plantation where all families are completely randomized in single-tree plots. That planting configuration closely predicted the magnitude of genetic gain realized through age 2.5 years in a simulated commercial plantation: up to 66 percent gain in tree height, 164 percent gain in stem volume, plus significant gains in stem straightness and freeze tolerance.

A small but intense eucalyptus research effort began in Florida in 1961 with the private, non-profit Florida Forests Foundation dedicated to investigating the commercial forestry potential of exotic hardwoods in south Florida. By 1965 we had established numerous eucalyptus experiments, including 14 screening trials testing a total of 156 seed sources representing 67 eucalyptus species. The Foundation was absorbed into the Southeastern Forest Experiment Station in 1967. Eucalyptus timber research was suspended until 1971 when a small research cooperative was formed with Federal, State, industrial, and private participants. Operational planting started in 1972 and in 10 years 8.8 million seedlings of Eucalyptus grandis Hill ex Maiden have been planted on 6,475 ha in southwest Florida. Every outplanted seedling was grown from genetically improved seed collected from local seed orchards.

Our tree improvement system had to accommodate two conditions:

(1) Imported seedlots will not produce commercial plantations in Florida. The most we can expect is that the better imported seedlots will produce occasional outstanding individuals which we can select and breed into a locally adapted strain.

(2) In 1972, industrial and private cooperators wanted to start commercial planting "immediately." Instant demand for improved seed dictated that provenance trials, tree selection, seed orchard establishment, and progeny testing be combined and accomplished concurrently instead of in the more conservative stepwise sequence.

[1]Presented at A Workshop on Eucalyptus in California, June 14-16, 1983, Sacramento, Calif.

[2]Tree Breeder, Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, Ft. Myers, Fla.

BREEDING METHODS

Grandis trees planted in southwest Florida constitute a landrace developed through three generations of selection and progeny testing in the local environment. Because of recurrent selection for local adaptation, the trees perform better in Florida than progenies of outstanding trees selected in Australia, South Africa, or elsewhere.

The breeding strategy involves importing as many E. grandis seedlots as possible--preferably collected from selected single trees in Australia. But some bulk lots have been included, plus many lots from exotic populations outside Australia. Each seedlot (called a family) contributes about 60 seedlings to a large outplanting called the genetic base population. All individuals of all families and all sources are completely randomized in single-tree plots. Stocking is 1,916 trees/ha in a precise row X column grid, mapped to preserve the location and pedigree of each tree. Trees are measured for growth rate and scored for cold hardiness, stem straightness, branch habit, and general adaptation. At 2.7 years (one-third of rotation age), the best trees are selected and the rest are rogued to convert the base population to a seedling seed orchard. The best families usually contribute three or four selects to the seedling seed orchard; most families contribute only one or two; and about one-third of the families drop out of the breeding population for lack of any worthy candidates.

Select trees exchange pollen in the first general bloom at age 3+ years. The following spring the resultant seed is collected and used to establish the next generation's base population, which is also the progeny test of the seedling seed orchard. Thus a generation is turned, from seed to seed, in 4 years. Progeny test results identify the best commercial seed trees as well as poor seed trees to be rogued from the orchard.

Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983.

Each generation of selection enhances the landrace's adaptation to local conditions, but new families must be imported to broaden the genetic base and guard against inbreeding depression. The current grandis population, planted in 1977 (G-POP77), consists of 31,725 trees representing 529 families on 17.3 ha. Nine percent of the families are fourth generation (great grandmothers selected for excellence in a Florida plantation); 24 percent, third generation (grandmothers selected in Florida); 40 percent, second generation (mothers selected in Florida); and 27 percent, first generation (newly imported families). Geographically, 37 percent of the families trace their maternal pedigrees back to New South Wales; 32 percent originate in Queensland; 21 percent from South Africa; 4 percent from many miscellaneous nations; and 6 percent cannot be traced beyond Florida.

The Florida breeding strategy presents two radical departures from usual methods. We combine a provenance trial, a genetic base population, a seedling seed orchard, and a progeny test in a single plantation. We do that simply to compress development time and to concentrate our meager resources of staff and budget.

Our other departure is to plant all the individuals representing a family in completely randomized, single-tree plots. This contrasts with the replicated square plots or row plots used in most tree improvement plantings. Completely randomized, single-tree plots offer several advantages: (1) Each family is maximally dispersed across the planting site, encouraging a thorough sampling of microsites and an accurate estimate of site adaptation. (2) Maximal dispersion promotes random mating of select trees and eliminates the need to choose between outstanding sibling selection candidates standing side by side in the same multitree plot. (3) Different families can be represented by different numbers of individuals with no statistical or operational problems; likewise, mortality causes no problems. (4) Each tree is a replicate of its family and represents a statistical degree of freedom. This efficient, robust design enables us to screen more families with fewer trees.

INDICATED GAINS

In the current base population, G-POP77, comparison of first-, second-, third-, and fourth-generation families shows impressive evidence of genetic gain (fig. 1). At age 2.5 years the average first-generation tree contained 7.5 dm^3 of stem wood and bark from groundline to tip. Second-generation stems grew nearly twice as large, averaging 14.6 dm^3. Third-generation stems show an additional 16 percent increment up to 17.0 dm^3, and fourth-generation yet another 16 percent up to 19.7 dm^3.

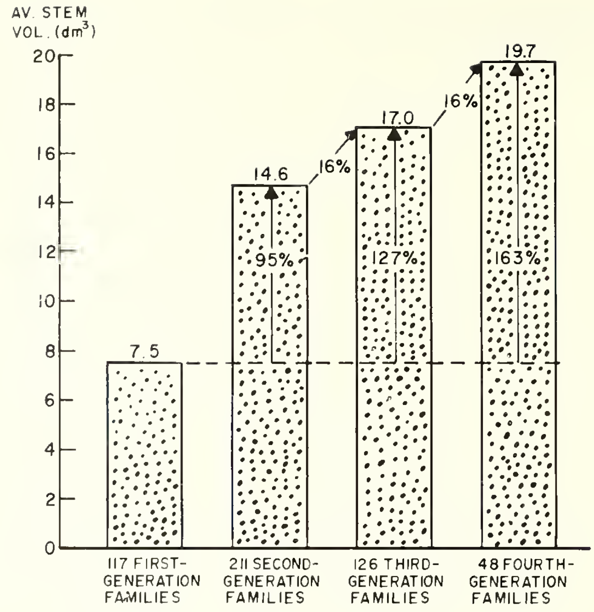


Figure 1--Family mean stem volume at age 2.5 years in G-POP77, the E. grandis base population planted in 1977.

These results imply that at one-third of rotation age, Florida landowners will be producing 2.6 times more wood from planting fourth-generation Florida seedlings instead of stock grown from imported seed. The case for local selection seems compelling considering that a large majority of first-generation families in G-POP77 are offspring of magnificent select trees in Australia and South Africa. But that parental magnificence is rarely reproduced by offspring planted in the Florida environment.

PERPLEXING QUESTIONS

Despite the promise, some thoughtful visitors and cooperators suggest that genetic gains measured in our combination base population-progeny test might seriously overestimate gains realizable in commercial plantations. The concern is that competition among trees might be far more severe in commercial plantations than in our base population.

Our base population-progeny test with its single-tree plots simulates commercial plantations in that offspring of all seed trees are randomly mixed on the planting site. Nevertheless there remains a perplexing difference between our base population and a commercial plantation: the range of genetic quality.

The difference is that our base population includes the entire spectrum of genetic resources ranging from the most advanced families down to new introductions which lack adaptation and compete poorly. In contrast, commercial plantations are the truncated, compressed upper end of the genetic range. For example, G-POP77 consists of 529 families, but the 1979 commercial plantations include only the best 34 of those families--that's skimming just the best 6 percent of the cream off the top of our gene pool. The perplexing question is: What happens when these best families must compete just among themselves over hundreds of hectares? Does the "cream" stay sweet, or does it curdle from the intense heat of best competing against best?

A corollary question is: Can southwest Florida's poor soils, spring droughts, and summer flooding support such intense competition; or do environmental factors become limiting and render the most genetically advanced families no more productive than their ancestral, imported seedlots?

SEEKING ANSWERS

In 1979 we installed a small study called GAIN79 to answer those perplexing questions by measuring realized gain in a commercial plantation setting. This paper reports those gains and compares them with gains forecast by G-POP77.

GAIN79 compares three populations in four replications of 7- X 7-tree plots. The populations are:

Ancestral: Four imported seedlots from which many advanced-generation families descend. All Ancestral trees are first generation.

Commercial: The commercial seed mix for the 1979 planting season, composited from 34 advanced-generation families chosen for excellent early performance at G-POP77. Of the 34 commercial families, 22 are descended from Ancestral seedlots. The average Commercial tree is generation 2.9.

Premier: Six advanced-generation families, top ranked for the combined traits of volume production, cold hardiness, form, and coppicing. All six Premier families descend from Ancestral seedlots, and five Premier families are also among the Commercial families. The average Premier tree is generation 3.5.

GAIN79 simulates a commercial plantation as closely as possible. It was planted in the commercial site-preparation area at the same spacing employed by the landowner.

The G-POP77 and GAIN79 sites are located about 23 km apart in Glades County on a landtype known locally as palmetto prairie, a flat, naturally treeless expanse of saw-palmetto, wiregrass, runer oak, and wax myrtle. Soils are infertile, poorly drained acid fine sands underlain by spodic hardpans. We hand planted both studies in July (G-POP77 in 1977, GAIN79 in 1979) on sites prepared in the spring by burning, broadcasting with 1,120 kg/ha of ground rock phosphate, double chopping (GAIN79) or triple chopping (G-POP77), then bedding. A major difference is planting density: 1,204 trees/ha at GAIN79; 1,916 trees/ha (59 percent more) at G-POP77. Our commercial recommendation is 1,495 trees/ha. The shortfall at GAIN79 is unfortunate but was dictated by the spacing of the commercially prepared beds.

We measured growth in both studies at 0.5, 1, 1.5, and 2.5 years and also scored tree form at 2.5 years. Additionally, GAIN79 was scored for damage following freezes at 1.5 and 2.5 years, and remeasured at 3.5 years.

EARLY GAINS

Growth Traits

GAIN79 demonstrates impressive early growth gains similar to those forecast by G-POP77. Improved trees rapidly expressed superiority at both sites. Analysis of variance first detected highly significant gains for height growth at age 6 months in G-POP77 and at 1 year in GAIN79, and at 1.5 years for diameter and volume growth at both sites. At the oldest common measuring age, 2.5 years, Commercial and Premier trees stand a quarter to half again as tall as Ancestral trees with over twice as much wood in their stems (fig. 2).

Gains illustrated in figure 2 for GAIN79 amount to the following returns from breeding imported seedlots up to a Premier population: an average tree 2.3 m taller at age 2.5 years with 7.2 dm^3 of additional stem volume or 3.3 kg more dry energy fuel; and an average hectare carrying 8 m^3 more volume or 3.7 tons of additional dry energy fuel.[3] Figure 3 characterizes breeding gains per stem, and figure 4 on a stand basis.

Figure 2 depicted percentage gains of comparable magnitude in both studies. The similar percentages are reassuring because they are based on markedly different growth rates at the two sites. The site difference is so extreme that the shortest population at G-POP77, Ancestral, averages taller at 2.5 years than the tallest trees, Premier, at GAIN79 (fig. 3). The pooled 2.5-year height of all three populations is 7.1 m at G-POP77 slipping to 4.8 m at GAIN79, a 32 percent reduction.

---

[3]Volume of stem wood and bark from groundline to tip; dry weight of wood and bark in stems and branches from ground to tip (formulas on file with Forest Service, USDA, Ft. Myers, Fla.).

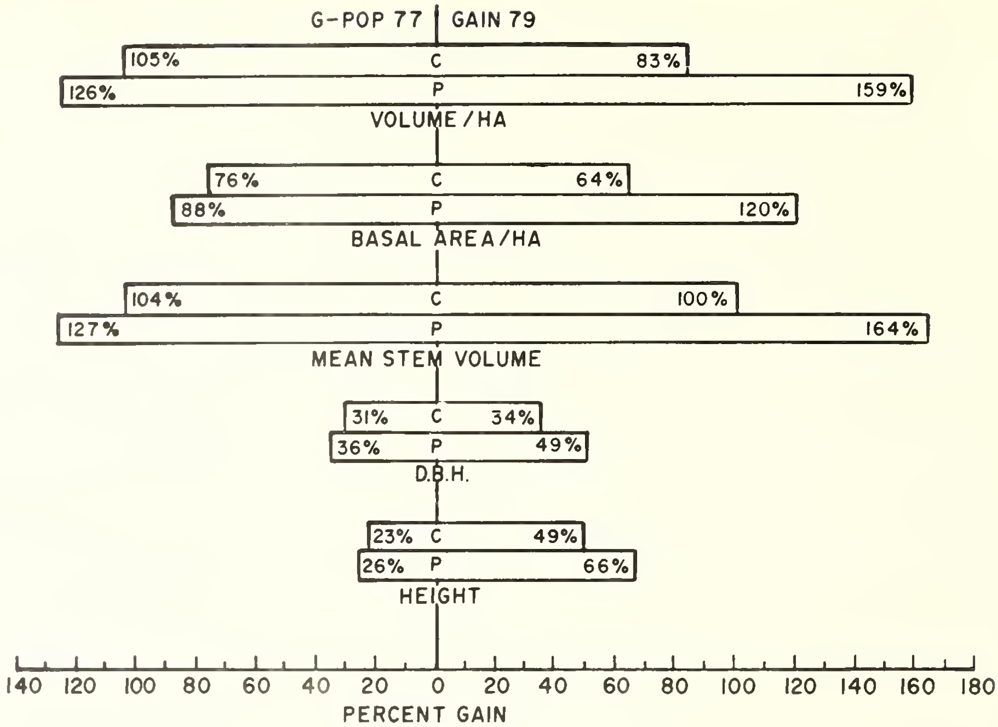


Figure 2--Percentage gains in growth traits at age 2.5 years for Commercial (C) and Premier (P) trees over Ancestral trees as predicted at G-POP77 and realized at GAIN79. All bars represent statistically significant gains.

Four factors could conceivably contribute to the site-growth differential: (1) inherent differences in site quality; (2) different stocking levels; (3) partially different growing years, July 1977-January 1980 at G-POP77 versus July 1979-January 1982 at GAIN79; or (4) the effects of competition within populations at GAIN79 versus competition among populations at G-POP77. Competition among populations would seem to disadvantage the unimproved Ancestral trees. Yet Ancestral trees grew 79 percent as tall as Premier trees while competing with them at G-POP77, but only 60 percent as tall while not competing with them at GAIN79. Empirically, stocking levels may play a large role in the site-growth differential. G-POP77, planted at 1,916 trees/ha had eliminated herbaceous competition by age 1.5 year; but GAIN79, with 1,204 trees/ha, still competes with a heavy ground cover after 3.5 years.

Whatever the adversities at GAIN79, improved trees coped better than unimproved trees. Ancestral trees grew only 55 percent as tall at GAIN79 as they had at G-POP77, but Commercial trees achieved 70 percent and Premier trees 76 percent of their G-POP77 performance. Our base population-progeny tests cannot be expected to predict actual growth on all sites. Nevertheless, in this case G-POP77 seems a reliable predictor of the magnitude of gains that improved populations will express in commercial plantations.

Tree Form

We evaluated tree form at age 2.5 years using the following scoring systems:

Stem straightness: 0 = too crooked for pulpwood, 1 = acceptable for pulpwood, 2 = good straightness, 3 = excellent straightness.

Branch habit: 0 = too limby for pulpwood, 1 = acceptable for pulpwood, 2 = good natural pruning and small branched, 3 = good natural pruning and fine branched.

G-POP77 forecast highly significant gains in stem straightness which were realized in GAIN79. G-POP77 also forecast highly significant gains in branch habit, but these were not realized in GAIN79 (fig. 5). The contradiction in the two traits is not surprising viewed in the context of tree selection.

As we search our base populations for selection candidates, the first trait we look for is vigor--candidates must be conspicuously larger than their neighbors or their siblings. We notice repeatedly that grandis stem straightness is independent of bigness, but branch habit is not. It is just as easy to find straight big trees as crooked big trees, and there is no need to compromise selection standards for either trait.

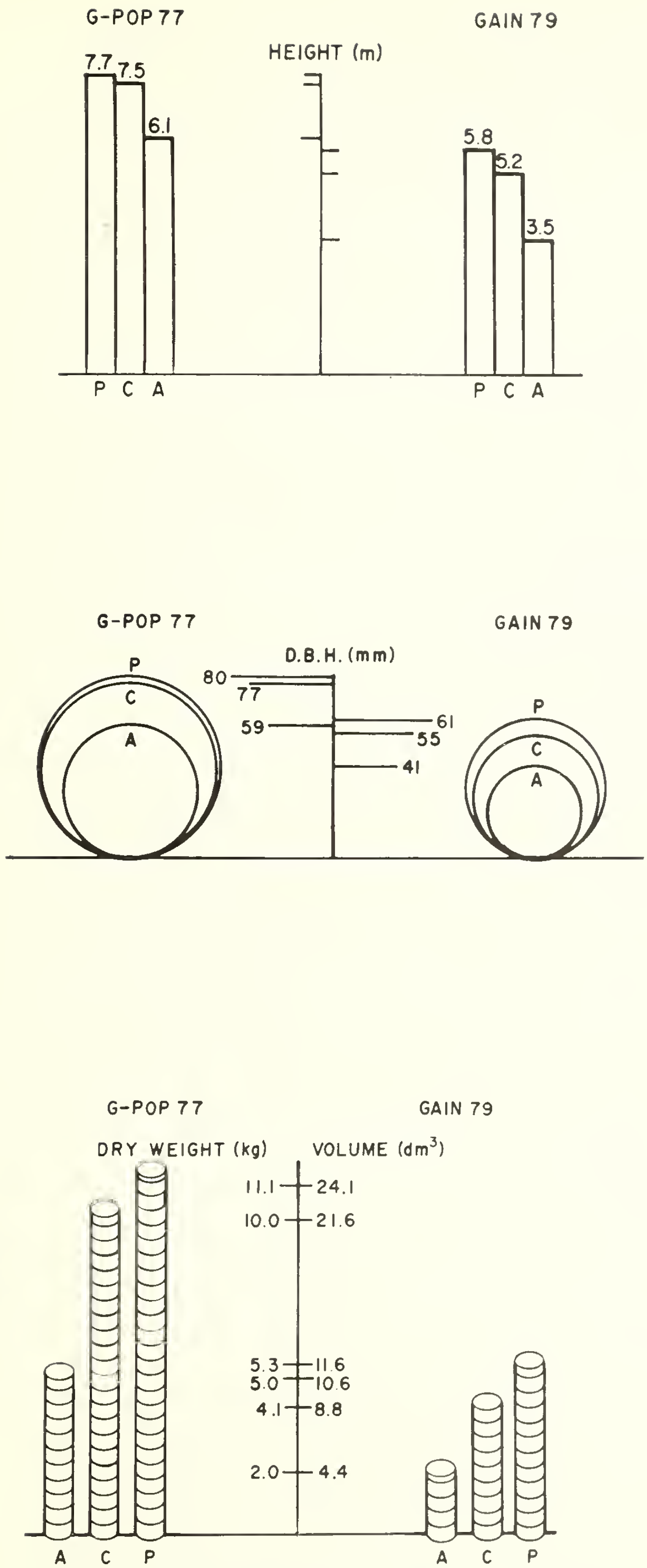


Figure 3--Mean stem values at age 2.5 years for Ancestral (A), Commercial (C), and Premier (P) trees.

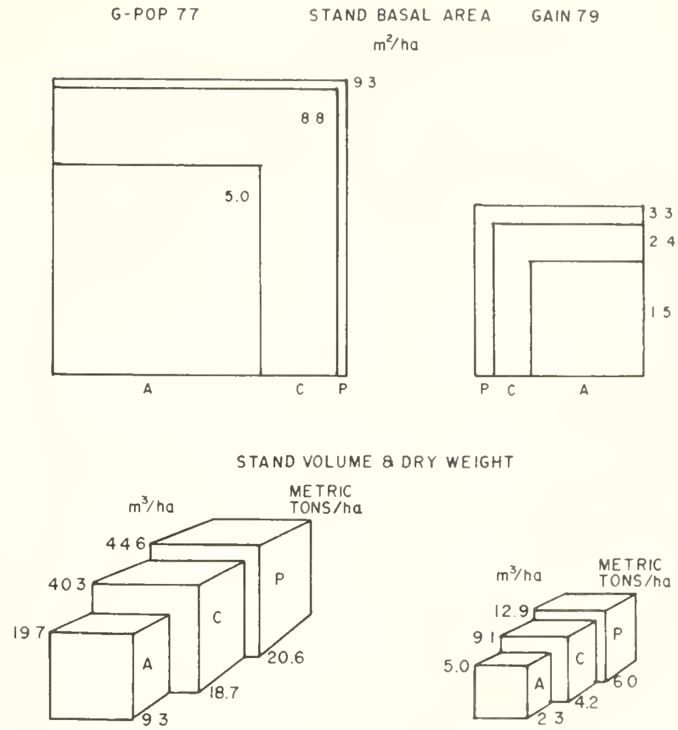


Figure 4--Stand basal area, volume of stem wood and bark from ground to tip, and dry weight of wood and bark in stems and branches for Ancestral (A), Commercial (C), and Premier (P) populations at age 2.5 years.

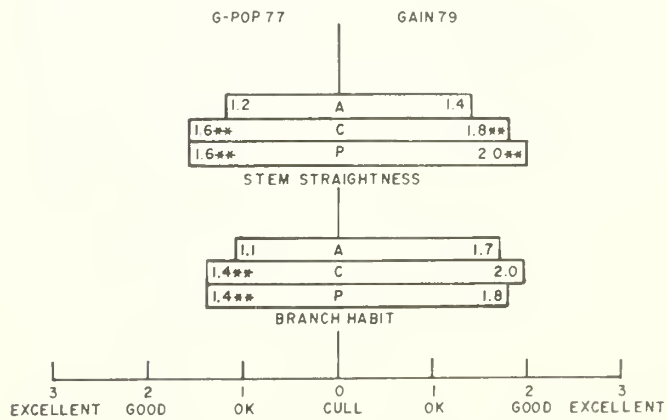


Figure 5--Mean scores for branch habit and stem straightness for Ancestral (A), Commercial (C), and Premier (P) trees, age 2.5 years, at GAIN79 and G-POP77. Asterisks signify significant (0.01 level) gains over Ancestral population.

In contrast, big trees have coarse branches far more commonly than fine branches. We have had to compromise--but never abandon--our standards on branch habit, especially when selecting from first-generation families.

The failure of GAIN79 to demonstrate predicted gains in branch habit may also be attributable to smaller tree size and wider spacing than at G-POP77. At the evaluation age of 2.5 years, trees at GAIN79 averaged 2 m shorter than at G-POP77. It is difficult to infer the mature relationship between branch size and bole size until saplings are quite advanced. Also the natural pruning aspects of branch habit are not evident until growth rate and stocking converge at partial crown closure. The natural expression of branch habit might also have been altered or delayed at GAIN79 by recovery sprouts arising after freeze damage 1 year earlier.

Gains in form may seem miniscule--no more than 0.6 of a scoring unit--but that perception changes if gain is expressed as the percentage of movement along the scale from the score of unimproved trees to the maximum score of 3. A sample calculation follows for Premier stem straightness at GAIN79:

$$\frac{\text{Premier score - Ancestral score}}{\text{3 - Ancestral score}} \text{ X } 100 = \text{percent gain}$$

$$\frac{2.0 - 1.4}{3.0 - 1.4} \text{ X } 100 = 38 \text{ percent gain}$$

So computed, the Premier and Commercial scores presented in figure 5 translate to the following percentage gains:

	G-POP77	GAIN79
Stem straightness		
Premier	22**	38**
Commercial	22**	25**
Branch habit		
Premier	16**	8
Commercial	16**	23

**Represents gain significant at the 0.01 level, based on ANOVA of actual scores.

Freeze Damage

Severe frost damages grandis even in the recommended planting zone, but the trees rarely die. They may freeze back, but they sprout and regrow vigorously. Frost has cost a season's growth several times but never a plantation. Southwest Florida usually has inversion freezes with temperatures coldest at ground level but moderating dramatically in the first meter or two above ground. Marginally hardy trees like *E. grandis* can reduce risk simply by growing fast--elevating tender crown tissue above lethal temperatures while building larger stems with thicker, insulative bark close to the ground. Each additional year of growth reduces risk. Since research planting started in 1961, severe damage has been suffered 1 out of 3 years by seedlings in their first winter, 1 out of 4 years by saplings in their second winter, and 1 out of 11 years by trees in their third winter or older. We make freeze tolerance a prime selection criteria--whenever nature "blesses" one of our base populations with a severe freeze.

In its four winters to date, GAIN79 has been statistically unlucky with two significant freezes. A moderately hard freeze occurred January 13, 1981, with low temperatures near -8.5°C (16°F). Damage was moderate to severe at GAIN79, then in its second winter; in contrast, damage was slight at G-POP77 in its fourth winter.

One year later a catastrophic freeze struck with temperatures as low as -11.5°C (11°F), and subfreezing for 8 hours. The 1982 freeze devastated all grandis trees in Glades County, regardless of age or size. The eucalypts were particularly vulnerable to the 1982 freeze because of a total lack of preconditioning. The preceding month included 21 days with afternoon highs above 27°C (80°F). We scored damage from both freezes at GAIN79. At G-POP77, damage was too light to score in the first freeze, and other priorities precluded scoring the severe freeze.

We score cold damage on an 11-point scale ranging from 10 (undamaged) down to -1 (frozen dead); categories 9 down through 5 denote increasingly severe damage confined to leaves; and categories 4 down through 0 describe increasingly severe wood destruction in branches or bole. Figure 6 details the scoring system. Figure 7 profiles damage suffered by Ancestral, Commercial, and Premier trees at GAIN79.

Figure 7 starkly illustrates that while breeding has made substantial progress toward minimizing damage from moderate freezes, some south Florida freezes are so severe as to probably exceed the natural variation available for selection in the species. In the moderate freeze, Ancestral trees suffered bark splitting and injury to primary branches and main stems, but Commercial trees only lost their leaves, and Premier trees actually retained about 25 percent of their leaves.

If these gains in a moderate freeze are converted to percentages computed in the same manner as for tree form, they amount to a 31 percent gain for Commercial trees and a 53 percent gain for Premier, gains notably similar to the percentage gains for height growth presented in figure 2. We do not think that we are breeding a meaningful improvement in physiological cold resistance, but we do think we are breeding a significant improvement in cold tolerance based primarily on growing big enough, fast enough to avoid lethal temperatures in the inversion layer.

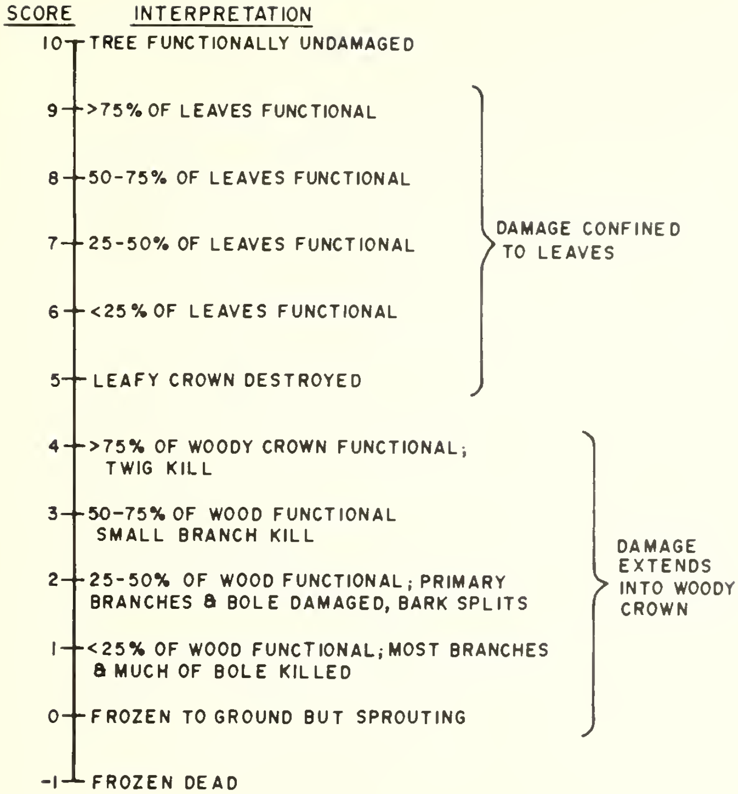


Figure 6--Cold damage scoring system.

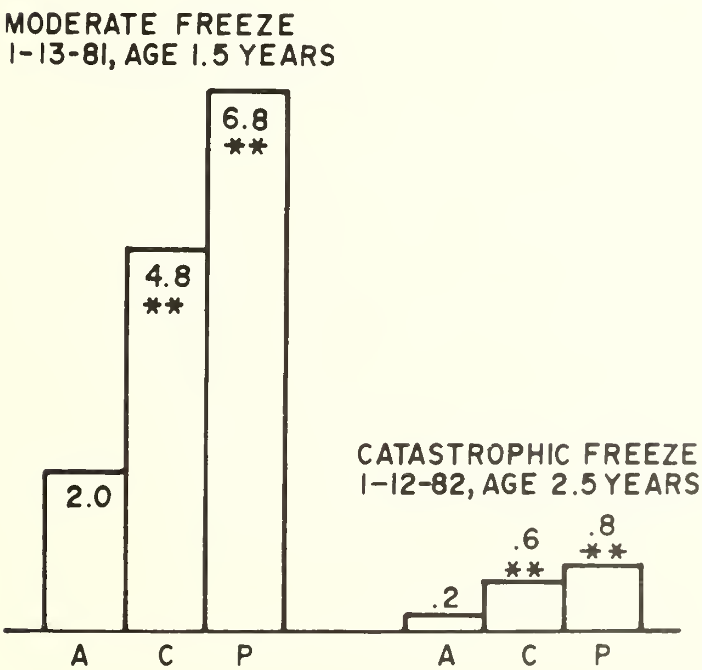


Figure 7--Mean cold damage scores for Ancestral (A), Commercial (C), and Premier (P) populations in two freezes at GAIN79. Asterisks denote scores significantly (0.01 level) above Ancestral score.

Whatever the nature of our gains, the catastrophic freeze overwhelmed them. Ancestral, Commercial, and Premier trees averaged respectively 0.2, 0.6, and 0.8 on the damage scale (fig. 7), and no individual tree scored higher than 1. Converted to percentages as before, these miniscule gains amount to 4 percent for Commercial and 6 percent for Premier.

In a freeze of this magnitude, breeding gains need to be expressed in the most basic trait: survival. During the year following the great freeze, 22 percent of Ancestral trees died compared to 7 percent of Commercial trees and 4 percent of Premier trees, significantly heterogeneous mortality (χ^2 test, 0.01 level). Before the freeze, populations had not differed significantly in survival.

One year after the great freeze, GAIN79 has the following stand characteristics at age 3.5 years:

	Ancestral	Commercial	Premier
Survival (pct)*	73	81	89
Stocking (trees/ha)*	879	975	1,072
Mean height (m)**	3.2	4.7	4.8
Number of persistent freeze-recovery stems per stool	2.7	2.6	2.2

*Trait reflects population differences significant at the 0.05 level (χ^2 test); **trait reflects population differences significant at the 0.01 level (ANOVA).

The 1982 freeze seems so devastating in the context of this report that we need to view it in broader perspective. The freeze was isolated, almost confined to a single county. Damage was slight to eucalyptus plantations in other suitable growing areas. Freeze damage approaching this severity has not been seen in southwest Florida since 1962. In the interim, two complete rotations could have been planted, grown, harvested, and regenerated. Within the freeze zone the loss of wood inventories depended on age class. Plantations in their first or second winter were frozen to the ground and regenerated from ground level coppice shoots. They will develop as normal coppice stands. Plantations in their fifth, sixth, seventh, or eighth winter suffered severe damage to crown tissues but not to product boles. Those age classes will refoliate and grow on to scheduled harvest with little economic loss. Plantations in their third and fourth winters (GAIN79) suffered profound damage to product boles; stems that recovered are often badly forked or so weakened that subsequent wind breakage seems likely. These age classes, however, would constitute only 25 percent of plantation area in an even distribution of age classes. Freeze damage is an acceptable investment risk that can be ameliorated by adding freeze resilience--swift, graceful recovery--to our tree selection criteria.

CONCLUSIONS

Back-to-back freezes savagely reduced growth and stocking at GAIN79 and converted it from a single-stemmed seedling stand to a multistemmed coppice stand. These transformations are not economically or esthetically pleasing, but they demonstrate graphically that breeding advanced-generation strains from local selections is probably the most important element in managing the investment risk of growing eucalypts in Florida.

Despite great discrepancies in stocking and productivity, G-POP77 either accurately or conservatively forecast the magnitude of genetic gains realized at GAIN79. It seems both efficient and efficacious to breed local landraces in genetic plantings that combine the functions of provenance trial, base population, progeny test, and seed orchard. Completely randomized, single-tree plots seem to be a reliable planting design for ranking populations and predicting the magnitude of realized gains.

ACKNOWLEDGMENT: I thank Lykes Bros., Inc., for experimental sites and land preparation.

Standiford, Richard B.; Ledig, F. Thomas, technical coordinators. **Proceedings of a workshop on *Eucalyptus* in California, June 14-16, 1983, Sacramento, California.** Gen. Tech. Rep. PSW-69. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 128 p.

To provide up-to-date information on *Eucalyptus* in California, researchers from California, Florida, Hawaii, Oregon, and France presented papers on species selection, products, uses, and economics, growth and yield, cultural requirements, propagation, and breeding programs. This Proceedings of the Workshop should serve as a useful reference for landowners, foresters, nurserymen, horticulturists, and others who are planning to plant *Eucalyptus*.

Retrieval Terms: Eucalyptus, short-rotation trees, biomass, wood energy

United States
Department of
Agriculture

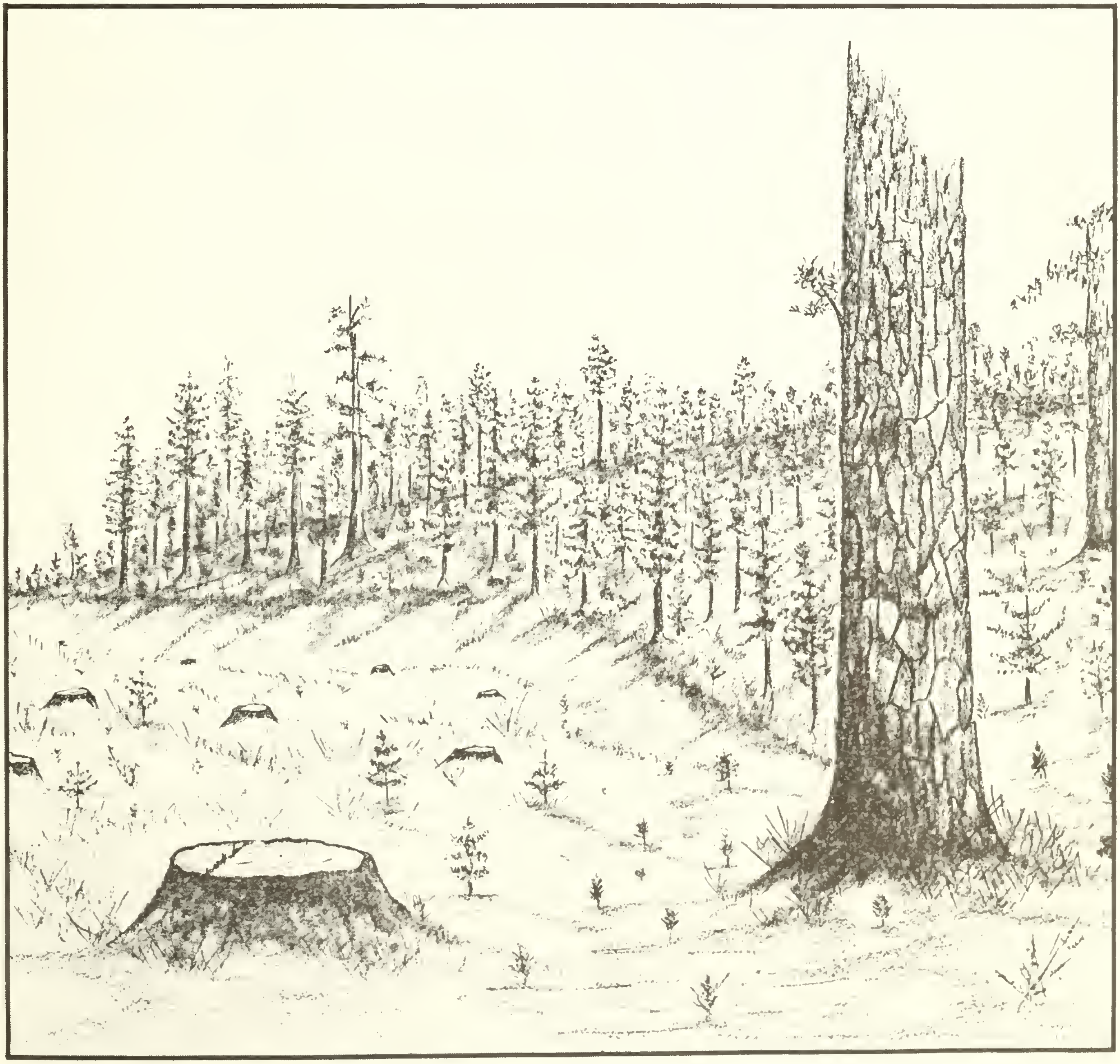
Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

General Technical
Report PSW-70

Clearcutting and Natural Regeneration ... Management Implications for the Northern Sierra Nevada

Philip M. McDonald



The Author:

PHILIP M. McDONALD is doing research on silviculture of Sierra Nevada forest types, with headquarters in Redding, Calif. He holds bachelor's (Washington State University, 1960) and master's (Duke University, 1961) degrees in forestry, and a Ph.D. degree in forest science (Oregon State University, 1978). He has been in silvicultural research at the Station since 1963.

Cover — Conifer seedlings grow along the edge of a clearcutting in the northern Sierra Nevada, California. (Drawing by Bob Laacke)

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

October 1983

Clearcutting and Natural Regeneration ... Management Implications for the Northern Sierra Nevada

Philip M. McDonald

CONTENTS

Introduction 1

Challenge Experimental Forest 1

Clearcutting 2

Layout and Logging 2

Slash Disposal and Site Preparation 2

Seedfall 5

Rodent Control 6

Natural Regeneration 7

Conifers 7

Woody Shrubs 8

Hardwoods 9

Management Implications 9

Slash Disposal and Site Preparation 9

Regeneration 9

Recommendations 10

References 10

Clearcutting in stands of young-mature mixed-conifer and hardwood trees in north-central California is a relatively new method of silvicultural regeneration. It is increasingly practiced in the area because a biological basis for it exists. This basis is the persistent hardwood understory beneath the conifer canopy that adversely affects conifer regeneration and growth.

From 1963 to 1977, a series of clearcutting experiments were done on the Challenge Experimental Forest in Yuba County, California. The experiments were designed to test an approach to clearcutting in which 892 acres (361 ha) were cut in 41 compartments ranging from 7 to 60 acres (3 to 24 ha). More than 316 acres (128 ha) were designated for the study of natural regeneration. Slash disposal, site preparation, and rodent surveys, however, were done on acres that were regenerated by both artificial and natural techniques. Because artificial regeneration is discussed in another paper (Neal 1975) and not included here, the acreages expressed are not additive.

Broadcast burning, windrow and burning, rodent trapping, and seedfall surveys were done intermittently from 1964 through 1977. Broadcast burning was studied on 375 acres (152 ha) and windrow and burning on 576 acres (233 ha). Rodent populations were surveyed at various times on 440 acres (178 ha), natural seedfall was measured on 68 acres (27 ha), and natural regeneration was surveyed on 316 acres (128 ha). Surveys of clearcuttings having natural regeneration began in 1964 and ended in 1982.

This report is the product of 20 years of research on forest regeneration after clearcutting in the young-mature mixed-conifer and hardwood forests of north-central California. It describes an approach to clearcutting, suggests the management implications of this approach, and offers recommendations for reducing delays in regeneration.

CHALLENGE EXPERIMENTAL FOREST

Research done on the Experimental Forest applies to about 1.5 million acres (607,035 ha) of highly productive timberland along the west slopes of the Sierra Nevada. These young-mature mixed-conifer and hardwood forests at low- to mid-elevations form a transition zone between the chaparral and mixed hardwoods at lower elevations and the mixed-conifer forest at higher. Within this zone, and often in complex mixture, the California Black Oak, Douglas-fir–Tanoak–Pacific Madrone, Pacific Ponderosa Pine, and Pacific Ponderosa Pine–Douglas-fir forest cover types are found (Eyre 1980). A chaparral type also is present. Conversion of the mixed hardwood and conifer stands to conifers alone is both difficult and costly.

The hardwoods, often of sprout origin, compete vigorously with young conifers and must be controlled. Reducing sprout numbers by knocking down all remaining trees in conjunction with slash disposal generally is cheaper and more effective than girdling and poisoning trees or treating cut surfaces or sprouts with herbicides. Flattening unmerchantable trees puts a large amount of fuel near the ground and leads to broadcast burning.

A valuable attribute of the Experimental Forest is its high site. Soils often are more than 100 ft (30 m) deep, mean annual temperature is 55° F (13° C), and annual precipitation averages 68 inches (1727mm). These conditions ensure that vegetation is abundant and fast-growing. Indeed, the dominant species, ponderosa pine (*Pinus ponderosa* Dougl. ex Laws. var. *ponderosa*), will average 140 ft (43 m) in height in 100 years (Arvanitis and others 1964). Trees 170 ft (52 m) tall at this age are not unusual.

Other tree species on the Experimental Forest are Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), sugar pine (*Pinus lambertiana* Dougl.), California white fir (*Abies concolor* var. *lowiana* [Gord.] Lemm.), and incense-cedar (*Libocedrus decurrens* Torr.). Hardwoods, principally California black oak (*Quercus kelloggii* Newb.), tanoak (*Lithocarpus densiflorus* [Hook. and Arn.] Rehd.), and Pacific madrone (*Arbutus menziesii* Pursh), are scattered throughout as individual trees, clumps, or groves (*fig. 1*). Generally, trees larger than 3.5 inches (8.9 cm) in diameter-at-breast-height (d.b.h.) number 248 per acre (613/ha) and contain about 270 ft^2 (62 m^2) of basal area.

The stands are classified as young-mature. Dominant and codominant trees are about 120 years old. They number about 35 per acre, 70 percent of which are ponderosa pine. Trees in these crown classes produce more than 80 percent of the cones in a seed crop (McDonald 1973, 1976b).

Shrub species also grow on the Experimental Forest. The most abundant are whiteleaf manzanita (*Arctostaphylos viscida* Parry) and deerbrush (*Ceanothus integerrimus* Hook. and Arn.). When logged, the clearcut compartments show no signs of manzanita and deerbrush. Killed long ago by the shady forest, the shrubs died and decayed until not a trace remained above ground. Below ground, however, thousands, if not millions of viable shrub seeds per acre awaited conditions that would stimulate germination (Quick 1956).

Figure 1—This young-mature stand on a high site on the Challenge Experimental Forest, Yuba County, California, typically has mostly ponderosa pine in the overstory with shade-tolerant conifers and hardwoods beneath.

CLEARCUTTING

Layout and Logging

In the summer of 1962, 12 circular units of 2, 5, and 10 acres (0.8, 2.0, and 4.0 ha) were cut on the Experimental Forest. Each size was replicated twice on a northeast aspect and twice on a southwest aspect. Slopes varied from 5 to 51 percent on the southerly aspect, and from 10 to 35 percent on the northerly aspect. Positions of the clearcuttings varied from near the top to near the bottom of the slopes. By adjusting slope measurements to horizontal distances, each cutting unit became a perfect circle.

Logging began in January 1963 and continued intermittently, as weather permitted, until mid-June. Other than in the small landings, which were located within the cutting units, soil compaction appeared to be negligible.

Clearcuttings after 1963 were more conventional in shape. Most were nearly rectangular and followed natural boundaries, such as streams or ridgelines and, occasionally, roads. They varied in size from 15 to 60 acres (6 to 24 ha). Each year several of various sizes were cut.

Slash Disposal and Site Preparation

After merchantable logs were skidded, remaining stems were flattened by a large tractor-dozer, usually in late spring. A few California black oaks, too large to be pushed over, had to be felled. The downed trees were not deliberately crushed after felling, although some crushing took place incidentally as skidding and pushing progressed. Pushing was accomplished at a rate of about 5 acres (2 ha) per tractor-day.

Slash Weight

The weight of residual slash and unmerchantable trees after logging in young-mature stands on high sites tended to be high (*fig. 2*). Once on the ground, the slash was sampled and dry weights were determined.

In clearcuttings on the southwest aspect, slash weights ranged from 53 to 89 tons per acre (119 to 200 t/ha), averaging 74 tons per acre (166 t/ha). Hardwoods made up 31 percent of the slash, conifers 45 percent, and litter and humus 24 percent (Sundahl 1966). On the northeast aspect, where more California white fir and sugar pine grow, residual weights ranged from 88 to 110 tons per acre (197 to 247 t/ha), averaging 97 (217 t/ha). Of this total, hardwoods constituted 29 percent, conifers 45 percent, and litter and humus 26 percent. Although the amount of residual material differed between the two aspects, the percentage makeup among hardwoods, conifers, and litter was similar. Conifer cull logs contributed only 5 percent to total slash weight. About 66 percent of the material on each aspect was fine fuel—less than 4 inches (10 cm) in diameter. The high percentage of fine fuel and low amount of large cull logs were conducive to broadcast burning.

Broadcast Burning

Altogether, 20 compartments ranging from 2 to 46 acres (0.8 to 18 ha) and totaling about 375 acres (152 ha) were broadcast-burned from 1963 through 1966. A prescription stating acceptable conditions of fuel moisture, temperature, and weather was formulated (McDonald and Schimke 1966) before slash was burned. When the prescribed conditions are

Figure 2—A typical clearcutting after logging and pushing on the Challenge Experimental Forest, Yuba County, California. Large amounts of evenly distributed material facilitate broadcast burning.

met, slash can be burned in spring, winter, or fall. Fall burns generally are favored over spring and winter burns because they remove the most fuel, consume more heavy fuel, and are soaked "dead out" by winter storms. Winter and spring burns consume fuels that have been wetted and at least partially dried. Heavy fuels remain wet, except for outer surfaces and, therefore, less of them burn.

The problem with fall burns is that the first rain of the season could last for a week or more, wet the fuels, and thereby result in impossible burning conditions.

A storm in mid-October 1963, which deposited 2.85 inches (72 mm) of precipitation, set the stage for the first broadcast burning trial. By October 22, fuel moisture sticks indicated that fuels in the clearcuttings were drying rapidly, while those on the forest floor were wet. All conditions in the prescription were met and burning was scheduled.

Slash was ignited by drip torches. Weather during the first day was suitable and 19 acres (8 ha) were burned without incident. Despite a favorable weather forecast, an unexpected storm arrived that night and halted burning. Another 10-acre (4.0-ha) clearcutting was successfully broadcast-burned several days later. Again, a storm curtailed burning operations, although most of the remaining cutting units were burned partially. Only 29 of 68 acres (5 units of 12), therefore, were broadcast-burned successfully in 1963. The remaining cutting units were unacceptably burned and the fuels that remained were bunched into piles and burned later.

For broadcast burning in the 1964-66 compartments, weather continued to be a critical factor. The fall 1964 burns were drowned out by the first storm of the season. The fuels became so wet that they never were dry enough to be burned in the fall. Long dry spells in February and April, however, permitted winter and spring burning. The broadcast burns planned for fall 1965 also were washed out by the first storm. These compartments and those cut in 1966 totaled 195 acres (79 ha). All were satisfactorily burned in the fall of 1966 when the weather was nearly ideal.

For the acceptable broadcast burns, between 70 and 90 percent of the fine fuels below 4 inches (10 cm) in diameter, and slightly less than 50 percent of the coarse fuels above 4 inches were consumed (Hall 1967) (*fig. 3*). The overall fuel reduction by compartments ranged from 68 to 84 percent (McDonald and Schimke 1966).

Proportion of area burned and intensity of burning also are noteworthy. Data from the successful burns on the Experimental Forest indicated that broadcast burning left about 42 percent

Figure 3—When the weather cooperates, broadcast burning on the Challenge Experimental Forest, Yuba County, California, removes most of the smaller fuels and much of the larger.

of the area unburned, 53 percent burned lightly, and only 5 percent burned sufficiently to remove the entire litter layer and alter the structure of the uppermost soil layers (Neal 1975). A highly variable seedbed was formed.

Broadcast burning generally has been found to have no consequential effect on physical properties of soils in the northern Rocky Mountains (Roe and others 1971). And it has statistically nonsignificant effects on both physical and chemical soil properties in the western Cascade Mountains of Oregon and Washington (Kraemer and Hermann 1979).

Erosion is not a problem on the Experimental Forest either. Even where bared, the deep clay-loam soils have high internal capacity for water storage, and precipitation infiltrates fairly rapidly. Needles, twigs, pieces of charcoal, holes and furrows resulting from pushing, and charred logs impede the flow of surface water. After the first year, woody pioneer species increasingly cover the area, thereby checking erosion even more.

The total cost of slash disposal and site preparation by broadcast burning depends upon the number, size, shape, and distance between the units to be burned. Topography also can increase costs in proportion to increases in slope and roughness of terrain. Weather always is a factor in determining costs. The amount of men and equipment on the job is predicated on the entire acreage to be burned. Should adverse weather cause only one-half of it to be burned, most of the costs remain. These are then spread over only one-half the acreage, increasing costs per acre.

The cost of broadcast burning (1966 rates) varied from $8.42 per acre ($20.81/ha) for 75 acres (30 ha) to $36.24 per acre ($89.55/ha) for 28.5 acres (12 ha) (Hall 1967). Current rates have increased greatly. A good job of broadcast burning in 1981 cost about $125 per acre ($309/ha).

Windrow and Burning

Windrow and burning is the slash disposal and site preparation technique most commonly used in the northern Sierra Nevada on other than steep ground. A heavy tractor, usually with brush rake, windrows the slash (*fig. 4*). Costs in 1981 were $80 to $90 per acre ($198 to $222/ha) for tractor piling, with a burning cost of $25 to $35 per acre ($62 to $86/ha).

Advantages of the windrow and burn method are that almost all of the slash is pushed into the windrow, leaving a mineral soil seedbed. After piling, the surface of the ground is rough. Thousands of little earthen dams and, indeed, the windrow itself, check surface erosion. A windrow and burn compartment is safer to burn than one with broadcast slash because the

Figure 4—After windrowing slash in the northern Sierra Nevada, a mineral soil seedbed is available for regeneration.

surrounding forest can be much wetter, and the windrows still readily burnable. On the Experimental Forest, the forest floor usually was soaking wet before the windrows were ignited. Once lit, fire tends to spread the length of the windrows, particularly if on sloping ground. Ignition costs are low, and because the chance of escape is almost nil, standby crews are small. And the concentrated slash burns hot, thereby reducing smoke and air pollution.

A possible disadvantage of windrow and burning is that the high temperatures from the concentrated fuels cause clay particles to fuse into larger particles. Water percolates rapidly through the spaces between the large particles and the effect on plants may be likened to that in a desert. No conifers and only a few herbaceous species grow in the portions of the windrows that are hot-burned. After 8 to 10 years, however, the clay particles break down and ponderosa pine seedlings can become established. Less than 10 percent of an area is burned hot enough for clay particle fusion to become serious. The area affected is long and narrow and, because pines often become abundant in the rich loose soil on either side, the amount of area lost to the growing of trees is small.

Seedfall

Natural seedfall of several of the more valuable conifer species in California has been studied for years (Barrett 1966, Curtis and Foiles 1961, Fowells and Schubert 1956, Roy 1960). In general, most sound seeds are dispersed within a distance of 1½ to 2 times the average height of the dominant and codominant trees. Foresters have observed, however, that natural regeneration is almost totally lacking in some clearcuttings, absent in portions of others, and abundant in still others. In some instances regeneration becomes established in locales with no apparent seed source. Obviously, seeds of some species are being distributed farther than anticipated. A basic need for information on seed flight distance of several young-mature conifer species in the northern Sierra Nevada was recognized.

To help fill this need, the eight compartments of 1963 that resembled perfect circles were clearcut (*fig. 5*). The circular shape facilitates measurements of distance from the seed source at the forest edge.

To quantify seedfall at various distances into the clearcuttings, each clearcut was divided into concentric zones. Each zone extended inward toward the plot center for 100 ft (30 m), except the centermost. The number of zones in each size of circular clearcutting (radius of cutting shown in parentheses) was: 2 acres (166 ft)—2 zones; 5 acres (263 ft)—3 zones; and 10 acres (372 ft)—4 zones.

Foot-square (0.09 m^2) seed traps were used to sample seedfall. They were located on scaled maps that showed their placement in each clearcutting. Cutting tests determined seed soundness.

Seedfall was studied for 4 years, from 1964 through 1967. During this time, ponderosa pine produced three seed crops that ranged from light to heavy. Douglas-fir yielded three light seed crops, incense-cedar two light crops, and California white fir two medium crops.

Most seeds were distributed in the fall on days when winds were from the northeast and the atmosphere was warm and dry. When warm temperature and low humidity combine to lower the moisture content of cones and scales, a shower of seeds takes place. If this weather continues, most of the seeds fall, often within a week. If it does not last long enough, remaining seeds dribble out in warm weather between storms from the southwest, or again under the influence of northeasterly winds.

Seedfall estimates varied from 76 to 40,691 sound seed per acre (188 to 100,547/ha) for a single species in a given year

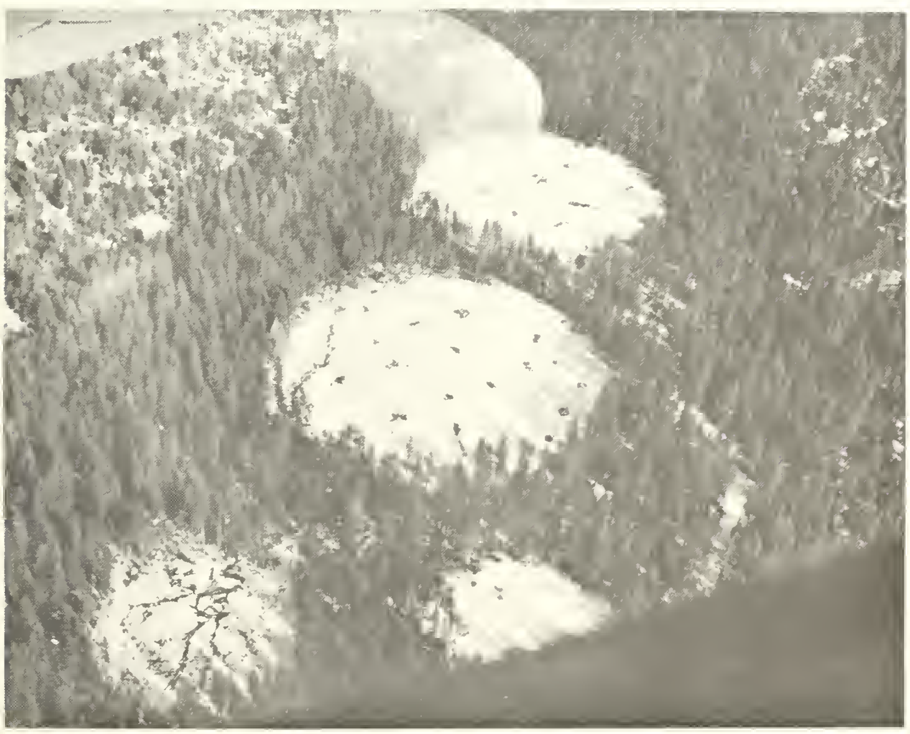


Figure 5—Aerial view of two 10-acre and two 2-acre circular clearcuttings on the Challenge Experimental Forest, Yuba County, California.

(McDonald 1980). Seedfall decreased successively in each zone with increased distance from the forest edge. The highest seedfall was 67,488 sound seed per acre (166,763/ha) in the outer zone of the 2-acre (0.8-ha) clearcutting, and the lowest 2520 per acre (6227/ha) in the innermost zone of the 5-acre (2.0-ha) opening. Douglas-fir seed carried up to 300 ft (92 m) into the 10-acre (4.0-ha) clearcuttings, incense-cedar reached 200 ft (61 m), and at least some seeds of California white fir and ponderosa pine were dispersed well into the innermost zone (350 ft or 107 m). Altogether, from 89 to 100 percent of each species' sound seed fell within a distance of 1 ½ times the height of the average dominant tree or 200 ft (61 m) into the clearcutting (McDonald 1980).

Rodent Control

The principal rodents on the Experimental Forest are deer mice (*Peromyscus maniculatus*). Nocturnal and inconspicuous, they seldom are seen and their effect on natural regeneration in clearcuttings in this area is not known. Deer mice in California feed largely on seeds (Jameson 1955), which often are coniferous. In Oregon, mice and shrews, but mostly deer mice, destroyed 40 percent of the Douglas-fir seed crop (Gashwiler 1970). In Montana, deer mice populations were affected by the previous year's ponderosa pine and Douglas-fir seed crops (Schmidt and Shearer 1971), implying that the conifer seeds were a significant portion of their diet.

Populations of deer mice in mature forests of the Sierra Nevada are relatively stable at about 5 mice per acre (12/ha) (Ingles 1965). Clearcuttings, however, produce environments favorable as mice habitats. Supplies of seeds and other foodstuffs become abundant and new areas for shelter and reproduction are provided. Under normal conditions, deer mice produce up to four litters of three to six young each year. As mice increasingly reproduce and immigrate into clearcuttings, populations rapidly expand.

Population Size

Before natural regeneration could be evaluated, information on the size of the rodent population and its potential for depredation was needed. In the newly made clearcuttings of 1963, for example, rodent surveys of March 10-13, 1964, averaged 9.2 mice per 100 trap-nights, a population large enough to mandate rodent control measures when direct seeding ponderosa pine (Wetherbee 1964). In the spring, warmer parts of clearcuttings probably are preferred habitats. Centers of clearcuttings and sunny edges are more desirable than cold frosty areas along southern edges that remain shaded by standing timber.

Potential for Damage

The potential for depredation of ponderosa pine seed by deer mice was evaluated in a study on the Experimental Forest with seed having radioactively labeled (Scandium 46) seedcoats. Some seeds were placed near the forested edge of clearcuttings and others near the center. Seeds were also positioned on the surface and others buried about ½ inch (1.8 cm) deep. Movement and fate of the seeds was traced with a scintillator (*fig. 6*). Even seeds that were eaten were detected easily because the radioactive seedcoats were left behind.

Figure 6—Movement of radio-tagged seeds is traced with a scintillator.

Movement of the seeds into and out of the soil was studied. Some buried seeds became uncovered and even a few became buried again. Likewise, some surface seeds were buried, a few even twice. Surface seeds were more vulnerable than buried seeds: 68 to 80 percent of surface seeds were destroyed compared with 35 to 70 percent of buried seeds. In one instance, a seed was moved a considerable distance and buried, then dug up and eaten on the spot several days later. Of the seeds moved (and usually destroyed) by rodents, 67 percent were within 1 ft (0.3 m) of their original position, 90 percent within 5 ft (1.5 m), and 98 percent within 8 ft (2.4 m). One seed was moved 17 ft (5.2 m). In general, depredation of seeds was greater in the interiors of clearcuttings than near the edges.[1]

That deer mice, and in some instances large numbers of them, were present and actively eating conifer seeds in the clearcuttings is a safe assumption. During the heavy California white fir and ponderosa pine seed years of 1965 and 1968, mice probably did not have as great an effect as in years of lighter crops. The effect of depredation by deer mice on the lower amounts of conifer regeneration near the center and westerly portions of most of the cutting units is not known. But the presence of deer mice should not be ignored.

---

[1]Unpublished data on file, Pacific Southwest Forest and Range Experiment Station, Redding, California.

NATURAL REGENERATION

Conifers

Adequacy of natural regeneration was evaluated periodically for 19 years. The evaluation was subjective and took into account numbers of conifer seedlings by species, distribution, and a general assessment of vigor. Number and distribution of hardwood trees and woody shrubs also were assessed. Twenty-four clearcut units ranging from 2 to 60 acres (0.8 to 24 ha) were surveyed annually for the first 2 to 4 years after cutting and periodically thereafter to age 15.

Regeneration categories and rating criteria were these:

- Adequate or better—Seedlings no farther apart than 12 ft (3.7 m) and well distributed throughout the compartment.
- Marginal—Spacing of seedlings near 12 ft (3.7 m) but distribution clumpy.
- Failure—Large areas devoid of seedlings.

The marginal category was similar to a plantation not understocked enough to require starting over, but one that needed interplanting. Compartments rated adequate tended to be overstocked and to require precommercial thinning, those deemed failures to need new site preparation and artificial regeneration. Regeneration adequacy and number of clearcut units in each category were adequate 7, marginal 13, and failure 4. Acreage of adequately stocked clearcuttings ranged from 5 to 60 acres (2 to 24 ha), marginally stocked from 2 to 42 acres (0.8 to 17 ha), and failures from 2 to 10 acres (0.8 to 4 ha). Aspect, slope, or position of clearcutting on slope showed no trend as to why regeneration was adequate or inadequate in a given clearcutting.

Amount and distribution of natural regeneration followed the general pattern, as discussed earlier for seedfall. Regeneration was most abundant near the forest edge and least abundant near the center. It also was best in the northeast quadrant, extending in a pie-shaped wedge to near the clearcut center. In addition to the northeast quadrant, a shallow wedge of increased regeneration also was observed in the southwest quadrant in many clearcuttings. Westerly portions of most clearcuttings tended to have fewer conifer seedlings than other portions.

Adequately stocked clearcuttings, although having less conifer regeneration near the center and in westerly portions than elsewhere, nevertheless had seedlings distributed in adequate numbers throughout. One of these was a 60-acre (24-ha) unit that had well over a visually estimated 1000 seedlings per acre (2471/ha) along the eastern edge and about 500 seedlings per acre (1235/ha) near the center. Another clearcut unit had at least 3000 seedlings per acre (7413/ha) with fairly even distribution throughout.

Cutting units rated as failures generally had a few conifer seedlings near the forest edge and an occasional seedling elsewhere. Density was rated at less than 100 seedlings per acre (247/ha).

The adequacy rating in each clearcutting tended to be similar, in general, between the first and last surveys. On high sites such as those on the Experimental Forest, reinvasion of disturbed ground is rapid and complete, and only the first conifer seed crop stocks the ground. Seeds from subsequent crops fall into microsites already occupied by conifer seedlings or competing vegetation. In a case history of six clearcuttings intensively sampled to quantify plant succession, total plant species numbered 50 to 57 per acre (124 to 141/ha) and total number of plants 75,000 to 215,000 per acre (185,325 to 531,265/ha) 5 years after cutting and windrow and burn site preparation.[2] Mean number of plants was 142,721 per acre (352,664/ha) with standard error of 21,496 per acre (53,116/ha). Mortality of ponderosa pine and white fir seedlings is high the first growing season and decreases rapidly thereafter. After 2 to 3 years, early seedling losses from the principal causes—drought, damping-off fungi, cutworms, and birds—are mostly over. Should overtopping by competing vegetation take place, most conifer seedlings, including ponderosa pine, persist in partial shade and even live for a few years. For these reasons, regeneration counts did not change much during the 19 years of evaluation.

Mortality of ponderosa pine and California white fir seedlings followed the general pattern of large losses the first year and a rapid decrease in mortality in successive years. The few incense-cedar and Douglas-fir seedlings that got started in the clearcuttings generally survived well.

Browsing by deer, although of minor consequence overall, affected height growth of some ponderosa pine seedlings. After site preparation by either broadcast burning or windrow and burning, large amounts of nutrients that have accumulated in living and dead organic material are released. This flush of nutrients affects the woody and herbaceous vegetation for the first year and also the second to a lesser extent. The chief effect is that the tender shoots and new leaves of nearly *all* plants become palatable, including manzanita, tanoak, poison-oak, and others that usually are untouched. Not only is the new vegetation nutritious, it also is succulent. Evaporation of moisture from the soil and transpiration by vegetation are relatively low. Plants in the clearcuttings, especially in the first year, remain green in late fall when most other vegetation elsewhere is hard and dry.

Deer browsing in the clearcuttings increased as summer ended. By late October 1965, only nubbins of lesser vegetation remained, but pine seedlings were yet untouched. Browsing damage was noted first on November 24. By December 30, more than 80 percent of ponderosa pines in three units near the ridgetop on the northeast aspect were damaged. Apparently, the ridgetop was a travel route for deer moving to lower elevations. In some cutting units, damage was spotty, groups of seedlings were browsed in places; in others, single pines or a

[2] Unpublished data on file, Pacific Southwest Forest and Range Experiment Station, Redding, California.

line of pines were damaged. Few seedlings were killed by deer and nearly all developed a new leader the next year. By losing a year of height growth, browsed seedlings had one strike against them in the race for dominance with the woody shrubs.

Height growth of ponderosa pine seedlings ranged from good to poor depending on many variables, but mostly on the degree of competition from woody shrubs or other conifer seedlings. Fourteen-year-old pine seedlings, growing in dense manzanita, for example, ranged in height from 4 to 14 ft (1.2 to 4.3 m) with less leader growth each year as their general health and vigor declined.

Woody Shrubs

Stocking of whiteleaf manzanita and deerbrush was high initially and continued high throughout the study (*fig. 7*). For the compartments broadcast burned in 1965, density of whiteleaf manzanita and deerbrush averaged 6523 9-year-old plants per acre (16,118/ha) (McDonald 1976a). In all or portions of most other compartments, shrub density was high or even extremely high. In the compartments rated as adequately stocked with conifer seedlings, several contained solid masses

Figure 7—The western portion of a 10-acre clearcutting in 1964 (*A*) and 1977 (*B*) on the Challenge Experimental Forest, Yuba County, California. In *B*, a few clumps of hardwoods and occasional ponderosa pines grow among the shrubs. The uncut forest has become a seed-tree cutting.

of shrubs from which conifer saplings protruded. In portions of several other clearcuttings, pine seedling density was high and shrub density low. In one compartment, however, shrub density was uniformly low throughout.

Hardwoods

Hardwood regeneration consists of stump sprouts that number up to 100 per stump, seedling sprouts that average 1 to 4 per root crown, and seedlings that usually are single stems. Relative height growth potential is high for stump sprouts, moderately low for seedling-sprouts, and low for seedlings. Stocking of hardwood regeneration after clearcutting was spotty and density was low. Stump sprouts were scattered throughout and, where present, outgrew all other vegetation. Distribution of seedling sprouts was extremely clumpy and tended to be concentrated where a California black oak or tanoak seed tree had been before cutting. Hardwood seedlings were scanty, consisting of a few tanoak seedlings near the forest edge, and a few Pacific madrone seedlings scattered throughout. Birds apparently transported seeds and were responsible for the wider distribution of madrone.

MANAGEMENT IMPLICATIONS

Slash Disposal and Site Preparation

The condition of the seedbed has a major influence on regeneration. A detailed study of seedbeds formed in the broadcast-burned compartments showed that while broadcast burning improved a seedbed not otherwise disturbed, mechanical disturbance (windrowing) developed the best seedbed for establishment of ponderosa pine seedlings (Neal 1975).

One criterion of good seedbed condition is absence of competing vegetation. Seeds of woody shrubs stored in the duff and upper soil layers (Quick 1956) may number more than 2 million per acre (4,942,000/ha). Mechanical site preparation scoops much of these layers into windrows where they usually are burned. Broadcast burning, however, leaves substantially more of an area with at least some litter and duff and generates conditions that are near ideal for the breaking of dormancy of some shrub seeds. For varnishleaf ceanothus (*Ceanothus velutinus* var. *laevigatus*) in western Oregon, one study indicated that broadcast burning of logging slash stimulated a larger number of seeds to germinate (average, 8305/acre) than did burning of mechanically piled slash (average, 1568/acre) (Gratkowski 1962).

A disadvantage of broadcast burning is that it almost always takes place after the conifer seeds, which are intended to restock the land, have fallen. Consequently, a substantial amount of seeds, or even seedlings if the burn is delayed too long, are consumed. But if slash is windrowed, the area (seedbed) usually is prepared during the summer before seedfall begins. The only seeds burned are those in the windrows. Mechanical site preparation, moreover, destroys or disrupts almost all of the deer mouse habitat, especially breeding and resting areas. Although the windrows provide shelter, they lack food, and mice foraging in the open spaces between them are susceptible to predators. In broadcast burning, nearly all deer mouse habitat remains intact and the population is affected little. In some instances, therefore, an intact deer mouse population is forced to feed on a seed supply greatly reduced by burning.

Broadcast burning frequently affects the species of woody shrub that becomes most abundant. Noted visually in other compartments on the Experimental Forest and mentioned in the literature (Gibbens and Schultz 1963), ceanothus species are favored more by broadcast burning, and manzanita more by mechanical site preparation. Because manzanita grows slightly slower in height and crown width in the environment of the Experimental Forest, mechanical site preparation could give ponderosa pine seedlings a slight short-term advantage in the windrowed areas. Long-term gains are questionable, however, because manzanita is more severe in its competitive effect on height of pine reproduction than ceanothus (Dahms 1950).

Of the many variables in this silvicultural system, broadcast burning probably contributes most to the variation of natural regeneration in clearcuttings. This form of burning can be an effective technique for slash disposal. And, when the weather cooperates, direct costs can be low. Broadcast burning, however, does not modify the environment enough to adequately reduce the competitors and consumers common to the forest types in this study.

Regeneration

To be successful, natural regeneration of mixed-conifer and hardwood stands in clearcuttings in the northern Sierra Nevada depends on several interacting variables. Slash must be largely removed from the area and a large expanse of bare mineral soil present. Seedfall must be heavy, well distributed, and prompt, or favorable microsites will already be occupied by undesirable vegetation. Once on the ground, the seed must not be consumed by animals and birds nor destroyed by fire, frost, or other agents. Conifer seedlings need to become established and grow rapidly, free of severe competition from conifer counterparts or woody vegetation.

Different species of conifer seedlings fare differently in clearcuttings. The bright, warm, open environment favors the establishment of ponderosa pine, and California white fir to a lesser extent, but not Douglas-fir or incense-cedar. Few seedlings of the latter two species are present in the clearcuttings today, and then only near the shaded forest edge.

Although the initial clearcut environment is suited to establishment of California white fir seedlings, high mortality indicates that the subsequent environment is less than ideal. Part of the reason could be that white fir is not as competitive with the woody shrubs of the Experimental Forest as is ponderosa pine. Maximum daily water potential of 4-year-old white fir seedlings in a clearcutting having moderate shrub density was −22 bars; for ponderosa pine of similar age, −17 bars.[3] This difference probably should be expected. California white fir cannot control stomatal aperture as well as ponderosa pine. Also, white fir is at the lower end of its elevational range.

As stated earlier, the seedbed produced by broadcast burning is highly variable. Seedfall, both in frequency and magnitude, also is variable. Both are mostly beyond the practical control of the silviculturist. Windrowing and burning slash gives more control over seedbed variability. Rodents, chiefly deer mice, can be more of a problem after broadcast burning than after windrowing. Rodenticides can be used, but population dynamics are such that control often is limited in duration and effectiveness. Seeds of woody shrubs are numerous after both broadcast burning and windrow and burning. These seeds and resultant plants plague the forester almost from the time the conifer seeds germinate.

The strong adverse effect of the woody shrubs continues after conifer seedlings have become established. The shrubs' many adaptations to a wide range of environments are expressed in their physiology and morphology (McDonald 1982). Shrubs tend to grow taller and wider than young pines, and often are better suited to attain dominance in early succession than are conifer seedlings.

Repeated observations have shown that the clumpy distribution of conifer seedlings in clearcuttings is partly a function of chance. Seedlings that survive to become crop trees become established in areas where woody shrubs are few or lacking. These areas often are large enough to allow several or even a group of trees to become established. Elsewhere, occasional seedlings grow tall enough to survive before shrub crowns coalesce. Where the woody shrubs are dense and vigorous, few conifer seedlings survive. Those that do, suffer from insects and drought and seldom achieve the productivity inherent in the site. Controlling the density and vigor of woody shrubs is one part of the clearcut and natural seed system that can be practical, although costly.

Recommendations

For the silvicultural package as a whole, many variables affect the successful establishment and early growth of conifer seedlings. Most cannot be controlled sufficiently to ensure regeneration success with the degree of timing and consistency demanded by foresters. Even with additional expenditures for rodent control and other measures, variation of natural regeneration likely will be high. Although the variation may not be beyond the control of the manager, knowledge of its presence is valuable.

To the forest manager, time is money. Delays in establishing a forest stand or in achieving a high growth rate are costly. A more reliable way to avoid these delays in regenerating clearcuttings and to gain better stocking control is to windrow and burn slash, plant conifer seedlings, and control woody shrubs at plantation age 2 and again at age 4, as necessary.

[3]Unpublished data on file, Pacific Southwest Forest and Range Experiment Station, Redding, California.

REFERENCES

Arvanitis, L. G.; Lindquist J.; Palley, M. **Site index curves for even-aged young-growth ponderosa pine of the westside Sierra Nevada.** Calif. For. and Forest Prod. 35; 1964. 8 p.

Barrett, James W. **A record of ponderosa pine seed flight.** Res. Note PNW-38. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1966. 5 p.

Curtis, James D.; Foiles, Marvin W. **Ponderosa pine seed dissemination into group clearcuttings.** J. For. 59:766-767; October 1961.

Dahms, Walter G. **The effect of manzanita and snowbrush competition on ponderosa pine reproduction.** Res. Note 65. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1950. 3 p.

Eyre, F. H., editor. **Forest cover types of the United States and Canada.** Washington, DC: Society of American Foresters; 1980. 148 p.

Fowells, H. A.; Schubert, G. H. **Seed crops of forest trees in the pine region of California.** Tech. Bull. 1150. Washington, DC: U.S. Department of Agriculture; 1956. 48 p.

Gashwiler, J. S. **Further study of conifer seed survival in a western Oregon clearcut.** Ecology 51:849-854; Late summer 1970.

Gibbens, R. P.; Schultz, A. M. **Brush manipulation on a deer winter range.** California Fish and Game 49(2):95-118; April 1963.

Gratkowski, Henry John. **Heat as a factor in germination of seeds of *Ceanothus velutinus* var. *laevigatus* T. & G.** Corvallis, OR: Oregon State University; 1962. 122 p. Dissertation.

Hall, Dale O. **Slash disposal burns in pine patch-cuttings ... a dialogue.** Res. Note PSW-148. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1967. 6 p.

Ingles, Lloyd G. **Mammals of the Pacific states.** Stanford, CA: Stanford Univ. Press; 1965. 506 p.

Jameson, E. W., Jr. **Some factors affecting fluctuations of *Microtus* and *Peromyscus*.** J. Mammal. 36(2):206-209; May 1955.

Kraemer, James F.; Hermann, Richard K. **Broadcast burning: 25-year effects on forest soils in the western flanks of the Cascade Mountains.** Forest Sci. 25(3):427-439; September 1979.

McDonald, Philip M. **Cutting a young-growth, mixed-conifer stand to California Forest Practice Act standards.** Res. Paper PSW-89. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1973. 16 p.

McDonald, Philip M. **Forest regeneration and seedling growth from five major cutting methods in north central California.** Res. Paper PSW-115. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1976a. 10 p.

McDonald, Philip M. **Shelterwood cutting in a young-growth, mixed-conifer stand in north central California.** Res. Paper PSW-117. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1976b. 16 p.

McDonald, Philip M. **Seed dissemination in small clearcuttings in north-central California.** Res. Paper PSW-150. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 5 p.

McDonald, Philip M. **Adaptations of woody shrubs.** Hobbs, S. D.; Helgerson, O. T., editors. Proceedings of a workshop on reforestation of skeletal soils, 1981 November 17-19; Medford, OR. Corvallis, OR: Forest Research Laboratory; 1982; 21-29.

McDonald, Philip M.; Schimke, Harry E. **A broadcast burn in second-growth clearcuttings in the north central Sierra Nevada.** Res. Note PSW-99. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1966. 6 p.

Neal, Robert L., Jr. **Ponderosa pine seeding trials in west-side Sierra Nevada clearcuts: some early results.** Res. Note PSW-305. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1975. 8 p.

Quick, Clarence R. **Viable seeds from the duff and soil of sugar pine forests.** Forest Sci. 2:36-42; March 1956.

Roe, Arthur L.; Beaufait, William R.; Lyon, L. Jack; Oltman, Jerry L. **Fire and forestry in the northern Rocky Mountains—a task force report.** J. For. 69(8):464-470; August 1971.

Roy, Douglass F. **Douglas-fir seed dispersal in northwestern California.** Tech. Paper 49. Berkeley, CA. Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1960. 22 p.

Schmidt, W. D.; Shearer, R. C. **Ponderosa pine seed—for animals or trees?** Res. Paper INT-112. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1971. 14 p.

Sundahl, William E. **Slash and litter weight after clearcut logging in two young-growth timber stands.** Res. Note PSW-124. Berkeley, CA. Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1966. 5 p.

Wetherbee, Frank, U.S. Fish and Wildlife Service, Bureau of Sport Fisheries, Sacramento, CA. Personal communication. 1964.

McDonald, Philip M. **Clearcutting and natural regeneration ... management implications for the northern Sierra Nevada.** Gen. Tech. Rep. PSW-70. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 11 p.

In the young-mature mixed-conifer and hardwood forests of north-central California, a dense and persistent hardwood understory competes with the conifers for space, nutrients, and water. Clear-cutting with intensive site preparation often is the most appropriate silvicultural regeneration method. This report, the result of 20 years of research on the Challenge Experimental Forest in Yuba County, California, evaluates one approach to clearcutting. Topics discussed are broadcast burning, windrow and burning, seedfall, rodents, woody shrubs, seedling stocking, and early growth of conifers. Variation in seedbed and seedfall, uncertainty of amount of rodent damage, and competition from woody shrubs can result in inconsistent and unpredictable amounts of natural reproduction. Windrow and burning of slash and planting of conifer seedlings are recommended alternatives to broadcast burning and natural seeding.

Retrieval Terms: cutting methods, slash disposal, natural regeneration, ponderosa pine

General Technical Reports A 13.88:PSW-71, A 13.88:PSW-72, A 13.88:PSW-73 are separate and are just to the right of this volume.

12