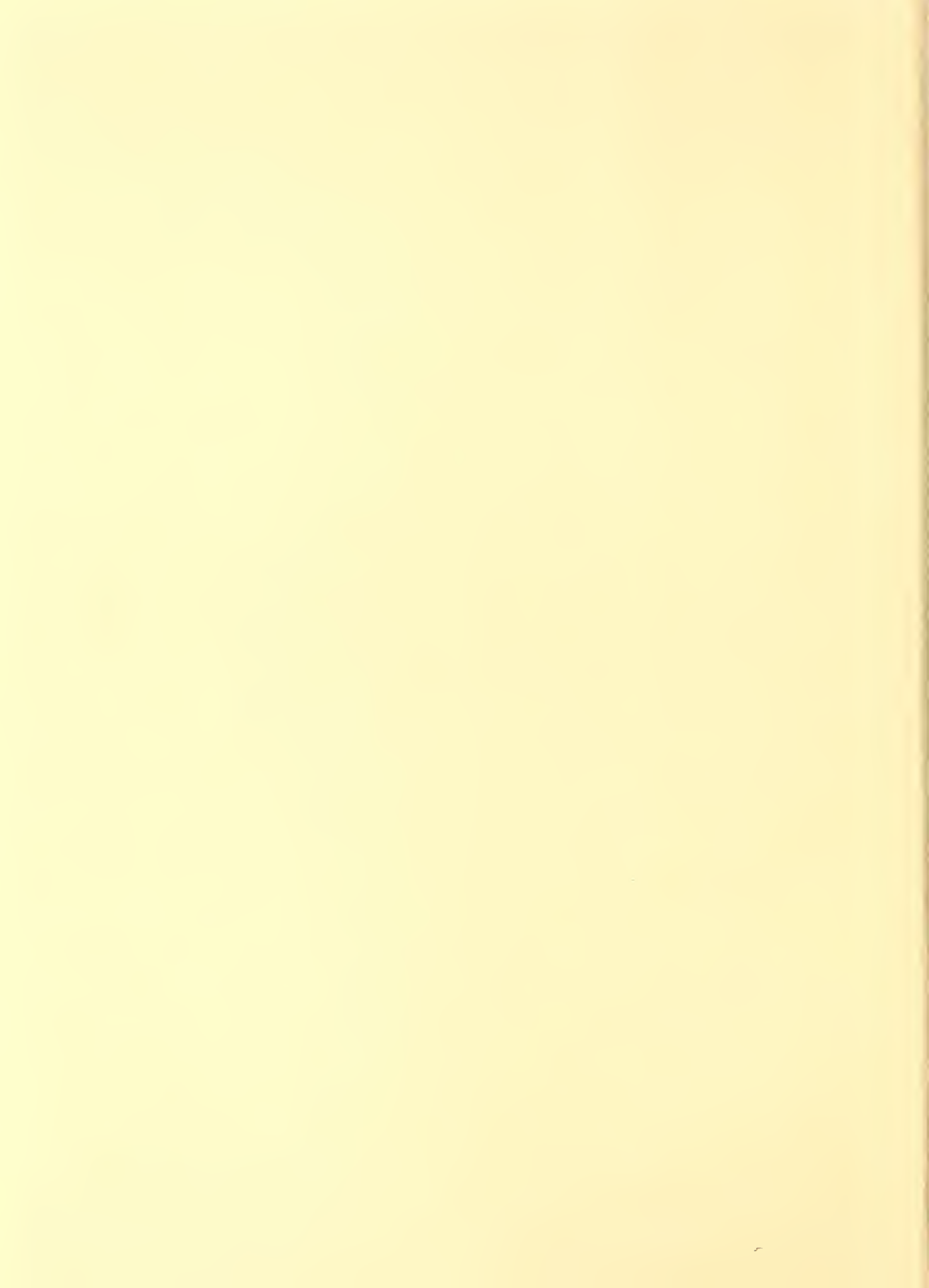# PINYON-JUNIPER WOODLANDS OF THE GREAT BASIN:

Distribution, Flora, Vegetal Cover

Paul T. Tueller, C. Dwight Beeson, Robin J. Tausch,
Neil E. West, and Kenneth H. Rea

PINYON-JUNIPER WOODLANDS OF THE GREAT BASIN:
Distribution, Flora, Vegetal Cover

**Paul T. Tueller, C. Dwight Beeson, Robin J. Tausch,
Neil E. West, and Kenneth H. Rea**

THE AUTHORS

PAUL T. TUELLER is a Professor of Range Ecology at the Renewable Resources Center, University of Nevada, Reno.

C. DWIGHT BEESON is a former Graduate Research Assistant who wrote his M. S. thesis under Dr. Tueller's direction. He is currently employed in Alturas, California.

ROBIN J. TAUSCH is a Graduate Fellow and Research Assistant in the Department of Range Science, Utah State University, Logan.

NEIL E. WEST is Professor, Department of Range Science, Utah State University, Logan.

KENNETH H. REA is a former Graduate Research Assistant and Research Technician in the Department of Range Science, Utah State University, Logan. He is currently Ecologist, Environmental Studies Section, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

ACKNOWLEDGMENTS

RESEARCH SUMMARY

The distribution of the pinyon-juniper woodlands of the Great Basin has been mapped from LANDSAT-1 satellite photography. Dot grid analysis of this map indicates that about 17.6 million acres (7.1 million ha) of this woodland are found in the Great Basin. The distribution map was field checked and floristic data were systematically taken at 482 stands on 66 of the approximately 200 mountain ranges in the study area.

A list of 240 positively identified species of vascular plants is provided to help other workers initiate studies in the pinyon-juniper vegetation type.

In this study, variations in total vegetal cover are related to latitude, longitude, and elevation. Vegetal cover increases strongly with elevation and slightly with latitude. Longitudinal patterns are related to increases in average elevation. The greatest average vegetal cover is found in the higher, central portion of the Great Basin. Sorting of the tree species is due more to elevation than latitude or longitude. Junipers occupy the lower, drier elevations, whereas pinyons increase at higher elevations. Double-needle pinyon is found more frequently in the southeastern Great Basin where more of the rainfall comes during the summer.

CONTENTS

INTRODUCTION

The pinyon-juniper woodland vegetation type has historically provided forage (for both livestock and big game), fenceposts, pine nuts, Christmas trees, firewood, charcoal, mine props, and railroad ties. Pinyon-juniper woodlands are becoming increasingly valued for their watershed, esthetic, and recreational values (Gifford and Busby 1975). Planning for the conflicting multiple uses of these woodlands requires better ecological understanding than is now available. Previous research in these woodlands has been confined to small, selected areas. Lack of a broad perspective has limited understanding of how the results of previous studies relate to each other. Without knowledge of variation within the pinyon-juniper type, we cannot efficiently extrapolate management successes to other areas or avoid actions that have produced known shortcomings at one or a few sites.

A cooperative research program designed to provide a synecological stratification of these woodlands was initiated in 1972 by the Department of Range Science at Utah State University; the Renewable Resources Center at the University of Nevada, Reno; and the Intermountain Forest and Range Experiment Station. The overall objective of this program is to gain a broad synecological perspective of pinyon-juniper woodlands in the Great Basin. The distribution of the woodland type, its flora, and variations in the vegetal cover and tree dominants are discussed in this report. Subsequent reports will deal with other aspects of floristic variation, successional patterns, subdivisions of the pinyon-juniper type and their relations to environmental factors, and localized applications of vegetation classification units to land use problems.

PREVIOUS WORK

The literature on pinyon-juniper woodlands has been itemized by West and others (1973), Aldon and Springfield (1973), and Smith and Schuster (1975). Various chapters in the compilation edited by Gifford and Busby (1975) provide an excellent overview of land use history and of current taxonomic, autecologic, and synecologic understanding of this ecosystem. Therefore most references to earlier research will be deferred until our discussion.

A consideration of the extent of pinyon-juniper woodland is, however, appropiate. This woodland is thought to cover from 43 to 100 million acres (17 to 40 million ha) in the southwestern United States. The vast difference in estimated acreage depends on the definition of the pinyon-juniper vegetation type. The smaller figure is based on Küchler's (1964) map of the potential (climax or pristine) juniper-pinyon woodlands centered in the Four Corners States plus Nevada. An estimate of 76 million acres appears in Senate Document 199 (Clapp 1936). Allred (1964) gives the highest estimate. The Clapp and Allred estimates include juniper that has invaded other areas since the activities of white men altered the original vegetation.

West and others (1975) estimate that about 30 million acres (12.5 million ha) of these woodlands occur in the Basin and Range Physiographic Province. This amounts to about 38 percent of the total area of pinyon-juniper dominated vegetation in the United States. Most of this pinyon-juniper is in the Great Basin portion of the Basin and Range Province. Thus, both in terms of area and proportion of the total pinyon-juniper woodland, the Great Basin has major amounts of this kind of vegetation.

STUDY AREA

The study area chosen lies within the boundaries of the Great Basin portion of the Basin and Range Province (Hunt 1974), and encompasses 100,437,610 acres (40,663,000 ha) (fig. 1). Sampling for this study was restricted to areas where stands of vegetation were occupied by any one or any combination of the species *Pinus edulis*, *Pinus monophylla*, and *Juniperus osteosperma*.

The topography of the Great Basin typically consists of linear, north-south oriented mountain ranges separated from one another by dry desert valleys (Thornbury 1965). The ranges vary in size, but are commonly 50 to 75 miles (80 to 120 km) long and 6 to 15 miles (10 to 25 km) wide (Lustig 1969). The mountain ranges rise 6,000 to 14,000 feet (1,800 to 4,300 m) above sea level. The details of the geologic origin of the Basin and Range Province are described by Noland (1943) and Hunt (1974). The rocks which make up these ranges are largely of sedimentary origin, but many ranges consist partly of wholly of igneous rocks (Hunt 1974).

Basic climatic patterns in this area are described by Wernstedt (1960) and Houghton (1969). An outline of the overall floristics of the Great Basin is discussed in Cronquist and others (1972). The general vegetation patterns in relation to environment are discussed by Billings (1951) and Young and others (1976).

Figure 1.--Map showing the major mountain ranges in the studied portion of the Great Basin. The lower mountain boundaries are the same as those in Cronquist and others (1972) The 66 mountain ranges chosen for this study are unshaded and numbered. See table 1 for the names of the studied mountain ranges.

Mounta ... lding our study area map (fig. 1)
into 1-minu ... ngitude. A random list of map
intersectio ... ? approximately 200 mountain ranges
(Cronquist ; ... ed intersections were chosen for
study. The ... tineraries planned so that the
more souther ... eason and the more northerly later.
Thus, the ma ... each location. These mountain
ranges, comp ... t Basin mountain ranges, were
sampled duri ... able 1).

Plots w ... one of the cardinal directions
and were pla ... lown the slope from a baseline of
6,560 ft (2, ... n common to pinyon-juniper wood-
lands over m ... made site selection objective
and facilita ... plots characterizing average
situations i ... e. This strategy gave each part
of the major ... d on elevation) equal opportunity
to appear in ... data set (Whittaker 1973). The strategy also provided for the
sampling of a wide variety of pinyon-juniper woodlands. Previous studies have been
concentrated on subjectively selected sites with high productivity or with potential
for vegetation manipulation to achieve high forage production (Daniel and others 1966).

The criteria used to determine the lowest and uppermost plots on each mountain
side were that a plot had to contain at least 25 pinyon and/or juniper trees per hectare
(about 10 per acre). Of these, at least one tree had to be of the mature size-age-form
class (Blackburn and Tueller 1970). These criteria kept the samples from extending
into brushlands or grasslands being invaded by a few small, young trees and concen-
trated our sampling on sites where woodland can definitely persist. Sampling was
further restricted to those sites which showed no evidence of recent fires, extensive
tree cutting, chaining, or cabling, in order to reduce part of the secondary succes-
sional variability encountered.

Northerly slope exposures sampled were limited to the slopes of the north ends of
mountain ranges or hill systems; southerly exposures to the slopes of the south ends of
mountain ranges. East and west exposures were sampled near the center of the mountain
ranges. Plot locations were marked on the largest scale U.S. Geological Survey maps
available (at least 1:25,000). The upper and lower boundaries of the pinyon-juniper
woodland for the entire mountain slope were also marked on these topographic maps to
aid in checking the accuracy of the woodland distribution map to be made from LANDSAT-1
imagery.

Two levels of sampling were employed--rapid and detailed. In the "rapid" approach
macroplots of approximately 66 by 165 feet (20 by 50 m) were paced off with the long
axis positioned perpendicular to the slope contour. The macroplots were located at
660-feet (200-m) intervals up the broadest, most even slope available. Within each
plot, all plant species were listed in one of four categories: trees, shrubs, grasses,
and forbs. With grasses and forbs combined, the resulting three categories represented
the layers visible in the physiognomy of the stands. Each of the original four cate-
gories was considered separately to assess the relative dominance of each species. A
dominance rating was assigned each species in the macroplot (Beeson 1974). A cover

Table 1.--*The mountain ranges sampled, showing the year the sample was taken, the number of plots sampled, the map code used in figure 1, and the type of sampling employed.*

Mountain range	:	Year sampled	:	Number of plots sampled	:	Map code[1]	:	Type of sampling[2]
California								
Panamint Range		73		4		1		R
White Mountains		72		7		2		D
Idaho								
Albion Mountains		73		2		3		R
Black Pine Peak		72		5		4		D
Sublett Range		73		2		5		R
Nevada								
Bald Mountain		74		6		6		R
Cherry Creek Range		72		6		7		R
Clan Alpine Range		72-73		3		8		R
Desatoya Range		72-73		6		9		R
Diamond Range		72		5		10		R
East Humboldt Range		72		6		11		D
Excelsior Range		72		4		12		D
Fish Creek Range		74		6		13		R
Fortification Range		72		4		14		R
Goose Creek Range		72		4		15		D
Grant Range		72		4		16		R
Highland Range		72		15		17		D
Kawich Range		73		5		18		R
Lower Egan Range		74		4		19		R
Lower Snake Range		72		6		20		R
McCullough Range		73		3		21		R
Monitor Range		72		10		22		D
Pequop Mountains		72		4		23		R
Pine Nut Range		73		8		24		R
Quinn Canyon Range		73		11		25		R
Roberts Creek Range		72		5		26		R
Ruby Mountains		72		4		27		R
Schell Creek Range		72		8		28		D

(con.)

Table 1.--Con.

Mountain range	Year sampled	Number of plots sampled	Map code[1]	Type of sampling[2]
Sheep Range	73	4	29	R
Shoshone Range	73	12	30	D
Silver Creek Range	74	6	31	R
Simpson Park Range	72	4	32	D
Spring Range	73	8	33	R
Spruce Mountain	74	5	34	R
Sulphur Springs Range	73	6	35	R
Toana Range	72	5	36	D
Toiyabe Range	72	9	37	D
Toquima Range	74	6	38	R
Upper Egan Range	74	4	39	R
Upper Snake Range	74	6	40	R
Virginia Range	73	5	41	R
Wassuk Range	73	9	42	R
West Humboldt Range	74	6	43	R
White Pine Mountains	72	5	44	R
Wilson Creek Range	72	4	45	R

Utah

Mountain range	Year sampled	Number of plots sampled	Map code[1]	Type of sampling[2]
Beaver Dam Mountains	73	5	46	R
Burbank Hills	72	2	47	D
Canyon Mountains	72	4	48	R
Confusion Range	72	4	49	D
Cricket Mountains	72	4	50	R
Deep Creek Range	73	8	51	R
East Tintic Mountains	72	5	52	R
Enterprise-Beryl Hills	72	7	53	D
House Range	74	4	54	R
Mineral Mountains	72	9	55	D
Needle Range	72-73	13	56	D
Oquirrh Mountains	72	4	57	R
Pavant Range	72	5	58	R
Pilot Range	72	9	59	D
Pine Valley Mountains	73	8	60	R
San Francisco Mountains	72	5	61	R
Sheeprock Mountains	74	2	62	R
Stansbury Mountains	72	4	63	R
Tushar Range	72	7	64	D
Wah Wah Mountains	72	8	65	R
West Tintic Mountains	72	5	66	R

[1] Map code is referenced to figure 1.
[2] R = rapid; D = detailed.

class rating was also assigned (Daubenmire 1959). A size-age-form class rating was assigned each individual tree on the macroplot (Blackburn and Tueller 1970). Further details of the "rapid" methodology, including collection of topographic and edaphic data, can be found elsewhere (Beeson 1974).

In the "detailed" level of sampling, the same plot size and methodology were used, but data were obtained from direct measurements using an expansion and intensification of the proviously described methodology. The 66 by 165 foot (20 by 50 m) macroplots were permanently marked. Four trees of each size-age-form class of each species situated closest to two predetermined points were measured. Crown spread of these trees in the widest and narrowest dimensions was recorded. Tree cover for the plot was estimated by taking an average of tree crown dimensions, computing elliptical area on the measured trees, and multiplying by the number of trees of each size-age-form class. Shrub crown cover was estimated to the nearest 2 percent (Daubenmire 1959) in randomly stratified 1 by 2 m microplots. Forb and grass basal cover was similarly estimated in 3 by 6 m plots located within the shrub sampling scheme. The "detailed" sampling approach is described more fully in Nabi (1978).

All mountain ranges sampled were selected by the same process. The 18 ranges sampled with "detailed" methodology were randomly selected from the larger set (table 1). The remainder were sampled with "rapid" techniques. The procedure for plot location was identical on all mountain ranges regardless of which sampling strategy was used. Plots were thoroughly searched for all plant species present under both "rapid" and "detailed" sampling strategies.

Taxonomic vouchers of plants were collected at each site with special attention given to sagebrush (*Artemisia* spp.). Specimens were checked for proper identification against vouchers at the Intermountain Herbarium, Utah State University. *Artemisia* specimens were segregated morphologically following the works of Brunner (1973) and Winward and Tisdale (1977). However, the more effective process of chromatographic differentiation was used to determine subspecies of *A. tridentata* as well as to confirm placement in other *Artemisia* taxa. The chromatographic procedures used were similar to those described by Hanks and others (1973). Vouchers specimens of all taxa are on file at Utah State University.

Vegetation Type Mapping

Pinyon-juniper woodlands were mapped during the winter of 1973-74, using LANDSAT-1 color-infrared composites (fig 2). Woodland boundaries for the entire study area were mapped to an approximate scale of 1:1,000,000 where 1 inch (2.5 cm) equals approximately 16 miles (26 km) on the ground. Areas of pinyon-juniper woodland as small as 62 acres (25 ha) were mapped. The pinyon-juniper vegetation type was identified by a reddish-orange color on the composites.

The low-elevation boundary of the woodland was easily mapped from summer color composites, but the upper boundary diffused into other, more infrared reflective vegetation types, making the pinyon-juniper difficult to map from photos taken during the growing season. The upper boundary was mapped using winter images taken when pinyon-juniper woodlands were the only infrared reflective vegetation type. All other types of vegetation were either dormant or covered with snow (Tueller and others 1975).

The extent of the pinyon-juniper woodland type in the Great Basin was determined from the completed map using a 256 dot/in^2 (150 dots/cm^2) grid. The total number of dots counted in the woodland was multiplied by an appropriate conversion factor to obtain acres or hectares per dot.

Figure 2.--A map of the pinyon-juniper woodlands of the Great Basin derived from LANDSAT-1 color-infrared imagery and field checking.

RESULTS AND DISCUSSION

Data Base

Sixty-six of the approximately 200 major mountain ranges in the Great Basin were visited and vegetation data were obtained at 482 plots (table 1 and fig. 1). These data, along with additional observations on vegetation boundaries, provided ground truth data for the mapping phase.

Type Map

A detailed map of the distribution of the Great Basin pinyon-juniper woodlands is provided in figure 2. This map is the most detailed and field-verified of any yet available for the pinyon-juniper vegetation type. The map should have many uses in inventory, planning, management, research, and teaching.

There is not complete congruence of the woodland boundaries shown on this map (fig. 2) with the lower boundaries of mountain ranges shown on the topographic-based map (fig. 1). The lack of congruence results from the woodland not occupying perfect belts around every Great Basin mountain range. In the northern Great Basin, pinyon-juniper woodland belts are narrower or lacking altogether on northern exposures. The woodland belt frequently diminishes on southern exposures in the southern Great Basin. East and west-facing woodland belts are not always at the same elevation or of the same width. In southwestern Utah and adjacent Nevada, valley bottoms are at higher elevations and a distinct change occurs from mountain-valley topography to rolling terrain. In these areas woodlands become continuous between ridges. Details of these differences in woodland and mountain range boundaries and their possible causes have already been discussed in West and others (1978).

Comparison of the location of pinyon-juniper boundaries on the map with boundary locations noted during field research allows us to estimate that less than 5 percent error exists; i.e., less that 5 percent of the boundary locations are delinated incorrectly from the LANDSAT-1 imagery. If areas of pinyon-juniper woodland were continuous, densities as low as 41 trees per hectare were visible on LANDSAT-1 color-infrared imagery. Areas of pinyon-juniper woodland as small as 62 acres (25 ha) were visible if there were at least 73 trees per hectare. A discontinuous area of pinyon-juniper having trees only on the lower slopes of many close ridges showed sufficient reflectance to be identified only when tree density exceeded 118 trees per hectare. Generally, a pinyon-juniper community larger than 25 ha with a density of about 75 trees per hectare can be identified on LANDSAT-1 color-infrared imagery.

The area of pinyon-juniper woodlands within the study area boundaries was estimated using the dot grid technique (table 2). This estimate is more that 4 million acres less than an estimate derived from planimetering the major forest-type overlay map (9-W) in Little (1971). This difference could be due to Little's inclusion of some higher mountain centers in his map and/or to his extension of the pinyon-juniper woodland into considerably more open juniper stands at the base of these mountains.

The differences betweeen our acreages and those available from the map on page 111 of Cronquist and others (1972) are less, probably due to Cronquist's distinction of the major mountain centers as "montane zone." The two maps cannot be compared precisely because of the extension of our study area further south than that given in Cronquist and others (1972). The map produced in this study provides more detail on the pinyon-juniper type boundary than theirs because of its larger scale.

Table 2.--*The extent of pinyon-juniper woodlands within the Great Basin, by state*

State	:	Acres	:	Hectares	:	Percent of total
Nevada		11,674,600		4,726,500		66.2
Utah		4,123,200		1,669,300		23.4
California		1,364,400		552,400		7.7
Arizona		298,300		120,800		1.7
Idaho		137,100		70,100		1.0
Total		17,653,600		7,139,100		100.0

Floristics

To help others initiate studies in pinyon-juniper woodlands, we have listed the 240 positively identified species of vascular plants which were found in our sample of Great Basin pinyon-juniper woodlands (table 3). An additional 127 specimens, nearly all annual forbs, could not be positively identified to the generic level because season of collection precluded obtaining specimens with the necessary taxonomic characters. This accounts for the 367 total number of species used in prior discussions (West and others 1978). The number of different species in a plot can be related to probability of sampling, size and height of mountain range, distance from adjacent mountains, and paleo-ecological influences, as well as present environmental variables (West and others 1978). The outstanding feature of the floristics of the pinyon-juniper woodland is the few species it has, considering the large area involved.

Of the positively identified taxa, a total of 5 were trees, 67 were shrubs and succulents, 46 were grasses, and 122 were forbs. Four percent of the total list were exotic (introduced); the remainder are native. None of the species identified were listed in the recent compilation of rare and endangered plant species (U.S. Congress 1976). All of the species are known to occur outside of pinyon-juniper woodland contexts.

Our sampling approach was designed to stress the most common conditions and perennial components of the woodlands of each mountain range. Larger numbers of samples, searches for atypical sites, and sampling earlier in the season would have resulted in the collection of more and rarer species and allowed identifiable vouchers of annuals to be obtained.

Table 3.--Plant species encountered in study and the percentage of the plots where each species was observed (constancy)

Scientific name and authority[1]	Common name[2]	Constancy
		Percent
TREES		
Juniperus osteosperma (Torr.) Little	Utah juniper	99.3
Juniperus scopulorum Sarg.	Rocky Mountain juniper	.5
Pinus edulis Engelm.	True pinyon pine	4.1
Pinus monophylla Torr. & Frem.	Single leaf pinyon pine	96.8
Pinus ponderosa Laws.	Ponderosa pine	.2
SHRUBS		
Amelanchier alnifolia Nutt.	Serviceberry	14.6
Artemisia arbuscula Nutt.	Low sagebrush	7.1
Artemisia frigida Willd.	Fringed sagebrush	.2
Artemisia ludoviciana Nutt.	Louisiana sagebrush	.7
Artemisia nova A. Nels.	Black sagebrush	26.3
Artemisia pygmaea A. Gray	Pigmy sagebrush	.5
Artemisia tridentata Nutt. ssp. *tridentata* Ward	Basin big sagebrush	28.5
Artemisia tridentata Nutt. ssp. *vaseyana* (Rydb.) Beetle	Mountain big sagebrush	46.7
Artemisia tridentata Nutt. ssp. *wyomengensis* Beetle	Wyoming big sagebrush	22.6
Atriplex canescens (Pursh.) Nutt.	Fourwing saltbush	2.7
Atriplex confertifolia (Torr. & Frem.) S. Wats.	Shadscale	2.2
Berberis repens Lindl.	Creeping barberry	3.7
Berberis fremontii Torr.	Fremont barberry	.2
Ceanothus greggii Gray	Mountain lilac	.7
Ceanothus sp. L.	Mountain lilac	.2
Ceratoides lanata J. T. Howell	Winterfat	3.1
Cercocarpus ledifolius Nutt.	Curl-leaf mountain mahogany	24.8
Cercocarpus montanus Raf.	Alder-leaf mountain mahogany	4.1
Chamaebatiaria millefolium (Torr.) Maxim	Fern bush	.7
Chrysothamnus greenei (A. Gray) Greene	Greenes rabbitbrush	.5
Chrysothamnus nauseosus (Pall.) Britt.	Rubber rabbitbrush	15.3
Chrysothamnus paniculatus (A. Gray) Hall	Desert rabbitbrush	.2
Chrysothamnus viscidiflorus (Hook.) Nutt.	Douglas rabbitbrush	47.2
Coleogyne ramosissima Torr.	Blackbrush	1.2
Cowania mexicana D. Dom.	Cliffrose	3.4
Dalea sp. Juss.	Indigo bush	13.6
Ephedra nevadensis S. Wats.	Mormon tea	.7
Ephedra viridis Coville	Mormon tea	11.7
Eriogonum microthecum Nutt.	Slenderbush eriogonum	43.6
Eriogonum sphaerocephalum Dougl.	Rock eriogonum	23.1
Eriogonum umbellatum Torr.	Sulfur eriogonum	1.5
Eriogonum spp. Michx.	Wild buckwheat	24.6
Fendlerella utahensis (S. Wats.) Heller	---	.5
Galium sp. L.	Bedstraw	.5
Glossopetalon nevadense Gray	Spiny greenbush	.2
Grayia spinosa (Hook.) Moq.	Spiny hopsage	2.9
Gutierrezia microcephala (DC.) Gray	Snakeweed	3.4
Gutierrezia sarothrae (Pursh) Britt. & Rusby	Snakeweed	33.3
Haplopappus linearifolius DC.	Narrowleaf goldenweed	.3
Haplopappus nanus (Nutt.) DC. Eaton	Dwarf goldenweed	1.5
Holodiscus dumosus (Hook.) Heller	Bush oceanspray	.5
Leptodactylon pungens (Torr.) Nutt.	Prickly phlox	18.7
Leptodactylon watsoni (A. Gray) Rydb.	---	.3
Lycium sp. L.	Wolfberry	.2
Prunus andersonii A. Gray	Anderson peachbrush	40.9
Peraphyllum ramosissimum Nutt.	Squawapple	4.1
Purshia glandulosa Curran	Desert bitterbrush	2.7
Purshia tridentata (Pursh) DC.	Antelope bitterbrush	6.8
Quercus gambelii Nutt.	Gambel oak	36.0
Quercus turbinella Greene	Shrub live oak	3.7
Rhus trilobata Nutt.	Skunkbrush sumac	1.0
Ribes cereum Dougl.	Gooseberry	.5

(con.)

Table 3.--(con.)

Scientific name and authority	Common name	Constancy
		Percent
Ribes montigenum McClatchie	Gooseberry current	5.6
Ribes velutinum Greene	Desert gooseberry	.2
Ribes sp. L.	Current gooseberry	7.1
Rosa woodsii Lindl.	Wild rose	1.2
Salvia sp. L.	Sage	.2
Sambucus racemosa L.	Elderberry	.2
Symphoricarpos albus L. (Blake)	Snowberry	1.5
Symphoricarpos longiflorus A. Gray	Longflower snowberry	11.2
Symphoricarpos oreophilus A. Gray	Mountain snowberry	8.5
Tetradymia canescens DC.	Gray horsebrush	4.6
Tetradymia glabrata A. Gray	Little horsebrush	15.6
Tetradymia sp. DC.	Horsebrush	1.2
Yucca brevifolia Engelm.	Joshua tree	.2
Opuntia acanthocarpa Engelm. & Bigel.	Buckhorn cholla	1.7
Opuntia polyantha Haw.	Plains prickly pear	3.6

GRASSES AND GRASSLIKE PLANTS

Agropyron cristatum (L.) Gaertn.	Crested wheatgrass	.5
Agropyron riparium Scribn. & Smith	Streambank wheatgrass	1.7
Agropyron saxicola (Scribn. & Smith) Piper	---	2.0
Agropyron smithii Rydb.	Western wheatgrass	1.0
Agropyron spicatum (Pursh) Scribn. & Smith	Bluebunch wheatgrass	30.7
Agropyron trachycaulum (Lin.) Malte.	Slender wheatgrass	2.4
Aristida fendleriana Steud.	Fendler three-awn	.5
Aristida longiseta Steud.	Red three-awn	1.5
Aristida sp. L.	Three-awn	.7
Avena fatua L.	Wild oats	.2
Bouteloua gracilis (H.B.K.) Lag.	Blue grama	4.9
Bromus marginatus Nees.	Big mountain brome	.7
Bromus rubens L.	Foxtail chess	2.7
Bromus tectorum L.	Cheatgrass	35.5
Carex sp. L.	Sedge	.2
Distichlis spicata Greene	Desert saltgrass	.2
Elymus cinereus Scribn. & Merr.	Wild rye	13.4
Elymus salina M. E. Jones	Salina wild rye	.2
Elymus sp. L.	Wild rye	.7
Festuca idahoensis Elmer	Idaho fescue	8.8
Festuca octoflora Walt.	Sixweeks fescue	1.5
Hilaria jamesii (Torr.) Benth.	Galleta	9.7
Hordeum jubatum L.	Foxtail barley	.2
Koeleria cristata (L.) Pers.	Junegrass	16.1
Leucopoa kingii (S. Wats.) Weber	Spike fescue	1.0
Melica bulbosa Geyer	Onion grass	.7
Melica stricta Bolnd.	Rock melic grass	1.5
Muhlenbergia torreyi (Kunth.) A.S. Hitch.	Ringgrass	.2
Munroa squarrosa (Nutt.) Torr.	Common false buffalograss	.2
Oryzopsis hymenoides (Roem. & Schult.) Ricker	Indian rice grass	53.5
Poa fendleriana (Steud.) Vasey	Muttongrass	9.5
Poa nervosa (Hook.) Vasey	Wheeler bluegrass	.7
Poa nevadensis Vasey	Nevada bluegrass	5.1
Poa sandbergii Vasey	Sandberg bluegrass	57.2
Poa sp. L.	Bluegrass	3.7
Sitanion hystrix (Nutt.) J. G. Smith	Squirreltail	79.8
Sporobolus cryptandrus (Torr.) A. Gray	Sand dropseed	.5
Stipa arida M. E. Jones	Needlegrass	1.2
Stipa columbiana Macoun	Columbia needlegrass	.2
Stipa comata Trin. & Rupr.	Needle-and-thread grass	16.3
Stipa coronata Thurb.	Needlegrass	.5
Stipa lettermani Vasey	Letterman needlegrass	.5
Stipa occidentalis Thurb.	Western needlegrass	16.3
Stipa speciosa Trin. & Rupr.	Desert needlegrass	1.7
Stipa thurberiana Piper	Thurber needlegrass	4.6
Stipa sp. L.	Needlegrass	1.7

(con.)

11

Table 3.--(con.)

Scientific name and authority	Common name	Constancy
		Percent
FORBS		
Abronia elliptica A. Nels.	Sandverbena	.5
Achillea millefolium L.	Yarrow	.5
Agoseris glauca (Pursh) Raf.	Page agoseris	1.7
Allium acuminatum Hook.	Tapertip onion	3.2
Antennaria rosea Greene	Rose pussytoes	2.2
Arabis holboellii Hornem.	Rockcress	39.2
Aster sp. L.	Aster	2.2
Aster canescens Pursh	Aster	.5
Aster chilensis Nees.	Aster	.2
Astragalus beckwithii Torr. & Frem.	Beckwith milkvetch	1.0
Astragalus calycosus Torr.	---	5.4
Astragalus casei A. Gray	---	6.1
Astragalus mollissimus Torr.	Thompson locoweed	1.7
Astragalus purshii Dougl.	Pursh locoweed	14.1
Astragalus whitneyi A. Gray	---	3.2
Astragalus sp. L.	Locoweed, Milkvetch	10.4
Brassica sp. L.	Mustard	.2
Balsamorhiza hirsuta Nutt.	Hairy balsamroot	.2
Balsamorhiza hookeri Nutt.	Hooker balsamroot	3.9
Balsamorhiza sagittata (Pursh) Nutt.	Arrowleaf balsamroot	15.8
Calochortus sp. Pursh	Mariposa lily	4.6
Castilleja linariaefolia Benth.	Wyoming paintbrush	2.7
Castilleja chromosa A. Nels.	Indian paintbrush	9.0
Caulanthus crassicaulis (Torr.) S. Wats.	Thickstem wild cabbage	4.1
Chaenactis douglasii (Hook.) Hook. & Arn.	Chaenactis	10.5
Chaenactis sp. DC.	Chaenactis	2.5
Cirsium sp. Adans.	Thistle	1.2
Collinsia parviflora Dougl.	Blue eyed mary	10.7
Comandra pallida A. DC.	Bastard toadflax	3.4
Cordylanthus sp. Nutt.	Birdbeak	.2
Crepis acuminata Nutt.	Tapertip hawk's beard	15.1
Crepis occidentalis Nutt.	Western hawk's beard	1.2
Cryptantha bakeri (Greene) Payson	Cryptantha	2.2
Cryptantha confertifolia (Greene) Payson	---	2.2
Cryptantha flavoculata (A. Nels.) Payson	---	13.9
Cryptantha nana (Eastw.) Payson	---	7.8
Cryptantha sp. Lehm.	---	3.4
Delphinium sp. L.	Larkspur	1.7
Descurainia pinnata (Walt.) Britton.	Tansymustard	6.3
Erigeron aphanactis (A. Gray) Green	Fleabane daisy	8.5
Erigeron argentatus A. Gray	---	5.6
Erigeron compositus Pursh	Fernleaf fleabane	.2
Erigeron sp. L.	---	6.3
Eriogonum caespitosum Nutt.	Mat wildbuckwheat	18.5
Eriogonum racemosum Nutt.	Redroot wildbuckwheat	4.1
Eriogonum ovalifolium Nutt.	Cushion wildbuckwheat	11.7
Eriogonum microthecum Nutt.	Slenderwild buckwheat	3.9
Eschscholzia californica Cham.	Calif. poppy	.5
Euphorbia albomarginata Torr. & Gray	Whitemargin spurge	1.5
Euphorbia ocellata Dur. & Hilg.	Spurge	.2
Galium sp. L.	Bedstraw	1.0
Geranium sp. L.	Geranium	1.0
Gilia aggregata (Pursh) Spreng.	Skyrocket gilia	3.4
Gilia congesta Hook.	Ballhead gilia	.5
Gilia leptomeria A. Gray	Gilia	12.4
Halogeton glomeratus (Bieb.) C. A. Meyer	Halogeton	.5
Haplopappus acaulis (Nutt.) A. Gray	Stemless goldenweed	6.8
Haplopappus stenophyllus A. Gray	---	8.8
Hedeoma nanum (Torr.) Briq.	Mock pennyroyal	.2
Hymenopappus filifolius Hook.	Fineleafhymenopappus	.5
Hymenoxys acaulis (Pursh) Parker	Stemless hymenoxys	4.6
Iva axillaris Pursh	Poverty sumpweed	5.8

Table 3.--(con.)

Scientific name and authority	Common name	Constancy
		Percent
Lappula sp. Moench.	Stickseed	7.1
Lepidium perfoliatum L.	Clasping pepperweed	2.7
Lepidium pubescens Desv.	Pepperweed	9.7
Lesquerella kingii S. Wats.	King's bladderpod	2.9
Leucelen ericoides (Torr) Greene	---	1.7
Linum lewisii Pursh	Lewis flax	1.5
Lithosperum ruderale Dougl.	Wayside gromwell	4.9
Lomatium sp.	---	.5
Lupinus alpestris A. Nels.	Mountain lupine	11.9
Lupinus argenteus Pursh	Silvery lupine	.7
Lupinus excubitus M. E. Jones	Inyo lupine	1.0
Lupinus sp. L.	Lupine	5.8
Lygodesmia spinosa Nutt.	Thorn skeletonweed	8.3
Machaeranthera canescens (Pursh) A. Gray	Hoary machaeranthera	13.1
Machaeranthera leucanthemifolia (Greene) Greene	Machaeranthera	13.1
Mammillaria sp. Haw.	Cushion cactus	2.4
Mentzelia albicaulis Dougl.	Whitestem blazing star	1.2
Mimulus densus Grant	Monkeyflower	1.5
Orobanche multiflora Nutt.	Broomrape	.2
Oxalis sp. L.	Woodsorrel	.5
Pedicularis centranthera A. Gray	Dwarf lousewort	4.1
Penstemon eatoni A. Gray	Eaton penstemon	1.0
Penstemon deustus Dougl.	Scabland penstemon	2.2
Penstemon hymilis Nutt.	Low penstemon	2.0
Penstemon pachyphyllus A. Gray	Thickleaf penstemon	6.6
Penstemon palmeri A. Gray	Palmer penstemon	3.7
Penstemon thompsoniae (A. Gray) Rydb.	Thompson penstemon	1.2
Penstemon sp. Mitch.	Penstemon	7.8
Petalostemon searlsiae A. Gray	Searls prairie clover	1.2
Petradoria pumila (Nutt.) Greene	Rocket goldenrod	5.1
Petrophytum caespitosum (Nutt.) Rydb.	Tufted rockmat	2.0
Phacelia sp. Juss.	Phacelia	3.9
Phlox austromontana Cov.	Desert phlox	3.2
Phlox diffusa Benth.	Spreading phlox	25.6
Phlox hoodii Rich.	Hood's phlox	13.4
Phlox longifolia Nutt.	Longleaf phlox	23.1
Phlox stansburyi (Torr) Heller	Stansbury phlox	23.1
Phlox muscoides Nutt.	Phlox	.5
Physaria chambersii Roll.	Twinpod	3.2
Physaria newberryi A. Gray	Newberry twinpod	2.0
Plantago sp. L.	Plantain	.7
Prunus emarginata (Dougl.) Walp.	Bitter cherry	.5
Psoralea juncea Eastw.	Scurfpea	.2
Salsola kali L.	Russian thistle	.7
Senecio intergerimus Nutt.	Columbia groundsel	2.9
Senecio multilobatus Torr. & Gray	Lobeleaf groundsel	11.9
Spergularia marina (L.) Griseb.	Saltmarsh sandspurry	5.6
Spergularia sp. J. & C. Presl.	Sandspurry	1.0
Sphaeralcea ambigua A. Gray	Desert globemallow	.2
Sphaeralcea caespitosa M.E. Jones	Tufted globemallow	2.4
Sphaeralcea coccinea (Pursh) Rydb.	Scarlet globemallow	3.7
Sphaeralcea parviflora A. Nels.	Globemallow	1.0
Stanleya pinnata (Pursh) Britton	Desert princesplume	1.2
Strepthanthus cordatus Nutt.	Heartleaf twistflower	7.1
Taraxacum officinale Weber	Dandelion	.5
Tragopogon sp. L.	Goatsbeard	.2
Vicia americana Muhl.	American vetch	.5
Vigueria annua (M. E. Jones) Blake	Annual goldeneye	.2
Viola sp. L.	Violet	.2
Zigadenus paniculatus S. Wats.	Foothill death camas	2.2

[1]According to Holmgren and Reveal (1966).

[2]According to Beetle (1970). Dash indicates no published common name available.

Variation in Total Vegetal Cover

Total vegetal cover for the 66 plots sampled at the detailed level varied from 9 to 80 percent. Average total vegetal cover for these plots was greater than 35 percent for about half of the mountain ranges sampled (table 4). Figure 3 shows that higher average vegetal cover is concentrated on the high plateau of central Nevada, the plateau's extensions toward southwestern Utah, and the higher elevation ranges such as the White Mountains of California-Nevada and the Deep Creek Mountains along the Utah-Nevada border. Woodlands on the mountain ranges with lower average elevation and/or lower latitudinal position have less average vegetal cover. The northernmost pinyon-juniper woodlands, in southern Idaho, have higher average total vegetal cover than would be expected from the low elevation of the woodlands there. In this instance, latitude strongly compensates for elevation.

Table 4.--*Average total vegetal cover of each mountain range in the "detailed" sample and relative cover of juniper and pinyon by aspect*

State and mountain range	Average total vegetal cover	All aspects Juniper	All aspects Pinyon	North aspect Juniper	North aspect Pinyon	East aspect Juniper	East aspect Pinyon	South aspect Juniper	South aspect Pinyon	West aspect Juniper	West aspect Pinyon
California											
White Mountains	31.5	10	90	4	96	--[1]	--[1]	27	73	0	100
Idaho											
Black Pine Peak	41.9	100	0	--[1]	--[1]	100	0	100	0	100	0
Nevada											
East Humboldt Range	34.9	45	55	--[1]	--[1]	4	96	83	17	48	52
Excelsior Range	23.9	0	100	0	100	0	100	0	100	0	100
Goose Creek Range	25.4	100	0	--[1]	--[1]	100	0	100	0	100	0
Highland Range	32.6	43	57	37	63	34	66	58	42	39	61
Monitor Range	50.0	12	88	2	98	8	92	19	81	18	82
Schell Creek Mountains	37.2	46	54	21	79	41	59	67	33	70	30
Shoshone Range	40.7	13	87	4	96	0	100	10	90	6	94
Toana Range	39.4	55	45	100	0	43	57	23	77	57	43
Toiyabe Range	48.4	24	76	2	98	33	67	0	100	7	93
Utah											
Confusion Range	26.3	48	52	0	100	69	31	--[1]	--[1]	27	73
Enterprise-Beryl Hills	35.8	70	30	61	39	97	3	65	35	82	18
Garrison Hills	32.4	84	16	68	32	100	0	--[1]	--[1]	--[1]	--[1]
Mineral Mountains	30.5	63	37	99	1	50	50	60	40	49	51
Needle Range	34.1	40	60	35	65	46	54	49	51	36	64
Pilot Range	43.2	45	55	45	55	47	53	37	63	49	51
Tushar Range	27.1	64	34	53	47	65	35	58	42	100	0

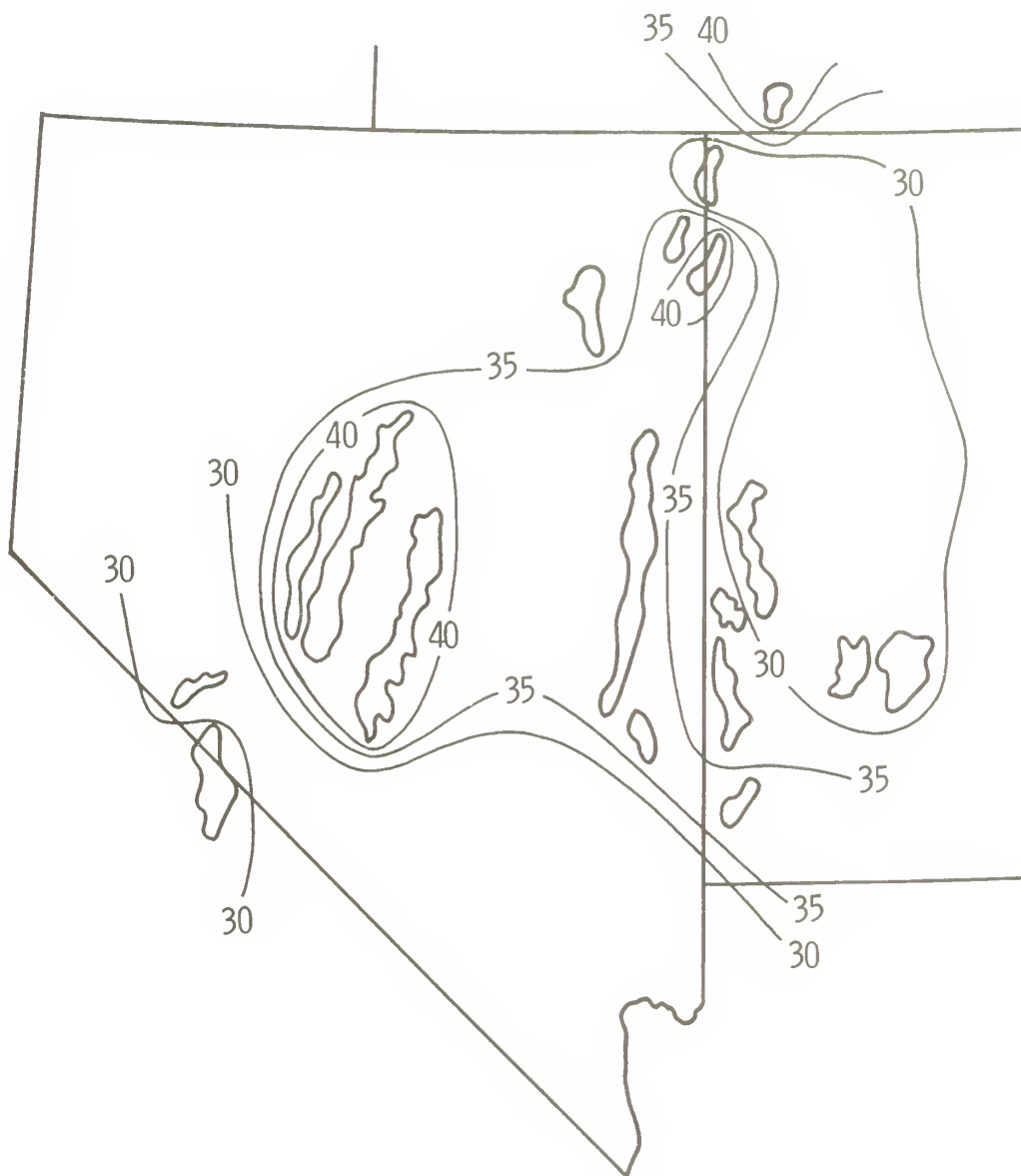[1]Plots on this aspect were not available, thus none were sampled.

Figure 3.--Map showing the 18 mountain ranges sampled at "detailed" level and isolines of the average total vegetal cover (percent) on these ranges. Average total vegetal cover for each mountain range is given in table 4.

The total vegetal cover per plot increased steadily as elevation rose from 1,800 to 2,200 m (fig. 4). The change in vegetal cover was insignificant between 2,200 and 2,600 m. All of the 1,600 m plots (2) were located at Black Pine Peak, Idaho, near the northernmost limits of the study area. Thus these plots involve cooler temperatures and more mesic sites. The only 2,800 m plot was located on the White Mountains on a site with rocky, shallow soil that could not support much vegetation.
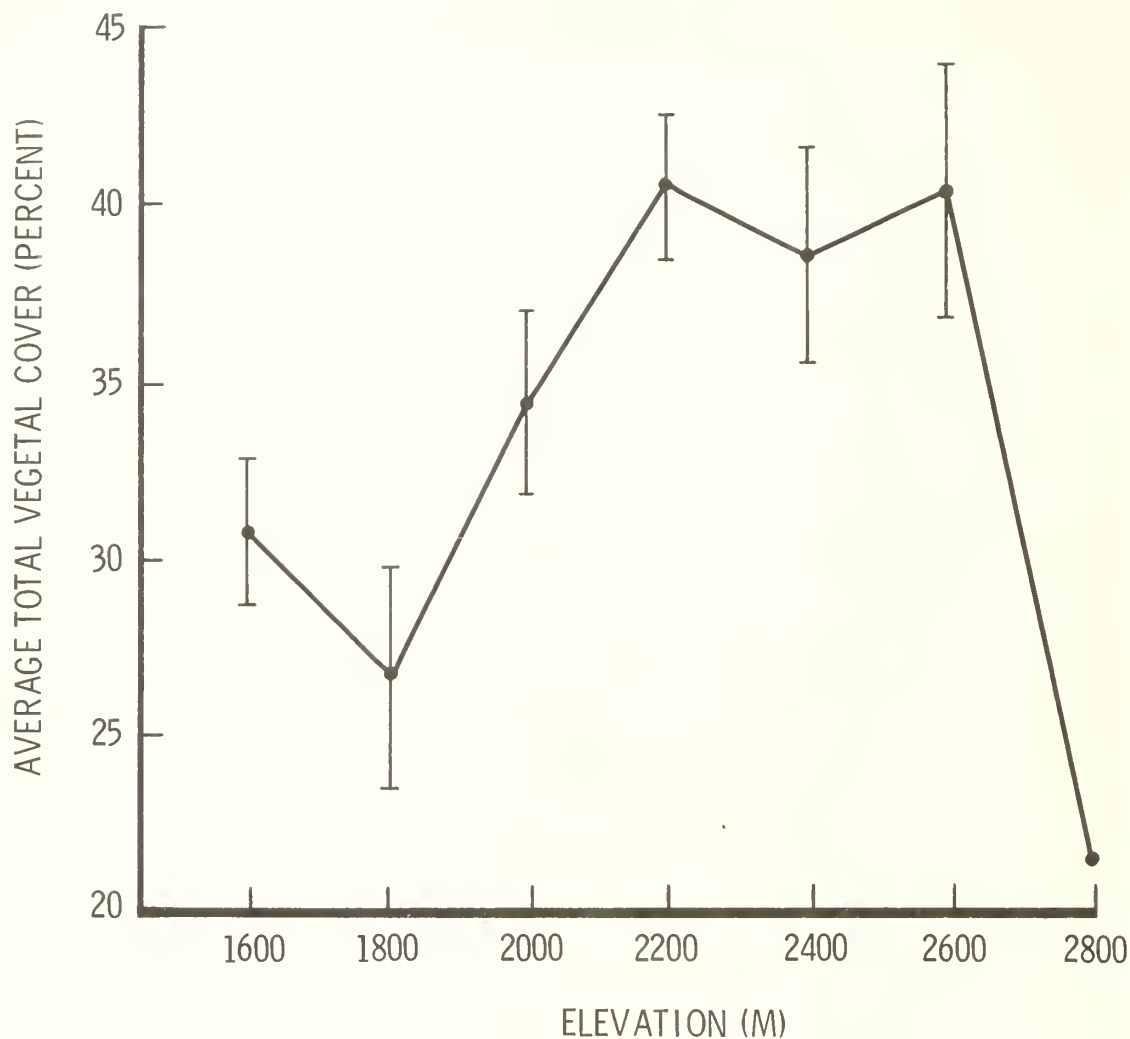
Figure 4.--Relationship of average total vegetal cover to elevation in woodlands sampled on the 18 mountain ranges with "detailed" data. Vertical bars represent one standard error. There is not a standard error bar at 2,800 meters because only one plot was available.

Variation in Tree Distribution and Dominance

The trees are usually the first organisms thought of in describing the pinyon-juniper vegetation type. It therefore seems worthwhile to consider the variation in tree distribution and dominance.

Figure 5 shows that Utah juniper occurs alone only along the northern boundary of the study area and in a few places in the Bonneville Basin of western Utah. Pinyon occurs alone only in the Excelsior Range along the California-Nevada border. Mixtures of pinyon and juniper occur throughout the rest of the study area.

Legend:
- Pinus monophylla
- P. m. and Juniperus osteosperma
- P. edulis and J. o.
- J. o.
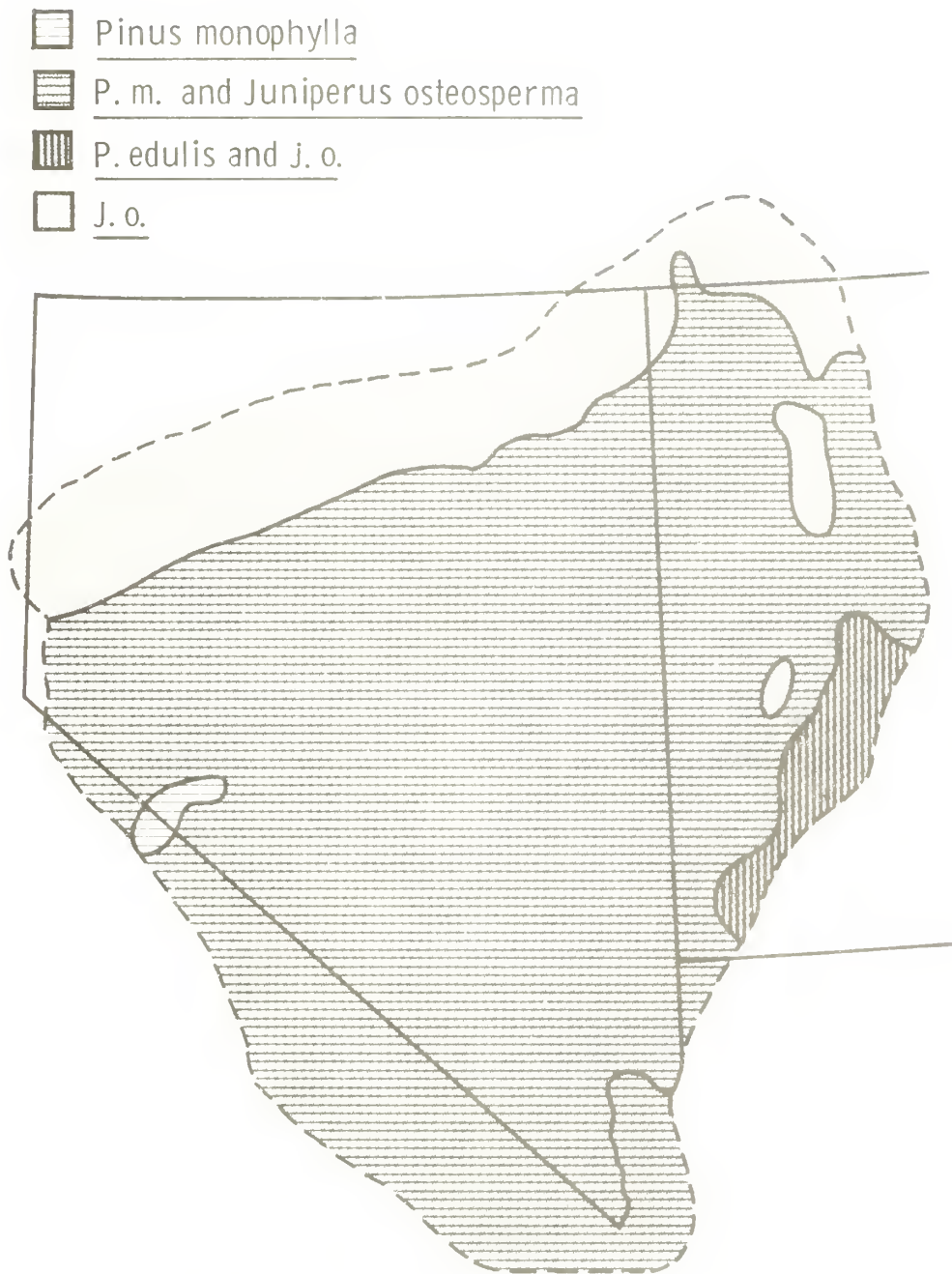
Figure 5.—Distribution of the three major tree species in the pinyon-juniper woodlands of the Great Basin.

The variation in tree dominance was assessed on the 18 mountain ranges on which detailed data were collected by dividing the percent cover of either juniper or pinyon by the total tree cover and multipling by 100 (table 4).

The average relative percent cover contributed by either pinyon or juniper trees shows a definite geographical distribution pattern in the Great Basin (fig. 6). The lowest average relative percent cover of juniper occured in southwestern and central Nevada. Juniper tends to dominate the woodlands in and near the Salt Lake Desert in
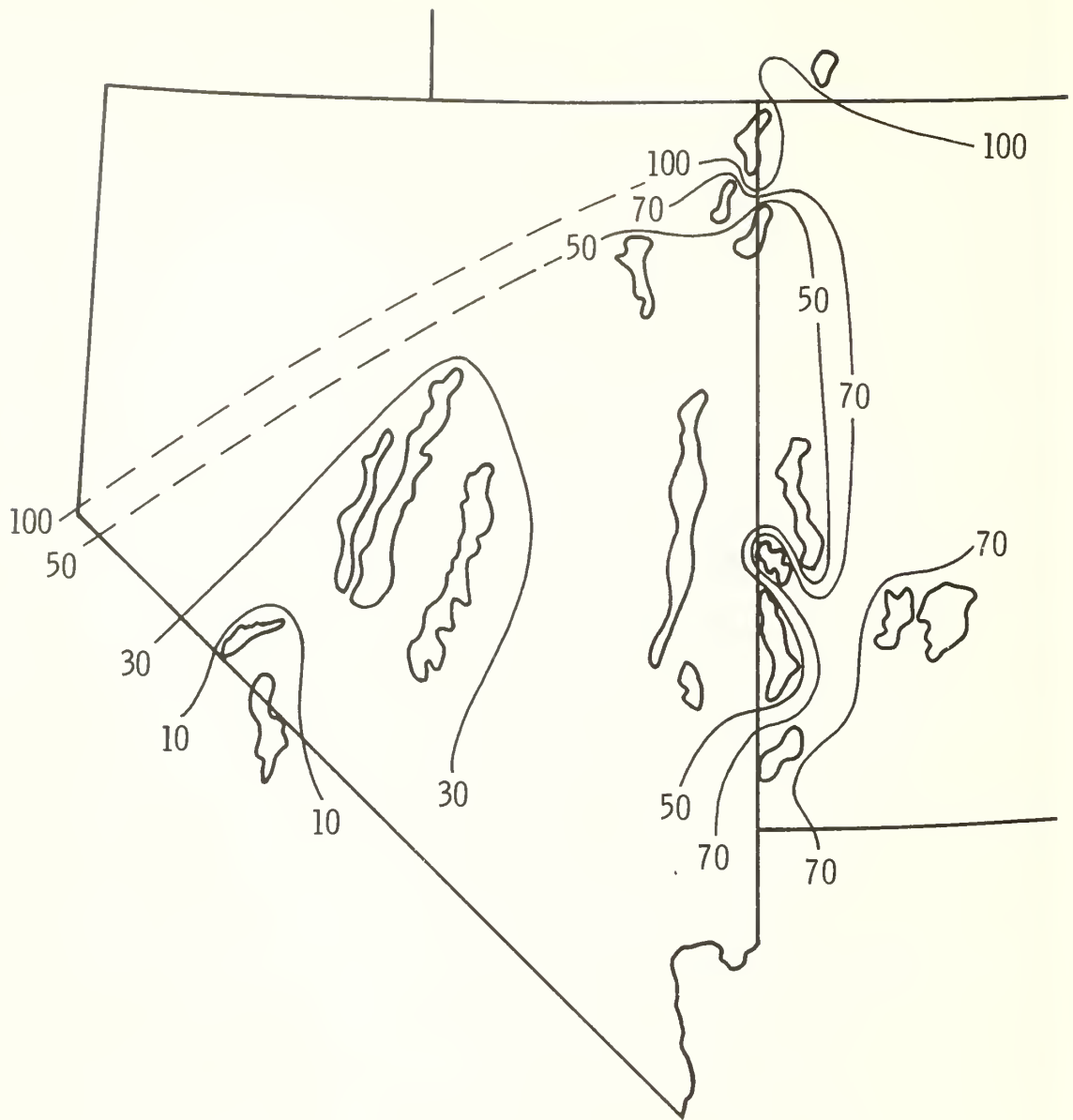
Figure 6.--*Map showing the 18 mountain ranges sampled at "detailed" level and isolines of the average percent cover of juniper relative to average total tree cover on these cover on these ranges. The average values for the mountain ranges are listed in table 4.*

western Utah, where the mountain ranges are only moderately high. The most northerly mountain ranges, such as the Goose Creek Range in northwestern Utah and Black Pine Peak Range in Idaho, contain predominantly pure stands of juniper trees. Many unsampled mountain ranges located in northern Nevada are also dominated by or contain only juniper (West and others 1978).

The plots were stratified according to their elevational intervals, and the average relative percent cover of pinyon and juniper was computed for each elevational interval. The results show that at 1,600 m juniper is completely dominant (100 percent

relative cover) and at 2,600 m pinyon is completely dominant (fig. 7). As elevation increases the relative percent cover of pinyon increases, while the relative percent cover of juniper decreases. At an elevation of 2,000 to 2,200 m the average relative percent cover of both species is about equal.

When these relative cover data are divided on the basis of slope exposures (table 4), the result show some small differences probably due to the modification of climate encountered on different exposures. On the south and east exposures the relative percent cover contributed by juniper is slightly higher at high elevations, although the difference is not statistically significant. The slight difference is probably due to warmer temperatures and effectively drier soils. On north and west aspects the average relative percent cover contributed by pinyon is slightly increased at lower elevations, apparently due to cooler, moister sites encountered. An exception is the White Mountain Range of California where the relative percent cover of pinyon is high even at the lower elevations. This apparently results from the combination of warmer temperatures and of overall aridity of this mountain range, particularly at lower elevations (St. Andre and others 1965).
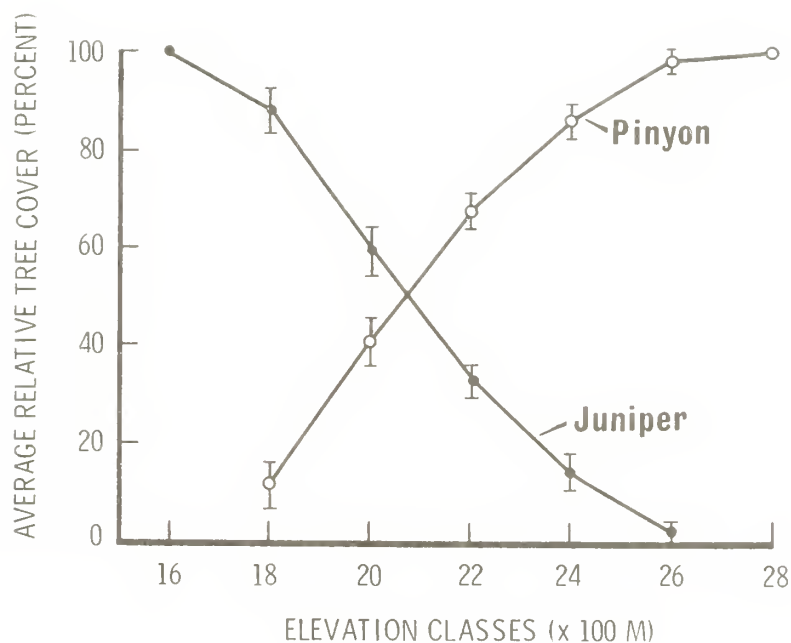
Figure 7.--The average relative cover (percent) of pinyon and juniper for plots of each elevational interval. Vertical bars represent one standard error. There are no bars for 1,600 and 2,800 meters because only one plot was available at these elevations.

In the central and southern Great Basin, where low temperatures are not likely to be a major controlling factor (West and others 1978), relative composition of tree species varies with longitudinal changes in seasonal moisture distribution (fig. 8). As the amount of summer precipitation (July-September) increases from west to east (Stidd 1967), the relative amount of juniper increases. Where summer precipitation exceeds about 3 inches (8 cm), single-needle pinyon is gradually replaced by true pinyon.
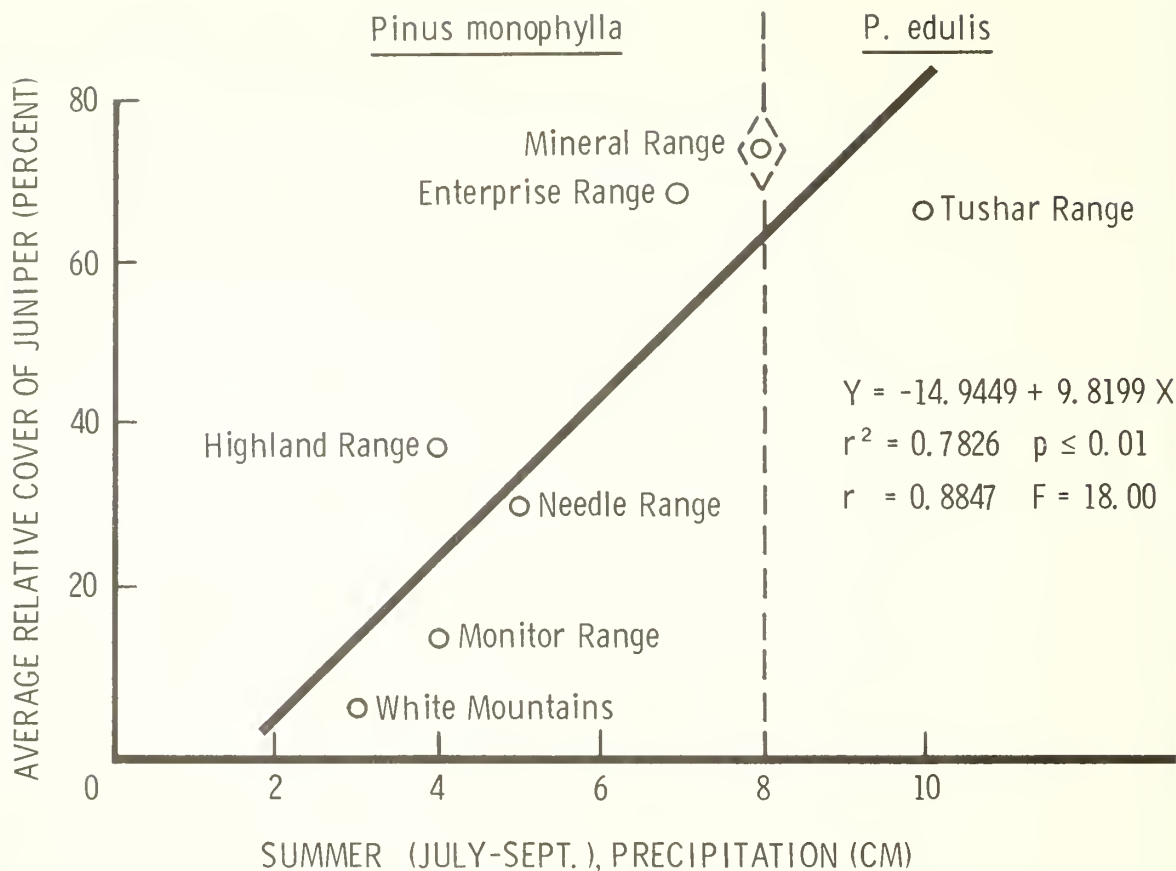
Figure 8.--*Relationship of relative juniper tree cover to amount of summer precipitation, derived from Visher (1966).*

CONCLUSIONS

The map of the pinyon-juniper vegetation type in the Great Basin provided in this study should more accurately depict the location of these woodlands than previously available maps. This increased accuracy is due to this map's small scale and objectively derived boundaries based on LANDSAT-1 imagery. The map shows that pinyon-juniper woodlands occupy 17.6 million acres (7.1 million ha) in the study area, about two-thirds of which occur in Nevada.

A floristic list of 240 positively identified species was obtained from sampling the woodland vegetation on 482 plots on 66 mountain ranges. This list could help other workers begin vegetation studies in Great Basin pinyon-juniper woodlands.

The proportion of pinyon and the total vegetal cover were found to increase more with elevation than with change in longitude or latitude. Dominance by juniper is associated with lower elevations and with increasing proportions of precipitation coming during the summer. The replacement of single-needle pinyon by double-needle pinyon at higher elevations is also associated with the southeasterly trend toward more summer precipitation. Higher average total vegetal cover is associated with higher altitudes and more northerly latitudes.

PUBLICATIONS CITED

Aldon, E. F., and H. W. Springfield, Jr.
  1973. The southwestern pinyon-juniper ecosystems: a bibliography. USDA For. Serv.
    Gen. Tech. Rep. RM-4, 20 p. Rocky Mt. For. and Range Exp. Stn., Ft. Collins, Colo.
Allred, B. W.
  1964. Problems and opportunities on U.S. grasslands. Am. Hereford J. 54:70-72, 132.
Beeson, D. W.
  1974. The distribution and synecology of Great Basin pinyon-juniper. M.S. thesis,
    Univ. Nev., Reno. 91 p.
Beetle, A. A.
  1970. Recommended plant names. Wyo. Agric. Exp. Stn. Res. J. 31, 124 p.
Billings, W. D.
  1951. Vegetational zonation in the Great Basin of western North America. *In* Les
    Bases Ecologiques de la Regeneration de Zones Arides, p. 101-122, U.I.S.B., Paris.
Blackburn, W. H., and P. T. Tueller.
  1970. Pinyon and juniper invasion in black sagebrush communities in east-central
    Nevada. Ecology 51:841-848.
Brunner, J. R.
  1973. Observations on *Artemisia* in Nevada. J. Range Manage. 25:205-208.
Clapp, E. H.
  1936. The major range problems and their solution: a resume *In* The western range:
    a great but neglected natural resource. U.S. Senate Doc. 199:1-621.
Cronquist, A., A. H. Holmgren, N. H. Holmgren, and J. L. Reveal.
  1972. Intermountain flora: vascular plants of the Intermountain West, U.S.A.,
    Vol. 1, 270 p. Hafner Publ. Co., New York.
Daniel, T. W., R. J. Rivers, H. E. Isaacson, E. J. Eberhard, and A. D. LeBaron.
  1966. Management alternatives for pinyon-juniper woodlands. A. Ecological phase:
    the ecology of the pinyon-juniper type of the Colorado Plateau and the Basin and
    Range Province. 242 p. Utah Agric. Exp. Stn.
Daubenmire, R. F.
  1959. A canopy-coverage method of vegetational analysis. Northwest Sci. 33:43-64.
Gifford, G. F., and F. E. Busby (eds.).
  1975. The pinyon-juniper ecosystem: a symposium. 194 p. Utah Agric. Exp. Stn.
Hanks, D. L., E. D. McArthur, R. Stevens, and A. P. Plummer.
  1973. Chromatographic characteristics and phylogenetic relationships of *Artemisia*
    section Tridentatae. USDA For. Serv. Res. Pap. INT-141, 24 p., Intermt. For. and
    Range Exp. Stn., Ogden, Utah.
Holmgren, A. H., and J. T. Reveal.
  1966. Checklist of the vascular plants of the Intermountain Region. USDA For. Serv.
    Res. Pap. INT-141, 24 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.
Houghton, J. G.
  1969. Characteristics of rainfall in the Great Basin. 205 p. Desert Res. Inst.,
    Univ. Nev. Syst., Reno.
Hunt, C. B.
  1974. Natural regions of the United States and Canada. 725 p. Freeman, San
    Francisco.
Küchler, A. W.
  1964. Manual to accompany the map--potential vegetation of the conterminous United
    States. Am. Geogr. Soc. Spec. Publ. 36, 111 p. With map, revised editions of 1965
    and 1966.
Little, E. L., Jr.
  1971. Atlas of United States trees. Vol. 1. Conifers and important hardwoods.
    USDA For. Serv. Misc. Publ. 1146, 209 p.
Lustig, L. K.
  1969. Trend-surface analysis of the Basin and Range Province, and some geomorphic
    implications. U.S. Geol. Surv. Prof. Pap. 500-D, 70 p.

Nabi, A.
  1978. Variation in successional status of pinyon-juniper woodlands in the Great
    Basin. M.S. thesis, Utah State Univ., Logan, 93 p.
Noland, T. B.
  1943. The Basin and Range Province in Utah, Nevada, and California. U.S. Geol. Surv.
    Prof. Pap. 197-D, 196 p.
Smith, M. S., and J. L. Schuster.
  1975. An annotated bibliography of juniper (*Juniperus*) of the western United States.
    ICASALS Publ. 75-2. Texas Tech. Univ.
St. Andre, G., H. A. Mooney, and R. D. Wright.
  1965. The pinyon woodland zone in the White Mountains of California. Am. Midl.
    Nat. 73:225-239.
Stidd, C. K.
  1967. The use of eigenvectors for climatic estimates. J. Appl. Meteorol. 6:255-264.
Thornbury, W. D.
  1965. Regional geomorphology of the United States. 505 p. John Wiley and Sons, New
    York.
Tueller, P. T., G. Lorain, R. Halvorson, and J. M. Ratcliff.
  1975. Mapping vegetation in the Great Basin from ERTS-1 imagery. Proc. 41st Annu.
    Meet. Am. Soc. Photogram., p. 338-370.
U.S. Congress.
  1976. Report on endangered and threatened plant species of the United States. Serial
    91-A. 94th Congr., 1st Sess., U.S. Govt. Print. Off.
Visher, S. S.
  1966. Climatic atlas of the United States. 596 p. Harvard Univ. Press, Cambridge.
Wernstedt, F. L.
  1960. Climatic fluctuations in the Great Basin, 1931-56. J. Range Manage. 13:173-178
West, N. E., D. R. Cain, and G. F. Gifford.
  1973. Biology, ecology, and renewable resource management of pigmy conifer woodlands
    of western North America: a bibliography. Utah Agric. Exp. Stn. Res. Rep. 12, 30 p.
West, N. E., K. H. Rea, and R. J. Tausch.
  1975. Basic synecological relationships in juniper-pinyon woodlands. *In* G. F. Giffor
    and F. E. Busby (eds.). The pinyon-juniper ecosystem: a symposium, p. 41-53. Utah
    Agric. Exp. Stn.
West, N. E., R. J. Tausch, K. H. Rea, and P. T. Tueller.
  1978. Phytogeographical variation within juniper-pinyon woodlands of the Great Basin.
    In K. T. Harper and J. L. Reveal (eds.). Intermountain biogeography: a symposium,
    p. 119-136. Great Basin Nat. Memoirs. no. 2. Brigham Young Univ., Provo, Utah.
Whittaker, R. H.
  1973. Direct gradient analysis. *In* R. H. Whittaker (ed.). Ordination and classifi-
    cation of communities. Vol. 5. Handbook of vegetation science, p. 7-75. W. Junk,
    The Hague, The Netherlands.
Winward, A. H., and E. W. Tisdale.
  1977. Taxonomy of the *Artemisia tridentata* complex in Idaho. Univ. Ida. For., Wildl.
    and Range Exp. Stn. Bull. 19, 15 p.
Young, J. A., R. A. Evans, and P. T. Tueller.
  1976. Great Basin plant communities--pristine and grazed. *In* R. Elston (ed.).
    Holocene environmental change in the Great Basin, p. 186-215. Nevada Archeol. Surv.
    Res. Pap. 6. Univ. Nev., Reno.

Tueller, Paul T., C. Dwight Beeson, Robin J. Tausch, Neil E. West, and
    Kenneth H. Rea.
        1979. Pinyon-juniper woodlands of the Great Basin: distribution, flora,
        vegetal cover. USDA For. Serv. Res. Pap. INT-229, 22 p. Intermt.
        For. and Range Exp. Stn., Ogden, Utah 84401.

        A map of the pinyon-juniper woodland type in the Great Basin was de-
    veloped from LANDSAT-1 imagery and from field checking of boundaries.
    A floristic list of 240 positively identified species associated with pinyon-
    juniper woodlands in the Great Basin is provided. Variations in total veg-
    etal cover and in the relative proportions of pinyon and juniper are related
   to latitude, longitude, and elevation.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field programs and research work units are maintained in:

Billings, Montana

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

INFLUENCE OF SOME ENVIRONMENTAL FACTORS ON INITIAL ESTABLISHMENT AND GROWTH OF PONDEROSA PINE SEEDLINGS

MICHAEL G. HARRINGTON AND RICK G. KELSEY
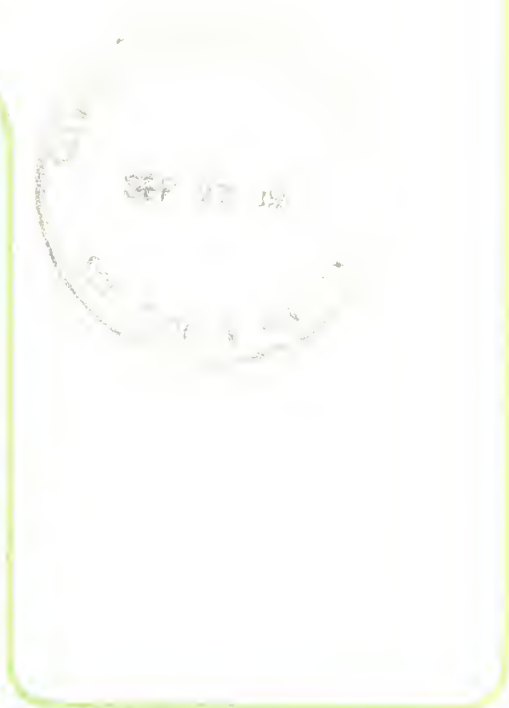
THE AUTHORS

MICHAEL G. HARRINGTON is currently a research forester with the Rocky Mountain Forest and Range Experiment Station, Tempe, Arizona. The research reported in this paper was conducted while he was employed at the Intermountain Station's Northern Forest Fire Laboratory, Missoula, Montana. Mr. Harrington received his B.S. in forestry (1970) and his M.A. in botany (1977) from the University of Montana, Missoula.

RICK G. KELSEY is currently a senior research associate with the Wood Chemistry Laboratory, Department of Chemistry, University of Montana. He received his B.S. (1970) and Ph.D. (1974) in forestry from the University of Montana.

ACKNOWLEDGMENTS

INFLUENCE OF SOME ENVIRONMENTAL FACTORS ON INITIAL ESTABLISHMENT AND GROWTH OF PONDEROSA PINE SEEDLINGS

Michael G. Harrington and Rick G. Kelsey

RESEARCH SUMMARY

Study plots were established to determine the effects of various environmental factors on ponderosa pine seed germination and initial seedling establishment and growth. A series of soil surface treatments were performed on plots in two locations: within or under the influence of overstory pine trees and in openings away from the pine influence. Seed germination was significantly greater in the opening plots. The overstory canopy and forest floor restricted the amounts of precipitation, light, and heat reaching the soil and probably decreased germination. Cutworms, birds, and small mammals caused the greatest seedling mortality. The largest seedlings occurred in the fire-treated plots. This was attributed to an increased nutrient supply and reduction of competition. Open-grown seedlings were larger than those growing under the overstory canopy. Amount of sunlight, degree of competition, and susceptibility to injury because of location appeared to be the major factors contributing to the seedling size differences. Because of abnormally high precipitation during the growing season, results may not be typical of average growing seasons.

CONTENTS

INTRODUCTION

Throughout much of its range, natural regeneration of ponderosa pine (*Pinus ponderosa* Laws.) is usually slow and frequently uncertain. In addition, obtaining artificial regeneration is difficult and often succeeds only after rather drastic measures are applied to the stand or to the site (Wellner 1970). Practices such as clearcutting, burning, and mechanical site preparation that enhance regeneration are questioned by the public (U.S. Congress 1970; USDA Forest Service 1970). Successful forest management requires either prompt regeneration following harvest cutting or the establishment of advanced reproduction. Knowledge of the intricate factors that affect the establishment of ponderosa pine reproduction is vital to obtain a complete understanding of regeneration problems.

Much research has been devoted to ponderosa pine regeneration problems (Hermann 1970). In most cases, these studies have failed to explain where in the pine stand the environmental factors most influential in pine regeneration are working and how various parts of the pine forest (canopies, litter, boles, etc.) affect them. The study reported here was undertaken to provide this information.

LITERATURE REVIEW

Natural restocking principally requires a good seed crop, a low rodent population, adequate available moisture, and bare mineral soil (Foiles and Curtis 1973). A bare mineral soil seedbed is thought to provide seeds and seedlings with more moisture, nutrients, and sunlight by reducing competing vegetation and by eliminating the dry, dense litter-duff layer. Baker (1951) and Fowells and Schubert (1951) observed that invading pines were more numerous on mineral soil seedbeds than on any other sites.

Removal of the organic layer is thought necessary because the litter and duff, having a lower thermal conductivity and volumetric heat capacity than mineral soil, raise daytime temperatures and lower nighttime temperatures at the litter-air interface (Cochran 1970). Furthermore, pine needles compact poorly and dry rapidly, allowing little moisture for seedling survival (Biswell 1973). Fisher (1935) found that ponderosa seed germination was best on bare or ash-covered soils and was poorest on duff-covered soils. Roe and Squillace (1950) found 8 times as many seedlings and Foiles and Curtis (1965) found 13 times as many pine seedlings on scarified mineral soil seedbeds as on duff-covered, natural soils.

Where mature ponderosa pine stands occur as open forest types, understory vegetation may be well established and vigorously compete with young pine seedlings. In the presence of grass associates, ponderosa pine reproduced at a very low rate compared to nearby areas lacking grasses (Baron 1962; Larson and Schubert 1969; Pearson 1934). Again, many authors advocate scarification of a site to reduce this competition (Fisher 1935; Foiles and Curtis 1965; Van Sickle and Hickmann 1959).

In some instances, intraspecific competition, especially between different age classes of ponderosa pine, can affect a stand. Saplings may reduce the vigor of the overstory enough to cause susceptibility to insect attack (Weaver 1955). Conversely, overstory pines very often leave understory seedlings and saplings stunted and severely weakened (Cooper 1960). Baker (1942) reported that in certain stands of 50 year-old pine, no reproduction existed and, generally, no vegetation whatsoever grew on the needle-strewn ground.

Once a seed has germinated and the seedling begins its struggle for survival, factors other than competition can be destructive. Because pine sites generally have high summer temperatures and low precipitation, the young trees, though drought resistant, can succumb to lack of moisture (Wellner 1970) and to insolation (Foiles and Curtis 1965). Frost heaving can uproot and kill young trees during their first winter. Livestock, big game, and porcupines feed on and often kill sapling pines (Black 1970) and trees of nearly all ages can be damaged by disease (Roth 1970). In addition, deep shade can adversely affect or even kill young trees (Pearson 1936).

Weaver (1943, 1951) states that fire played an important role in structuring the pine forests and permitted a continuation of their success on sites that are now stagnating or experiencing a species change due to fire exclusion. Cooper (1960) has also shown the values of periodic burning in ponderosa forests. Fire-treated sites had large trees, healthier regeneration, and a more open structure thereby providing less intra-specific competition than unburned sites. Biswell (1973) stated, "Ponderosa pine-grass lands are dependent on frequent surface fires for their health and stability and on the other hand, frequent surface fires are dependent on the plant communities that produce the fuels that carry fire, each being dependent on the other."

Because natural fire has often been shown to be beneficial, many feel that prescribed fire can likewise be an effective tool in ponderosa pine regeneration. Roe and Squilla (1950) have illustrated that prescribed fire markedly increased pine reproduction. In northwestern Montana, broadcast burning was followed by the establishment of twice as many seedlings as on unburned areas (Shearer and Schmidt 1970). Schultz and Biswell (1959) studied the effects of different seedbed preparations on ponderosa pine seedling emergence. They found that the sooner the seedfall occurred after burning, the more seedlings appeared. This was attributed to the deterioration of seedbed conditions through time, caused by the gradual buildup of competition, crusting and smoothing of the soil surface by rain and wind, and the accumulation of fallen needles.

Additional effects of fire upon ponderosa pine regeneration were demonstrated in a number of studies by Vlamis and associates. In the first study they showed that fire increased the amount of nitrogen and phosphates in the soil (Vlamis and others 1955). Later, their experiments revealed that ponderosa pine seedlings responded greatly, by increased growth, to artificially added nitrogen (Vlamis and others 1957), and to burned soils, presumably because of increased nutrients (Vlamis and others 1956).

STUDY AREA

The study site is 40 miles (64 km) northeast of Missoula and includes about 14 acres (5.6 ha) of level ground on the Blackfoot-Clearwater Game Range. The site is dominated by a ponderosa pine overstory with intermittent openings in the stand where pine regeneration is frequently abundant. Openings are of various shapes, and range in size from a few acres to small spaces between canopies. Pine regeneration is nearly absent in the understory.

The entire stand is located on valley-bottom alluvial soils (Clapp 1932), bound by large grass fields on the east and west and foothills on the north and south. The site is very good for ponderosa pine growth, with an index of 95 feet (29 m) in 100 years (Meyer 1938). However, close observation indicates that Douglas-fir is invading the understory and will probably become dominant. This site is therefore a Douglas-fir--pine grass habitat type (*Pseudotsuga menziesii/Calamagrostis rubescens, Agropyron spicatum* phase) (Pfister and others 1977).

Festuca scabrella is the dominant vegetative species in the large openings and the intermittent clearings within the stand. This species is also the major component of the understory vegetation beneath the pine as long as the trees do not form a continuous canopy. In heavily canopied areas, *Calamagrostis rubescens* is dominant.

Livestock grazing has not been a significant factor since the early 1950's and the impact of deer and elk has been minimal. Some of the largest pine trees were selectively logged in the early 1950's, but their removal did not influence this study.

METHODS

The field plots were established in the summer of 1974 and involved two major treatment groups. The first group of plots was situated within a ponderosa pine stand and contained six treatments. The second group was located in large openings near, but not under, the direct influence of the pine stand and had three treatments. Each treatment had three replications giving 27 total plots. Each plot was a square, 13 feet (4 m) on a side. The entire plot received a specific treatment and was fenced with 1/4-inch hardware cloth extending 30 inches (75 cm) above and 6 inches (15 cm) below the ground. A 12-inch (30-cm) strip of heavy-duty aluminum foil was secured along the top of the fence to discourage rodents from climbing into the plots.

A 10- by 10-foot square (3- by 3-m) was centered and permanently marked within each fenced plot. Each square was planted in November 1974 with 400 unstratified ponderosa pine seeds collected on site a month earlier from dominant or codominant trees. After the seeds were thoroughly mixed and their germinative capacity found to be about 84 percent, they were planted in 20 rows and 20 columns spaced 6 inches (15 cm) apart. The seeds were pushed slightly into the ground, but not buried, to prevent rolling or blowing out of place. In plots with organic layers and vegetation left, the seeds were placed next to mineral soil because this is where the majority of naturally fallen seeds were found.

The nine treatments were distinguished by differences in overstory canopy and varying amounts and methods of litter, duff, and vegetation removal (table 1). Treatment designations indicate site features which were emphasized.

A weather station was set up in a small opening near the middle of the study site and a continuous record of air temperature, relative humidity, and precipitation was kept from May 14 until November 11, 1975. Snow depths were determined on all plots on March 24, 1975.

Soil moisture contents were measured gravimetrically from soil samples collected five times during the growing season. Sampling depth varies with collection dates, starting with 0-2.8 inches (7.1 cm) on June 4, 0-4.3 inches (10.9 cm) on June 24, and 0-6 inches (15 cm) on July 21, August 13, and September 3. The depths of the first two collection dates were approximately equal to the lengths of the longest roots of newly germinated seedlings. This was done to compare moisture contents within the seedling root zone.

Table 1.--*Position and treatment of field plots*

Treatment designation	Pine canopy position relative to plot	Seedbed treatment
Pine-influenced		
Canopy	Directly overhead	Litter, duff, and vegetation removed to mineral soil
Litter	Not directly overhead	Litter and duff undisturbed, vegetation removed
Stemflow	Tree in center, small canopy overhead	Litter, duff, and vegetation removed to mineral soil
Near	Not directly overhead	Litter, duff, and vegetation removed to mineral soil
Natural	Directly overhead	Litter, duff, and vegetation undisturbed
Fire	Variable	Litter, duff, and vegetation burned
Opening		
Cleared	None	Litter, duff, and vegetation removed to mineral soil
Litter	None	Litter, duff, and vegetation removed and replaced with pine litter and duff
Natural	None	Litter, duff, and vegetation undisturbed

During the last week of October 1974, which was an excellent seed year, the number of naturally occurring ponderosa seeds was counted for each plot by a systematic sample using twelve 8- by 20-inch (20- by 50-cm) quadrats.

A spherical densiometer was used to determine amount of canopy covering each plot.

An Eppley pyrheliometer was used to measure solar energy falling on individual treatments. Measurements were made only once, on July 9, 1975, because of infrequent cloudless days and instrument complications. Readings were taken on all plots at approximately 10:00 a.m., 12:00 noon, and 3:00 p.m. (MDT). Total radiant energy from 9:30 a. to 3:30 p.m. was calculated by assuming the 10:00 a.m. reading represented energy received from 9:30 to 11:30, the 12:00 noon reading represented energy received from 11:30 to 1:30, and the 3:00 p.m. reading represented that from 1:30 to 3:30.

Maximum soil surface temperatures were measured with a series of heat-sensitive pellets on each plot in July 1975, the month during which the highest air temperatures were recorded.

Soils collected for moisture content were also analyzed for nutrient concentration. At each of the five dates mentioned earier, ammonium and nitrate ion concentrations were determined by specific ion electrode analyses following KCL and water extraction, respectively. A glass electrode measurement of the water extract was used to determine soil pH. Analyses were also made for manganese, potassium, magnesium, phosphates, calcium, sodium, iron, copper, and zinc on the June 4, July 21, and September 3 samples. Following ammonium acetate extractions, the cations were measured by atomic absorption. Phosphates were determined colorimetrically. The soil sampling depths varied with sample dates, as before, to better compare nutrient concentrations within the seedling root zone.

4

Seeds began to germinate around May 13, and seedling counts were made weekly from May 14 through June 23, then every 2 weeks until August 21. A record of seedling mortality was kept during seedling counts, including the seedling age and apparent cause of death. In this study the causes of death were placed into eight categories. (1) *Cutworm damage* was observed as clipping of the stem near ground level leaving whole or partially consumed cotyledons separated from the stem. Similar types of damage by cutworms were reported by Fowells (1940). A number of large, green cutworms were found eating freshly cut seedlings. (2) *Bird or small mammal damage* occurred predominantly within 4 weeks after germination while seed coats were still attached to the cotyledons. Both seed coats and cotyledons were removed leaving various amounts of the latter, from small stubs to three-fourths of the needle. Small mammals, probably voles or deer mice, and birds were the prime suspected causes of this type of seedling damage (Gashwiler 1971; Lawrence and others 1961). (3) An *unknown* agent caused seedlings to turn *chlorotic and brittle* while standing upright. They were obviously dehydrated, but water stress was not thought to be the cause of death because in most instances the soil was still moist. (4) When no evidence of a seedling could be found it was placed in the *disappearance* category. It is likely that death was due to cutworms and the entire seedling was consumed. Also if the seedling collapsed into the pine litter it could have blended in beyond recognition. (5) *Poorly developed roots* often occurred when root tips grew against large rocks near the soil surface. Fungal infected roots were rare. (6) *Sun scald* was usually determined by a heat lesion on the stem near ground level. (7) *Damping-off* was observed as a soft, mushy spot on the seedling at or slightly below ground level. (8) *Miscellaneous* mortalities included cotyledons wrapped in spiders' webs, seedlings crushed by falling pine cones, seedlings buried by erosion, and seedlings stepped on by observers.

Initial (first year) seedling establishment was calculated by dividing the number of seedlings remaining alive near the end of the growing season (September 25) by the number of seeds planted (400).

To determine the effect of treatment influences on productivity, five randomly chosen pine seedlings including their entire root systems were lifted from each plot during October 1975. Total shoot lengths, crown lengths, taproot lengths, and the lengths and number of all lateral roots over 1 cm long were measured. Seedling shoot and root biomasses were determined after overdrying. Before this, a very generalized estimate of mycorrhizal associations was made by placing each seedling into one of three categories according to observed number of mycorrhizal tips. Lightly infected roots were characterized by a few widely spaced mycorrhizae, usually existing as one tip alone, and heavily infected roots had great numbers of fungal tips, often forming clusters. Medium infections fell between these two.

Two tests were used in the statistical analysis of seed germination, seedling mortality, and seedling productivity. A two-sample T test was used to compare the average seedling characteristics of the three opening treatments to those of the six pine-influenced treatments at specified significance levels. To compare the average seedling characteristics of the nine individual teatments with each other simultaneously, Duncan's Multiple Range Test was utilized at the 5 percent significance level. Because of heterogeneous variances transformations of germination percentages, shoot lengths, lateral root lengths, and total and shoot biomasses were required.

RESULTS AND DISCUSSION

Fires

The three fire plots were burned in the fall of 1974. Litter and duff moisture contents prior to burning ranged from 6 to 9 percent, and 11 to 19 percent, respectively. During the fires, the average maximum soil surface temperatures for entire plots ranged from 200°F (93°C) to 360°F (182°C) with individual points reaching in excess of 650°F (343°C). Litter and duff reduction by both weight and depth ranged from a low of 65 percent to a high of over 91 percent, indicating that even though the areas involved were small, the fires burned effectively.

General Weather Conditions

Table 2 presents the average monthly air temperatures and total monthly precipitation occurring on the study site. In addition, this table includes a summary of temperature and precipitation data collected approximately 12 miles (19 km) due east at the Ovando weather station from 1941 to 1970 (U.S. Dep. Comm. 1973). The Ovando data correspond to "normal" weather conditions encountered near the study site, since the same weather systems influenced both areas.

Table 2.--*Average monthly air temperatures and total monthly precipitation at the study site, 1975, and normal monthly approximations*

Month	Average temperatures		Total precipitation		
	Study site	Normal (Ovando)	Study site	Normal (Ovando)	Difference
	- - - - - - °F - - - - - -		- - - - - - - - Inches - - - - - - - -		
June	50.4	54.3	2.69	2.47	+0.22
July	64.7	61.3	2.81	1.00	+1.81
August	57.3	59.6	2.10	0.99	+1.11
September	51.3	50.7	1.15	1.22	-0.07
October	38.8	41.4	3.91	1.18	+2.73
Average or total	52.4 (11.3°C)	53.5 (11.9°C)	12.66 (31.7 cm)	6.86 (17.2 cm)	+5.80 (+14.5 cm)

Average monthly temperatures varied little from the approximated normal monthly temperatures. The study site was slightly cooler than normal during the months of June, August, and October and slightly warmer during July and September. The precipitation varied greatly from normal with all but 1 month receiving above-average amounts of rainfall, resulting in 5.8 inches (14.5 cm) above the normal for the 1975 growing season. The 12.66 inches (31.7 cm) that fell during the 5-month period amounted to over 77 percent of the normal yearly precipitation, and was unequaled during the period from 1931 to 1960.

The greatest snow depths (30-35 inches) (75-88 cm) were found on the opening sites where the pine canopy had no influence. The least snow depths (8-20 inches) (20-50 cm) were associated with areas of heavy canopy, although there were exceptions suggesting that the physical arrangement of the canopy and wind drifting could be important.

Soil Moisture Content

The moisture content of the soil was highest in June, decreased through July and August, and started to rise again in early September (fig. 1). For the three opening treatments, the opening-litter plots tended to have a higher soil moisture than the opening-cleared or opening-natural plots. This was likely due to the absence of herbaceous vegetation and the presence of the litter layer that helped retain the moisture. For those sites associated with the pine trees, the litter and near plots had the highest soil moisture levels throughout the summer. The lowest soil moistures for the summer were found in the fire and canopy treatments.

Natural Seed Occurrence

The plots associated with the pine stand had much greater numbers of natural seeds than plots in the openings. The greatest number of seeds $(14.0/ft^2)$ $(151/m^2)$ occurred on the canopy plots, and the least $(2.7/ft^2)$ $(29/m^2)$ were found on the opening-cleared plots. As a group, the opening treatments averaged only 2.9 seed/ft^2 $(31/m^2)$ compared to 10.4 seeds/ft^2 $(112/m^2)$ on the pine-associated plots. Thus, the areas immediately adjacent to seed-producing trees have the greatest potential for seedling occurrence due to greater seed numbers.
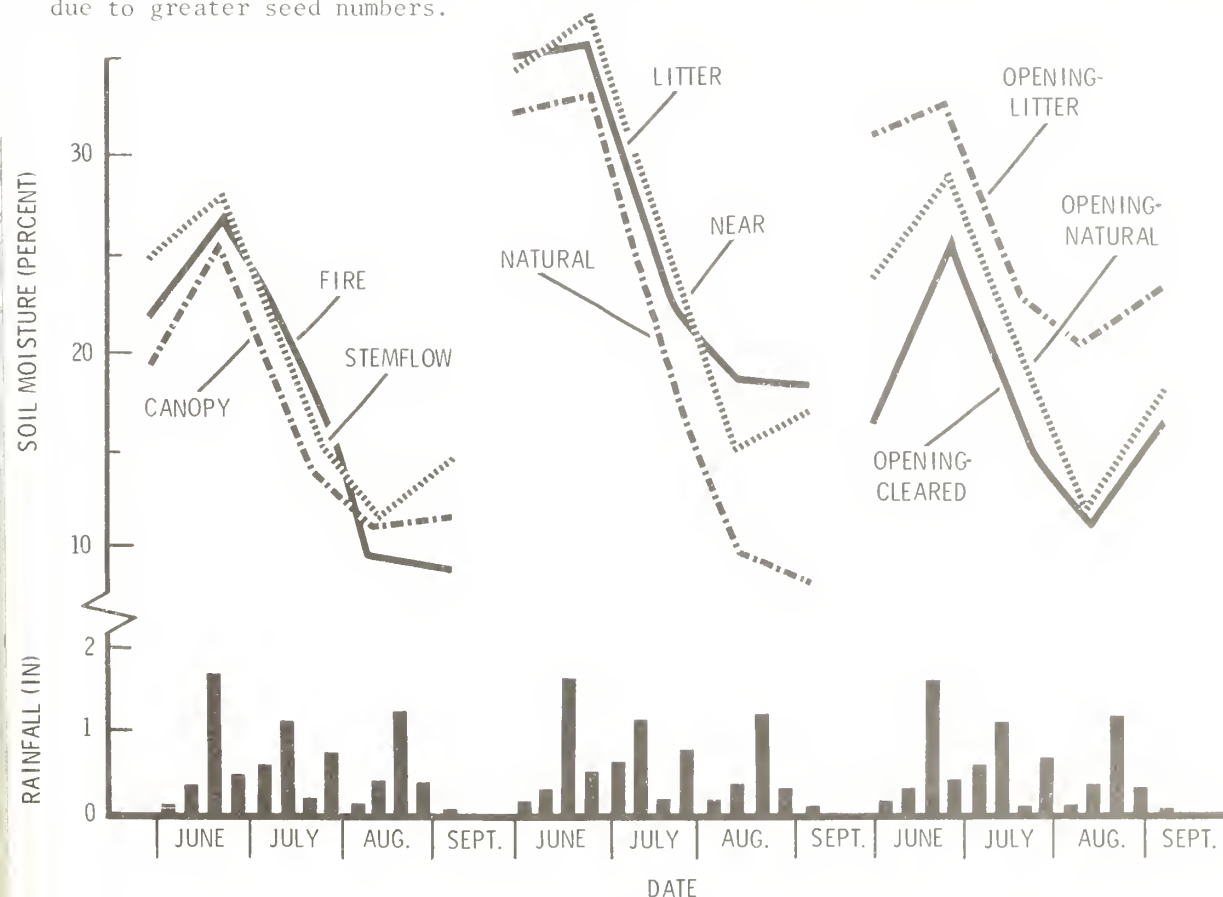

Figure 1.--Temporal changes in soil moistures compared to amounts of rainfall.

Canopy Cover

The plots located in the openings had the least canopy coverage, ranging from 2 to 6 percent. The natural and canopy plots had the greatest canopy influence, with over 80 percent coverage. The canopy coverage on the other plots fell between these two groups, ranging from 35 to 72 percent.

Linear regression analyses comparing percentage of canopy cover to other physical factors give the following correlation coefficients: litter depth, +0.85; total radiation (9:30 a.m. - 3:30 p.m.), -0.91; maximum soil surface temperatures, -0.78; soil moisture 2 days after a rainfall, -0.84. These correlations indicate that increased canopy probably leads to greater amounts of organic matter, and decreased sunlight, soil temperatures, and rainfall occurring on the forest floor. Other factors such as vegetation and litter depth will also affect soil moisture, but the interception ability of the pine canopy must be emphasized.

Solar Radiation

Total solar radiation amounts for 6 hours received on the opening and pine-associated treatments ranged from 350 to 390 g-cal/cm^2 (9 to 10 Btu/in^2) and from 130 to 340 g-cal/cm^2 (3 to 9 Btu/in^2), respectively. The plots in the openings, having little canopy influence, received the highest amounts of radiant energy. Some pine-associated plots also received long periods of full sunlight because they were positioned with few or no potential shade trees to the south or overhead. Nearly all variations of shading were encountered.

Maximum Soil Surface Temperatures

The range of maximum soil surface temperatures for the opening plots was 138° to 151°F (57°-66°C). This was similar to temperatures encountered on the pine-influenced plots, 109° to 158°F (43° to 70°C). Maximum temperatures were recorded where litter and other organic matter were present; the litter, the opening-litter, the opening-natural, and the fire treatments (due to the black surface). The removal of litter and live vegetation in the openings resulted in lower surface temperatures as was observed on the opening-cleared treatment. Heavy canopy reduced temperatures somewhat, but surface temperatures were lowest on those treatments with the combined effects of bare mineral soil and large amounts of canopy cover. This latter situation occurred on the canopy and near treatments.

Soil Nutrient Analysis

Three of the eight exchangeable cations--iron, copper, and zinc--showed very little variation between treatments throughout the summer. The iron averaged 2 to 4 μg/g of soil, the copper averaged 2 to 3 μg/g, and the zinc averaged 1 to 2 μg/g.

The amounts of calcium and sodium showed slightly greater treatment variation, but seemingly not enough to cause growth differences. The calcium content in the opening treatment soils averaged 2,300-1,800 μg/g of soil throughout the summer, whereas soil from the pine-influenced plots averaged 2,200-1,600 μg/g over the same period. Sodium from the pine-influenced plots averaged 11 μg/g of soil throughout the growing season. The opening plots contained 2 to 3 μg/g less than these.

The remaining three cations--manganese, potassium, and magnesium--were more variable, but it is obvious that those treatments associated with the ponderosa pine stand

had equal or greater amounts of these cations than the opening plots (table 3). The fire-treated soil had appreciably greater amounts of extractable potassium and manganese than all other treatment soils during the entire growing season.

Table 3.--*Treatment effects on soil nutrients from June to September, 197_.*

Treatments	Nutrient concentrations					
	Mn	K	Mg	NH_4^+	NO_3^-	PO_4^{-3}
				$\mu g/g$		
Fire treatment	50-100	715-1195	150-265	26-76	2.0-7.5	27-55
Pine-associated treatments	15-80	480-880	165-200	4-7	1.5-4.0	18-28
Opening treatments	10-65	240-410	145-170	4-7	1.5-5.0	8-20

Probably because of increased mineralization of organic nitrogen, fire-treated soil had an extremely high ammonium ion content that varied with fire intensity. The fire plots that burned the hottest, causing the greatest litter reduction, had the highest NH_4^+ concentrations. There was very little difference in NH_4^+ and NO_3^- levels between the rest of the pine-associated plots and the opening plots (table 3). The increased amounts of NH_4^+ in the fire treatments did not lead to excessively high NO_3^- concentrations, but the nitrate values were slightly higher than those found in most other treatments.

The phosphate content was noticeably higher on the tree-associated sites than in the openings (table 3). The fire treatment appeared to raise the PO_4^{-3} concentration slightly over some treatments and greatly over others.

These analyses indicated that the nutrient content of the soils within the pine stand was comparable to or exceeded that in the openings. Rating the treatments in terms of seedling growth potential on the basis of nutrients is very difficult. However, the fire-treated plots do stand out from the other treatments in their high nutrient content, but this was expected (Christenson and Muller 1975; Viro 1974). Of particular interest was the increase in nitrogen (NH_4^+), because this, along with other nutrients, can have a significant influence on the growth of ponderosa pine seedlings (Cochran 1972; Vlamis and others 1957) and may play a role in the drought-resistant capabilities of ponderosa seedlings (Loewenstein 1970). The particular form of nitrogen may also be important. Ponderosa seedling growth studies indicate that NH_4^+ is the preferred source over NO_3^- and urea (Wollum 1968, 1970).

All treatments had similar soil pH values, except for the fire plots which, as expected, had much higher values. In all cases, pH values were highest in June and continually decreased throughout the summer. The average soil reaction for the opening plots for June 4 was 5.5 compared to 5.6 for the pine-influenced plots. On September 5, the average pH had fallen to 4.7 in the opening treatments compared to 4.9 for the others. Average fire treatment pH dropped from a June 4 high of 6.5 to a September 5 low of 5.5, probably due to leaching of the oxides and carbonates found in the ash.

Seed Germination

Of the 10,800 ponderosa pine seeds that were planted on the 27 study plots the previous fall, 4,812 (44.6 percent) germinated. Germination percentages varied greatly ranging from 70 percent to only 16 percent, with the greatest germination occurring in the opening treatments compared to the pine-influenced treatments. Germination in the three opening treatments accounted for about 50 percent of the total germination. The three opening treatments had an average germination of 65.4 percent, which was significantly greater at the 1 percent level than the six pine-influenced treatments, with an average germination of 34.1 percent.

Germination in the opening-litter plots was very similar to that in the opening-cleared plots, indicating that under the environmental conditions of the 1975 growing season, pine litter and duff had no effect on germination in the openings (fig. 2). The opening-natural plots averaged about 12 percent less germination than the other two opening treatments, but the differences were not significant. Germination in the opening-natural plots was reduced somewhat because of unsatisfactory seedbeds, such as the middle of clumps of bunchgrass, or on crusted mosses or lichens. The opening-litter and opening-cleared treatments had significantly greater germination than all pine-influenced treatments. The natural and canopy treatments had by far the lowest germination.
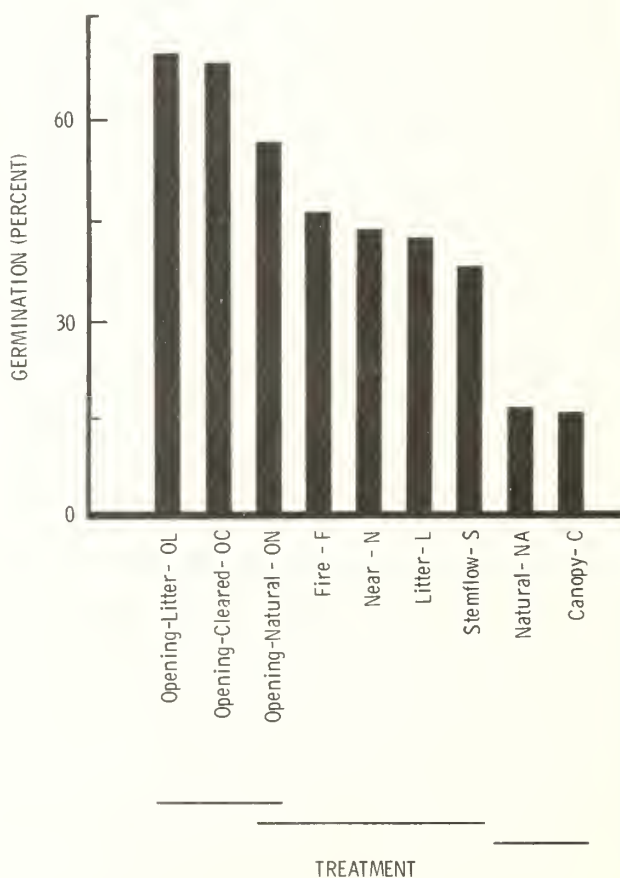

Figure 2.--Seed germination percent-ages, with statistical comparisons of treatments. (Treatments not underscored with the same line are significantly different at the 5 percent level.)

10

The lower germination in the pine-influenced treatment was probably due to cooler temperatures, as a result of shading, when moisture conditions were favorable. The organic matter could have created poor soil surface moisture conditions due to low water potentials and to the large, irregular shapes which provided inadequate contact between seeds and available moisture (Eyre and LeBarron 1944). Also, the amounts of far-red light in the shade may have had an inhibitory effect on germination (Harrington 1977). In addition to these factors, the absence of a protective snow cover under the over-story canopy may not have provided adequate overwintering conditions for seeds as was found in the openings. The possibility also exists that a chemical germination inhibi-tor could be subtly involved. Kelsey and Harrington (1979) found that soils from under pine canopies reduced ponderosa seed germination in the greenhouse compared to that in opening soils.

The germination rates, represented by the slopes of the curves, are shown in figure 3. Germination rates in the opening-cleared and opening-litter treatments averaged 18 seeds per day while that in the opening-natural treatment was 11 seeds per day. The fire, the litter, the near, and the stemflow plots had similar rates, averag-ing 7-8 seeds per day. The slowest rates occurred in the canopy treatment, with two seeds per day and the natural treatment with just over one seed germinating per day.
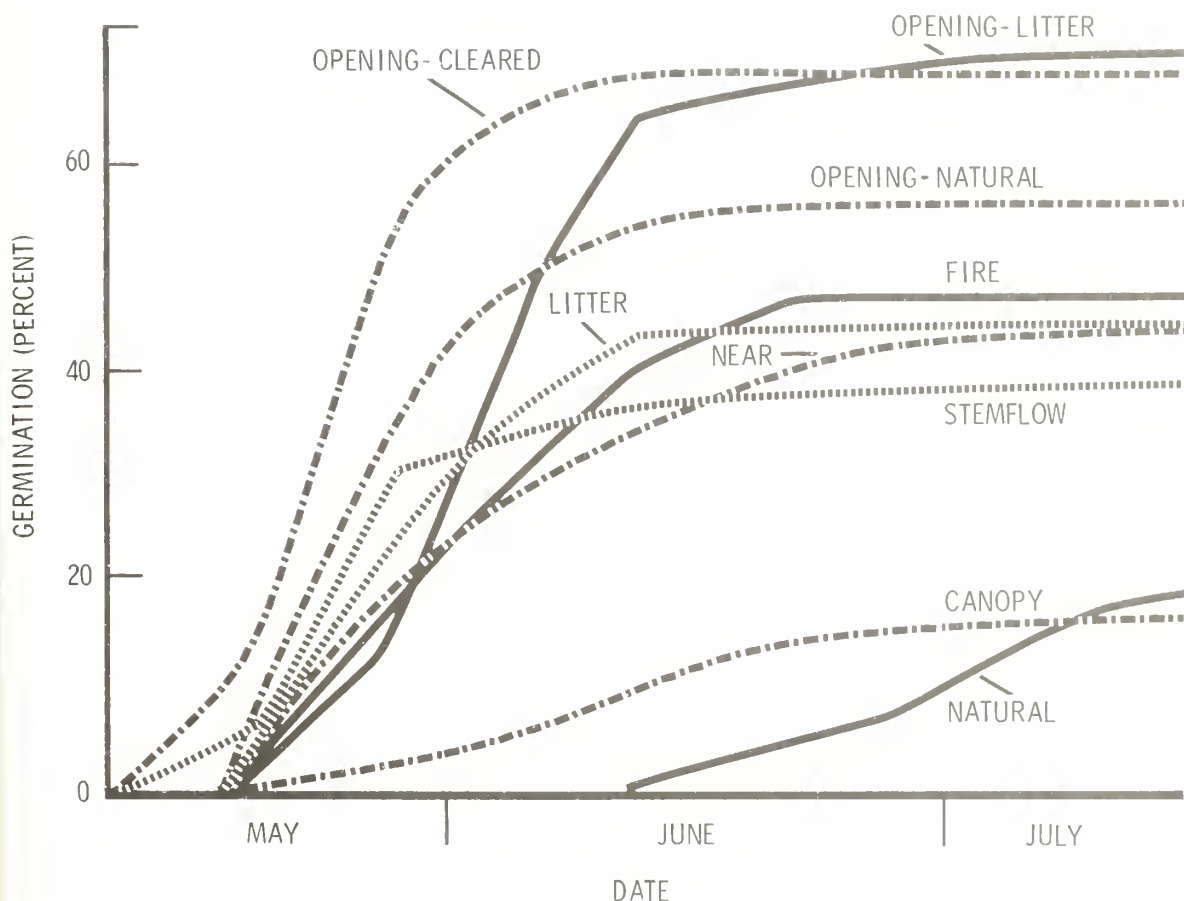

Figure 3.--Seed germination per treatment

11

Other obvious differences reflected by the curves in figure 3 are the time intervals for germination. Even though the rates may have been similar, germination may have occurred at later dates, thereby not permitting as long a growing period as first-season seedlings might need. The opening-cleared and opening-natural seeds germinated earliest with the opening-litter, the fire, the near, the litter, and the stemflow seeds appearing about 1 week later. The canopy and natural treatments created situations in which germination was 3 to 4 weeks behind the other treatments. This caused the average seedling age at the end of the growing season to be only 19.7 weeks for the canopy seedlings and 17.2 weeks for the natural seedlings compared to an average of 22 weeks for the other seven treatments.

Looking at replications within the natural, the near, and the fire treatments, those plots with the greatest overhead canopy had the slowest and latest seed germination. Reasons for this are probably the same as for the variation in total germination: differences in temperature, moisture, and perhaps light.

Seedling Mortality

A total of 1,323 seedling deaths were recorded during the 1975 growing season. This represents 27.5 percent of the seeds that germinated. The percent mortality ranged from 56.6 to 12.7 (fig. 4). The stemflow and litter treatments suffered the greatest damage, losing over half of their seedlings. The next six treatments all had very similar losses, 21 to 29 percent, while the opening-cleared treatment averaged only 12.7 percent. The average seedling mortality on the three opening treatments was 21.0 percent which was significantly lower at the 5 percent level than the 35.3 percent loss for the pine-influenced treatments.

Cutworm activity resulted in the greatest number of mortalities, more than 30 percent, and was most prevalent in the litter treatment causing more than 61 percent of the seedling deaths (table 4). Other treatments that were substantially affected by cutworms were the opening-litter, the opening-natural, the fire, and the stemflow. The only treatments which did not have significant cutworm activity were the opening-cleared plots due to lack of protective ground cover and the natural plots because the seeds germinated very late in the growing season, after larval activity had declined considerably. Although damage caused by these insects was observed on pine-associated treatments where the ground cover had been removed, their greatest influence appeared where ground cover was present.

The second most important cause of seedling death was cotyledon clipping due apparently to birds and small mammals. The treatments whose seedlings were most significantly affected by this category were the stemflow, the opening-natural, and the canopy. The near treatment showed rather high clipping mortalities (table 4), but 95 percent of these occurred in only one of the three replicate plots, so it was not a general trend. The fences were apparently only a partial deterrent to small mammal activity and were no obstacle for birds.

Seedling deaths caused by cutworms, and small mammals and birds were similar in that a portion of the seedling was severed. These two mortality types may be distinguishable by the region of the seedling receiving the injury. Cutworms apparently sever the stem near ground level, whereas mammals clip a portion of the cotyledons, or the upper stem directly below the cotyledons. Birds likely pluck the seed coats when

they are still attached to the seedling, thereby breaking a portion of the cotyledon.
These two types of mortal injury (cutworm versus birds and small mammals) seemed to
occur at different times, with only a slight overlap (fig. 5). The seedlings most
likely provided food for the mammals in the spring when little else was available, but
other more succulent vegetation that appeared later probably became their main food
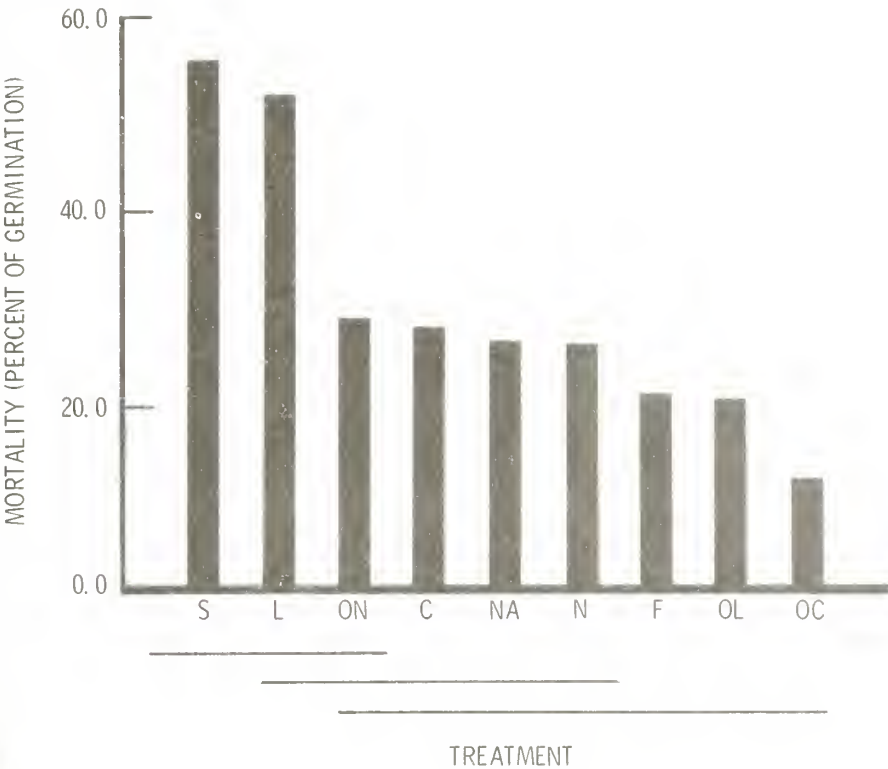source.

Figure 4.--Seedling
mortalities as per-
centages of germinants,
with statistical com-
parison of treatments.

Table 4.--Numbers and percentages of seedling mortality by cause for treatments.

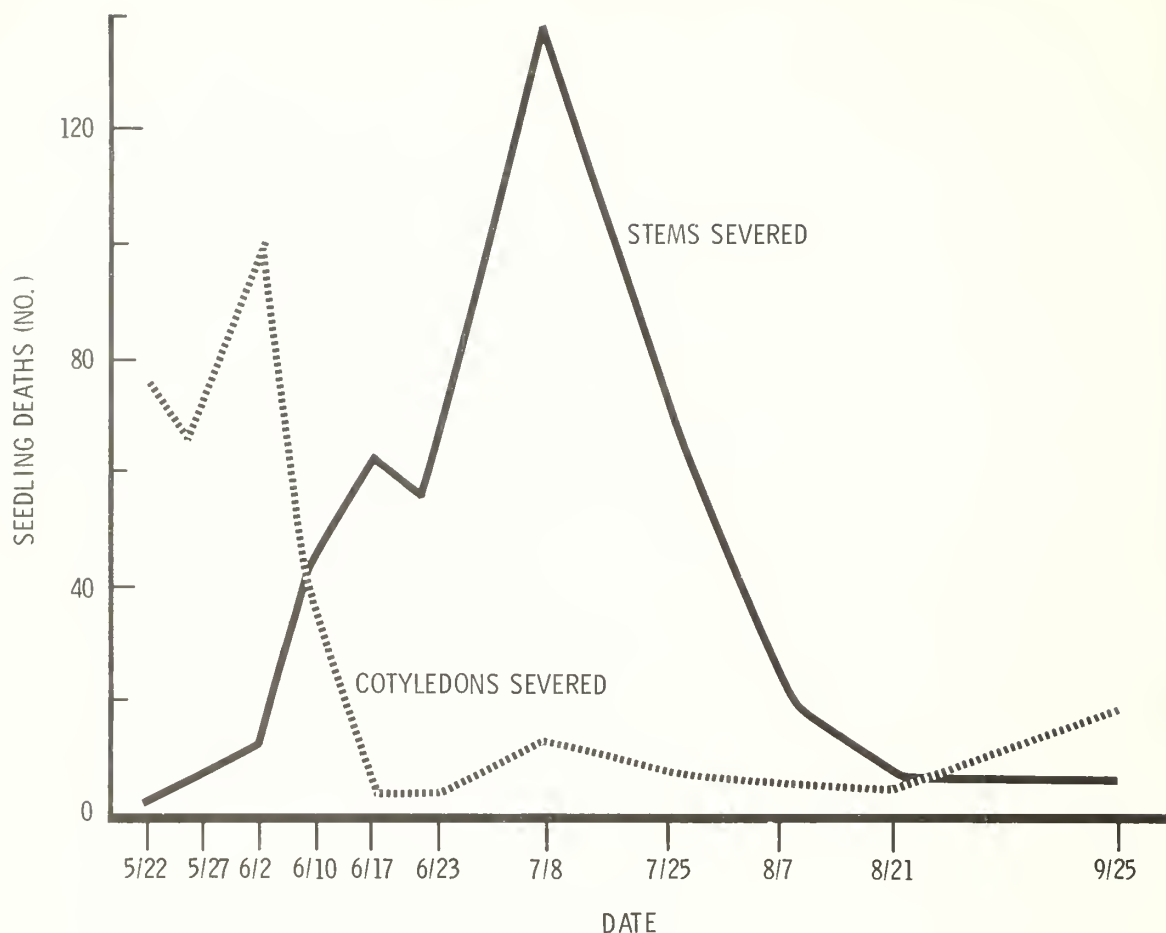| Treatment	Cutworms		Birds and rodents		Unknown (chlo-rotic)		Dis-appeared		Poor root develop-ment		Sun scald		Misc.		Damping-off		Total
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.
Opening-cleared	2	1.9	3	2.9	30	28.6	2	1.9	49	46.6	12	11.4	4		3	2.9	105
Opening-litter	76	42.0	32	17.7	44	24.3	18	9.9	0		7	3.9	3	1.7	1	0.6	181
Opening-natural	55	26.8	92	44.9	30	11.6	19	9.3	2	1.0	3	1.5	1	2.0	0		205
Fire	54	45.8	17	14.4	23	19.5	4	3.4	3	2.5	7	5.9	9	7.6	1	0.9	118
Canopy	6	15.8	13	34.2	14	36.8	1	2.6	0		0		1	2.6	3	7.9	38
Stemflow	46	18.3	136	54.2	49	19.5	5	2.0	5	2.0	5	2.0	4	1.6	1	0.4	251
Natural	5	9.6	2	3.8	12	23.1	26	50.0	1	1.9	0		0		6	11.5	52
Litter	169	61.5	9	3.3	43	15.6	12	15.3	4	1.5	5	1.8	2	0.7	1	0.3	275
Near	16	16.3	42	42.9	11	11.2	4	1.1	3	3.1	15	15.3	1	1.1	5	5.1	98
Totals and percentages	429	32.4	345	26.1	256	19.3	122	9.2	67	5.1	52	3.9	25	1.1	21	1.6	1,323

13

Figure 5.--*Seasonal variation of seedling deaths due to severed stems (cutworms) and severed cotyledons (birds and small mammals).*

Approximately 20 percent of the seedlings turned brown and became very brittle with no obvious cause. This type of casualty was common on nearly all treatments. There was no relationship between open versus canopy, or the presence or absence of litter with this type of mortality. Possible causes were heat stress, root death due to too much soil moisture or undetected root pathogens, or perhaps the expression of a lethal gene.

The disappearance of seedlings accounted for 10 percent of the losses. As mentioned earlier, this could have been the work of cutworms which devoured the entire seedling. The greatest number of disappearances occurred in treatments where there was ground litter or cover which was considered earlier as an important factor for cutworm presence, and where it was more difficult to find the evidence of chewed seedling remains.

The remaining four casualty classes--poor root development, sun scald, damping-off, and miscellaneous--were responsible for 13 percent of total seedling deaths. Poor root development had its greatest effect in the opening-cleared treatment and very little effect elsewhere. Sun scald was associated with plots receiving the greatest amounts of sunlight. Conversely, damping-off was more prevalent in plots with heavy shade and deep litter.

14

Drought has been shown to be the major cause of mortality in early establishment of ponderosa pine seedlings (Foiles and Curtis 1973; Pearson 1942; Rietveld and Heidmann 1976; Wagg and Hermann 1962). During this study, however, moisture stress was not thought to be significant because of the abnormally high precipitation in June, July, and August (table 2). Had the summer of 1975 been "normal" as far as rainfall, it is likely that drought rather than cutworms would have been the leading cause of seedling casualties.

Initial Seedling Establishment

Poor initial seedling establishment was due either to poor germination or to high mortality. Treatment averages show that the opening plots produced the most surviving seedlings (fig. 6). The opening treatments' 51.8 percent establishment was significantly greater than the 22.5 percent establishment of the pine-influenced plots at the 1 percent level.
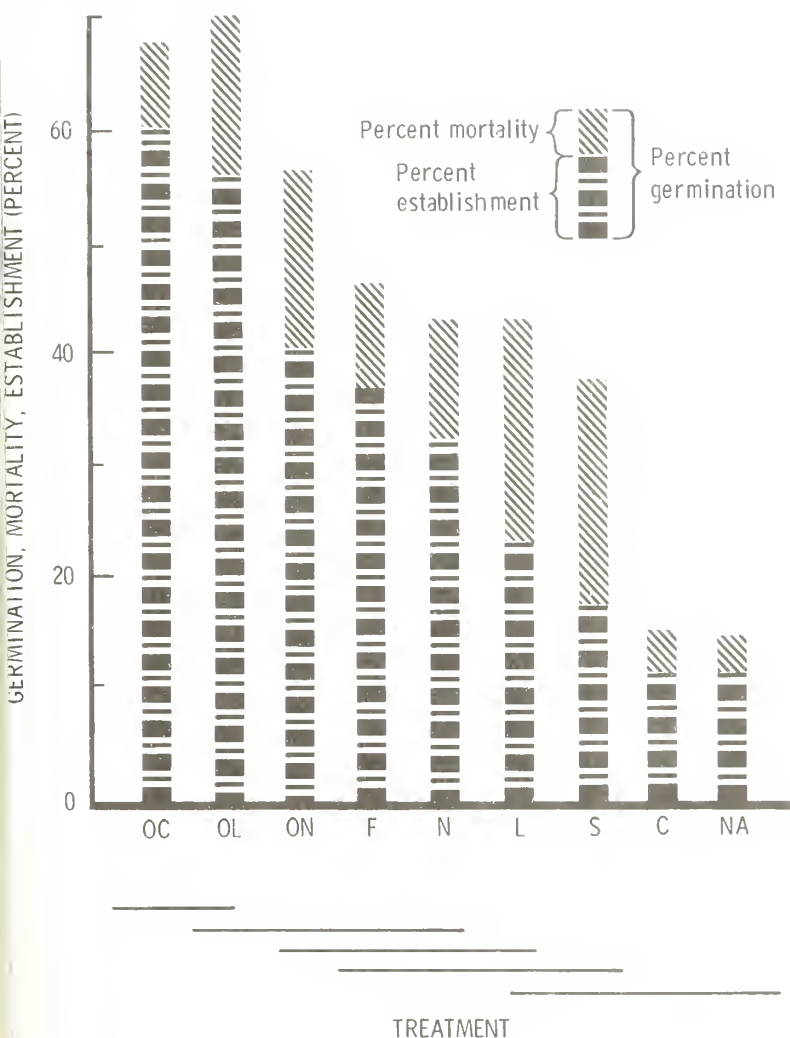

Figure 6.--Percentages of live seedlings after one growing season due to germination minus mortality, with statistical comparison of treatments.

15

The poor seedling establishment on most of the pine-associated treatments was apparently caused by direct or indirect effects of the organic layer, the overstory canopy, or a combination of these on seed germination and seedling mortalities. Providing the canopy was not too dense, seedling establishment was enhanced near overstory trees by removing the organic layer and competing vegetation. The method of removal, by fire or mechanical scarification, appeared to have little effect on initial establishment numbers if the method was carried out thoroughly. However, the specific type of litter and vegetation removal did have a rather obvious effect on seedling size and vigor, as will be discussed in the next section.

Seedling Productivity

Opening treatments vs pine-influenced treatments.--A comparison was made between the average characteristic sizes of seedlings grown in the openings and those grown under an overstory. Another contrast is shown in which the fire seedling dimensions are removed from the analysis for a better comparison of treatments in the openings with those in the pine stand (table 5).

The superiority of seedlings grown in the open is evident. Their average characteristic sizes are greater than pine-influenced seedlings in all cases.

Table 5.--*Characteristics of seedlings occurring in openings compared to those of seedlings occurring under an overstory pine influence*

Seedling characteristics	Average treatment measurements		
	Opening	Pine-influenced minus fire	All pine-influenced
Shoot length	7.1 cm	6.2 cm**	6.8 cm
Crown length	4.4 cm	3.4 cm*	4.1 cm
Taproot length	39.6 cm	32.4 cm**	34.6 cm*
Lateral root length	107.6 cm	45.8 cm**	64.5 cm**
Lateral root number	27.2	15.9 **	19.7 **
Total biomass	334.4 mg	203.2 mg**	267.8 mg
Shoot biomass	181.1 mg	103.3 mg**	148.3 mg
Root biomass	153.3 mg	100.0 mg*	119.5 mg

 * Treatment average significantly smaller than the opening treatment at the 5 percent level.
** Treatment average significantly smaller than the opening treatment at the 1 percent level.

16

Shoot lengths.--Average seedling shoot lengths ranged from 10.1 cm on the fire plots to 5.7 cm on the stemflow plots (fig. 7). The fire plot seedlings were significantly taller than those in all other treatments. These were followed by seedlings from the opening treatments, which were similar in size to those from the litter plots. Seedlings grown in the natural and stemflow treatments were the shortest.
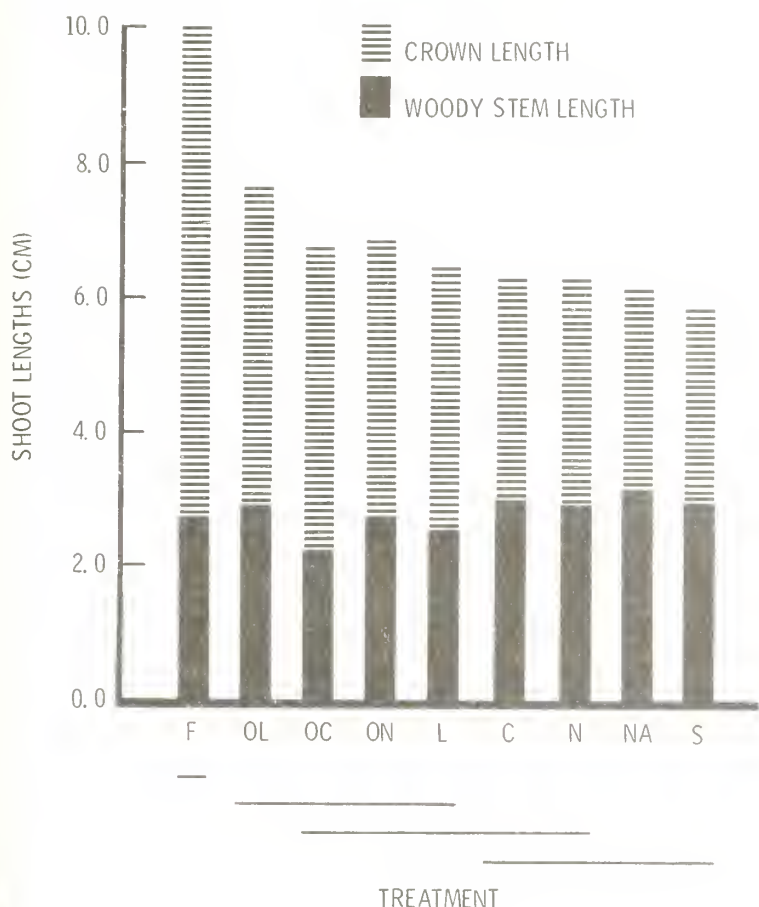

Figure 7.--Average seedling shoot lengths, with statistical comparisons of treatments.

The crown accounted for approximately one-half or more of the total shoot lengths, and an increase in total seedling height appeared to be caused by an increase in crown length rather than hypocotyl lengths. Again the fire plot seedlings produced the largest crowns by far, and were succeeded by seedlings from the opening and litter plots.

Root lengths and numbers.--Figures 8, 9, and 10 show root size and number comparisons. The fire plot seedlings produced vast root systems in contrast to other pine-associated plots. The opening plots generally contained seedlings with root systems also superior in size to the majority of seedlings grown within the pine stand.

Treatment mean taproot lengths varied from a high of just under 46 cm in the litter treatment to a low of 22 cm in the natural treatment (fig. 8). Seedling taproot lengths from the fire and opening treatments closely followed those from the litter treatment. The average number of lateral roots per seedling ranged from 39 on fire plot seedlings to just over five on the natural plots seedlings (fig. 9). These numbers also gave the fire treatment seedlings a distinct advantage in lateral root lengths with just under 160 cm of roots (fig. 10). The opening-cleared seedlings grew well with an average of 145 cm of lateral roots but the natural plot seedlings, with few and short roots, averaged only about 11 cm of total lateral root length.

Figure 8.--Average seedling taproot lengths, with statistical comparisons of treatments.
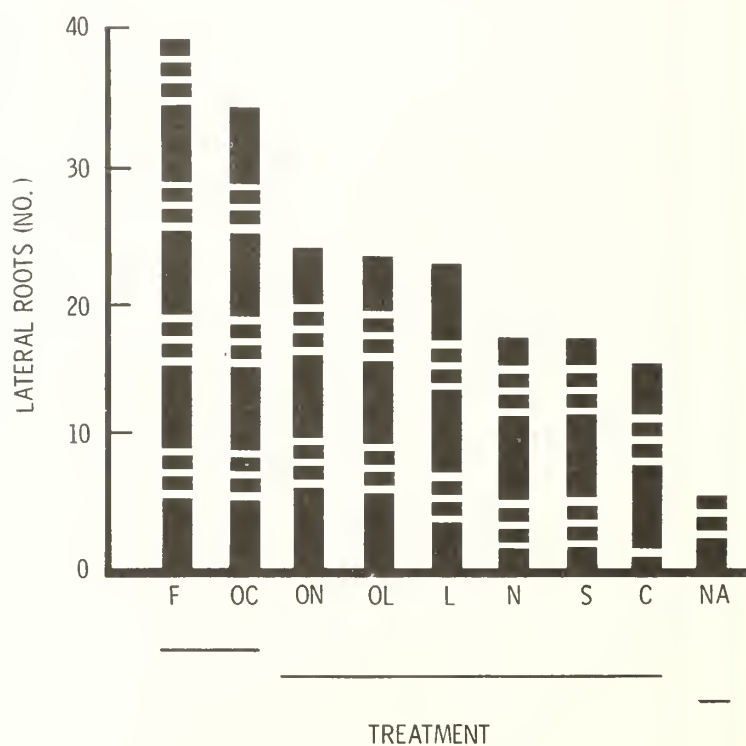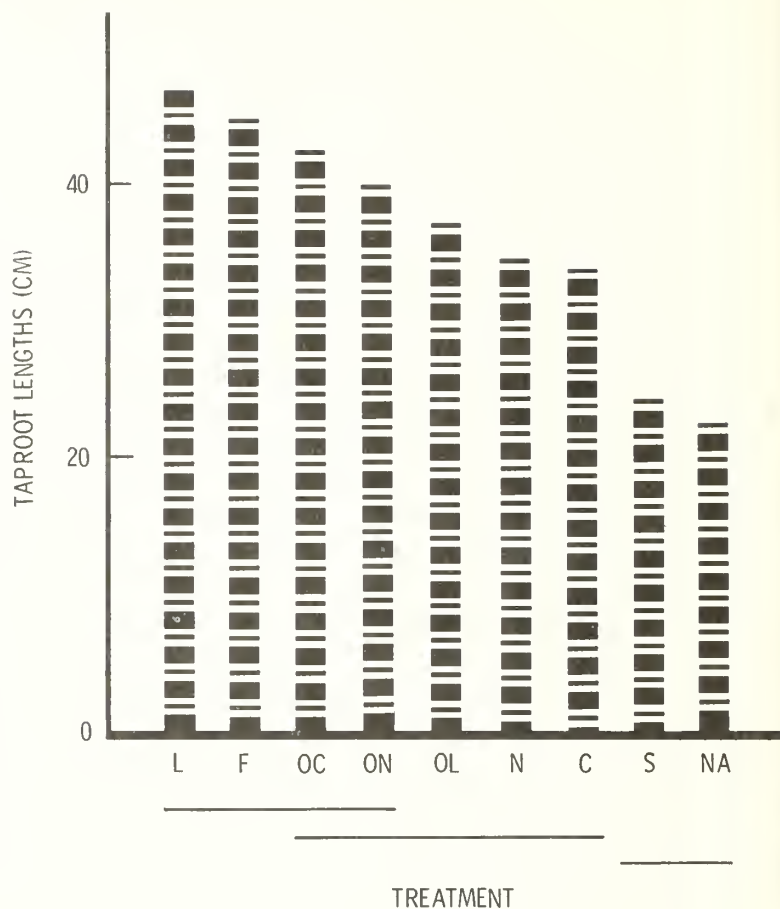

Figure 9.--Average number of lateral roots per seedling, with statistical comparison of treatments.
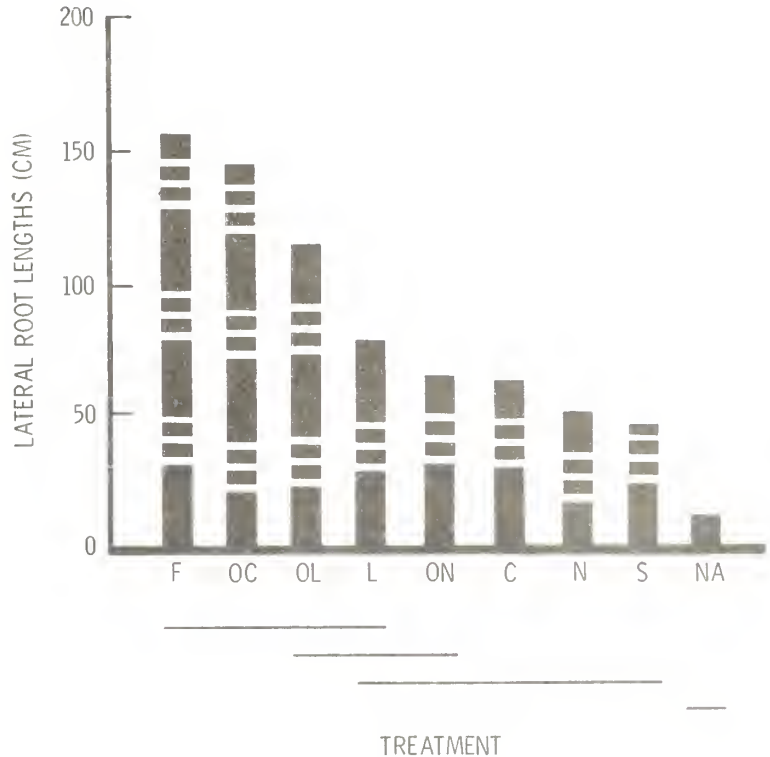
Figure 10.--Average length
   of lateral roots per seed-
   ling, with statistical
   comparison of treatments.

Seedling biomass.--The ovendry weights for shoots and roots of seedlings from in-
dividual treatments are shown in figure 11. The treatments are ranked according to
total seedling weights. The lines of significance above the x-axis point out shoot
comparisons, and the lines below show root comparisons. Total weight comparisons are
similar to those for root weights.

The fire plots, again, had the heaviest seedlings, including both shoots and roots.
The seedlings from the opening-litter and opening-cleared treatments were similar in
total weight, with the former having heavier shoots and the latter producing heavier
roots. The seedlings from the litter plots were next, having slightly heavier shoots
and roots than those from the opening-natural plots. The natural plots produced seed-
lings with the least biomass, including the smallest shoots and the smallest root
systems.

Mycorrhizae.--Figure 12 shows average mycorrhizal infection for the 15 seedlings
from each treatment. There were no seedlings that were completely devoid of mycor-
rhizae. The fire plots as a group had seedlings with the least infection because of
increased soil pH, increased soil nutrient status, and the physical action of heat on
the fungi (Hacskaylo and Snow 1959; Wright 1957). Mycorrhizal associations do not nor-
mally occur in great numbers and may be entirely absent when nutrients, especially nitro-
gen, become less limiting (Fowells and Krauss 1959). The natural plot seedlings had
the next lowest mycorrhizal numbers, slightly below the opening-litter seedlings. Sub-
stantial light is apparently a prerequisite for mycorrhizal formation because reserve
carbohydrates from high rates of photosynthesis are necessary for fungal associations
(Hacskaylo and Snow 1959). Therefore, the high degree of shading coupled with apparent
low soil temperatures caused by the deep litter layer on these natural plots could have
been an important factor in causing low numbers of mycorrhizae. The greatest number
of tips were observed on the litter treatment seedlings.

Figure 11.--Average seedling
shoot and root dry weights,
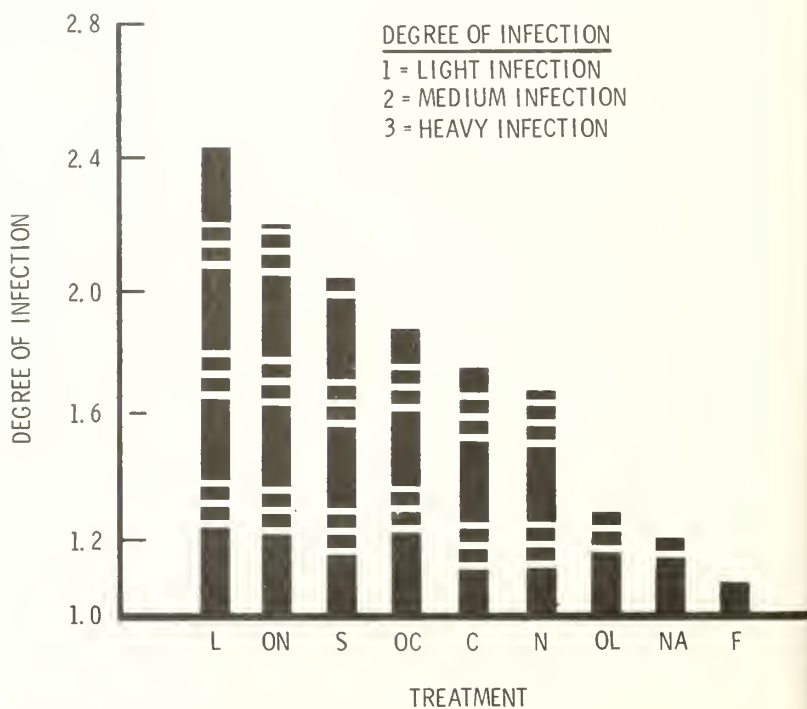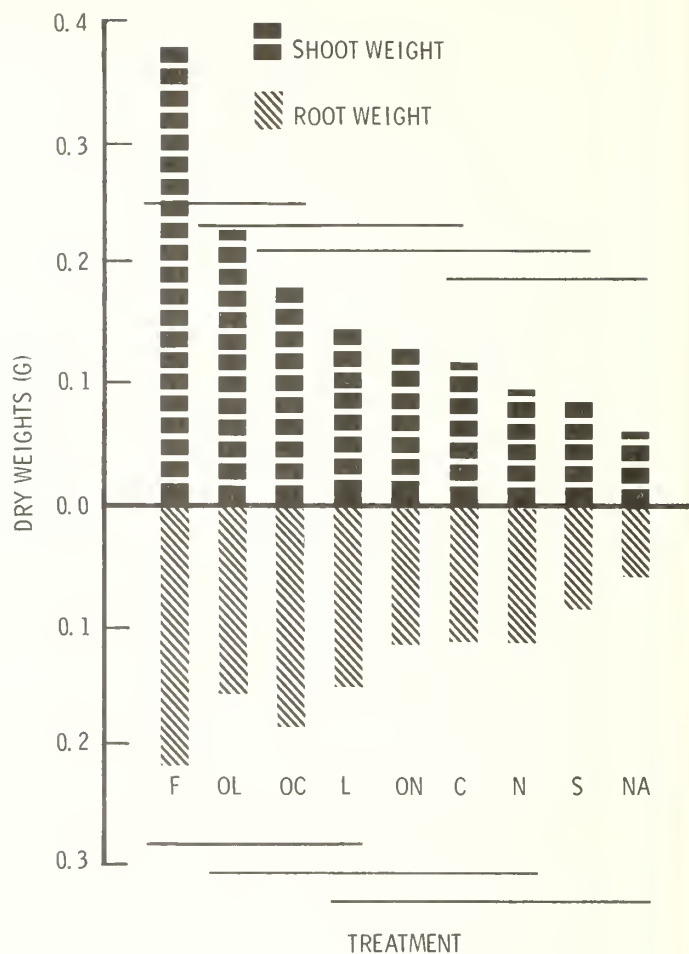with statistical comparison
of treatments.

Figure 12.-- Degree of seed-
ling root mycorrhizal
infection per treatment.

20

Discussion.--The possible factors influencing the growth of ponderosa pine seedlings, like most other plants, include light (quantity and quality), temperature, soil moisture, nutrients, competition, and phytotoxins. Potential phytotoxins were probably not naturally effective because in high concentrations they did not influence seedling growth in laboratory experiments (Kelsey and Harrington 1979).

Seedling productivity on the fire treatments was much greater than that on any other treatment. Comparing the environmental conditions of the fire treatment with those of the opening-cleared and opening-litter treatments, seedlings from the former had no advantage due to optimum temperatures, sunlight, or soil moisture, and experienced greater competition. The fire seedlings were, however, exposed to higher nutrient levels which was most likely responsible for the rapid growth. The lower light levels probably did not hurt the fire seedlings' growth because if soil conditions (nutrients and moisture) are near optimum then seedlings can, perhaps, tolerate exposure to much less light (Bates 1925).

The growth of seedlings in the opening-cleared and opening-litter treatments was nearly equal. Slight differences were likely due to the mulching effect of the litter which permitted higher soil moistures and probably lower soil temperatures.

It is clear, however, that the seedlings from the two opening plots discussed above grew better than those from the opening-natural plots. The physical characteristics of the opening-natural treatment were comparable to those encountered on the opening-cleared and opening-litter treatments in all respects except competition. These opening-natural plots had all of the native grasses and forbs present throughout the year and their presence can be considered most influential in reducing seedling growth.

The litter plots had environmental conditions which approximated those conditions found on the opening treatments and consequently, the growth was similar, being somewhere between that of the opening-cleared and opening-natural plots.

The reason for the poor growth in the stemflow plots is not apparent when examining the physical characteristics. Temperatures, light, and soil moistures in these plots were all comparable to those found in the openings and the nutrient levels were slightly higher. Time and rate of germination of the stemflow seeds were similar to those on the opening treatments. However, the seedlings on the stemflow plots experienced substantial mortalities due to cutworms and birds or small mammals early in the growing season. Many of the seedlings received cotyledon damage and did not die, but suffered growth impairment. It was also observed during the excavation of stemflow seedlings that some of their roots had grown into the outer corky layer of the large roots of the center tree. When this happened, there was a considerable reduction in the size of the seedlings' root systems which certainly affected shoot sizes.

The remaining three treatments--canopy, near, and natural--had some very similar characteristics which resulted in similar seedling growth responses. Soil moisture and nutrients appeared in sufficient amounts so as not to limit growth. However, surface temperatures were low, except for periodic intervals on the natural plots. The amount of light received on these three treatments was less than 50 percent of that received on the opening treatments. The reduced light and temperatures made themselves evident by causing later and slower germination rates, which reduced the growing period and, coupled with low temperatures and light levels, resulted in small seedlings. Larson (1967) also showed that ponderosa pine seedling epicotyl lengths, root penetration, numbers of lateral roots, and dry weights were positively correlated to number of degree-hours.

The natural plots differed from the canopy and near plots by the presence of a litter layer and understory vegetation. The effect of the litter layer on seedling growth was probably twofold. It reduced mineral soil surface temperatures and delayed

germination to a later date, thereby reducing the growing period. It also appeared to act as a physical barrier to vertical seedling growth. Competition from understory vegetation was low, but under those poor growing conditions any competition would be an additional detriment. McDonald (1976) also observed growth impairments where seedlings grew near large overstory pines.

SUMMARY AND CONCLUSIONS

Approximately 45 percent of all seeds planted during the fall of 1974 germinated in the spring and early summer of 1975. Germination was much higher on the opening treatments than on the pine-associated treatments. The presence of an overhead canopy or a combination of canopy and organic matter reduced germination percentages and rates.

Moisture, temperature, and light appeared to be the important factors in the germination of ponderosa pine seeds. Snow did not accumulate as deep under pine canopies and it often melted earlier in the spring than snow in the openings, exposing pine seeds to fluctuating temperature and moisture conditions. Therefore, proper stratification may not have been provided, thus reducing the seeds' ability to germinate. Also, soils with abundant organic matter may have higher moisture tensions and provide poorer seed-soil contact, thereby adding to the unfavorable germination conditions.

Two weeks after the start of germination, seedlings began to die. Eight categories of mortality were recognized and are listed in order of decreasing importance (numbers of seedlings destroyed); cutworm damage, bird or small mammal damage, chlorotic and brittle (unknown), disappearance, poor root development, sun scald, miscellaneous, and damping-off. When mortality and growth data are being considered, careful attention must be given to the unusually high summer precipitation occurring during this study. Drought, normally a significant detriment to seedling establishment, was not an apparent cause of mortality. Even though ponderosa pine is one of the region's most drought-resistant conifers, mortalities would have likely been higher and growth rates lower with normal rainfall.

Treatment, as well as location, was a determining factor in the number of seedlings lost. Survival tended to be best on those treatments that were devoid of all surface vegetation. The presence of litter had a variety of effects which likely worked synergistically with other factors such as plot location and amount of overhead canopy. In general, the least mortality was observed on treatments with no ground cover, that is, bare mineral soil.

Initial establishment, or actual numbers of living seedlings at the end of the first growing season, was greatest in the opening treatments. Ponderosa pine seed germination and seedling survival were enhanced in the presence of overstory pine trees by the removal of understory vegetation and the organic layer. However, better results were obtained when seedlings grew some distance from the overstory in addition to removing the ground cover.

Although the number of seedlings produced is important in the reforestation of conifers, seedling health and vigor are also significant. The effects of fire stimulated seedling growth above that in all other treatments. Fire reduced litter and competing vegetation, and enriched the soil by releasing nutrients, especially ammonium-nitrogen, phosphates, and potassium, from the organic matter.

Seedlings grown in the openings were superior in shoot and root lengths and bio-masses to seedlings from most of the pine-influenced treatments. Poorest growth in the openings occurred where fierce competition existed between the pine seedlings and grass species. Within the pine stand, reduced seedling size and vigor were attributed to the abundant overstory canopy, which decreased light quantity and soil and air temperature, to the organic layer, which created poor moisture conditions and a physical barrier to growing seedlings, and to the root systems of larger trees, which were a physical barrier to seedling root penetration. Moreover, the location of these plots allowed for more seedling injury, as well as mortality, because of cutworm, small mammal, and bird feeding activities.

The importance of the removal of litter and competing vegetation in reforestation practices is emphasized here. Small openings within a stand, either man-made or natural, appear to be ideal locations for regeneration, especially pine regeneration in a Douglas-fir habitat type. This study also points out the value of site preparation by fire. Seedlings grown in areas properly treated by fire will likely have distinct survival and growth advantages.

PUBLICATIONS CITED

Baker, F. S.
  1942. Reproduction of ponderosa pine at low elevations in the Sierra Nevada. J. For.
    40:401-404.
Baker, F. S.
  1951. Reproduction of ponderosa pine on old railroad grades in California. J. For.
    49:577-578.
Baron, F. J.
  1962. Effects of different grasses on ponderosa pine seedling establishment. USDA
    For. Serv., Pacific Southwest For. and Range Exp. Stn., Res. Note 199, 8 p.
    Berkeley, Calif.
Bates, C. G.
  1925. The relative light requirements of some coniferous seedlings. J. For. 23:
    869-879.
Biswell, H.
  1973. Fire ecology in ponderosa pine-grassland. Proc. Tall Timbers Fire Ecol. Conf.
    12:69-96.
Black, H. C.
  1970. Animal damage to forest regeneration in the ponderosa pine region of Oregon
    and Washington. *In* Regeneration of ponderosa pine: symposium proceedings, p.
    105-114. Sch. For., Oreg. State Univ., Corvallis, Sept. 11-12, 1969.
Christensen, N. L., and C. H. Muller.
  1975. Effects of fire on factors controlling plant growth in *Adenostoma* chaparral.
    Ecol. Monogr. 45:29-55.
Clapp, C. H.
  1932. Geology of a portion of the Rocky Mountains of northwestern Montana. Mont.
    Bur. Mines and Geol., Mem. 4:1-30.
Cochran, P. H.
  1970. Seeding ponderosa pine. *In* Regeneration of ponderosa pine: symposium pro-
    ceedings, p. 28-35. Sch. For., Oreg. State Univ., Corvallis, Sept. 11-12, 1969.
Cochran, P. H.
  1972. Temperature and soil fertility affect lodgepole and ponderosa pine seedling
    growth. For. Sci. 18:132-134.
Cooper, F.
  1960. Changes in vegetation, structure, and growth of southwest pine forests since
    white settlement. Ecol. Monogr. 30:129-164.
Eyre, F. H., and R. K. LeBarron.
  1944. Management of jack pine stands in the Lake States. U.S. Dep. Agric., Tech.
    Bull. 863, p. 66.
Fisher, G.
  1935. Comparative germination of tree species on various kinds of surface soil
    material in western white pine type. Ecology 16:606-611.
Foiles, M. W., and J. D. Curtis.
  1965. Natural regeneration of ponderosa pine on scarified group cuttings in central
    Idaho. J. For. 63:530-535.
Foiles, M. W., and J. D. Curtis.
  1973. Regeneration of ponderosa pine in the Northern Rocky Mountain--Intermountain
    Region. USDA For. Serv. Res. Pap. INT-145, 44 p. Intermt. For. and Range Exp.
    Stn., Ogden, Utah.
Fowells, H. A.
  1940. Cutworm damage to seedlings in California pine stands. J. For. 38:590-591.
Fowells, H. A., and G. H. Schubert.
  1951. Natural reproduction in certain cutover pine-fir stands of California. J. For.
    49:192-196.

Fowells, H. A., and R. W. Krauss.
   1959. The inorganic nutrition of loblolly pine and Virginia pine with special ref
      erence to nitrogen and phosphorus. For. Sci. 5:95-111.
Gashwiler, J.
   1971. Emergence and mortality of Douglas-fir, western hemlock, and western redcedar
      seedlings. For. Sci. 17:230-237.
Hacskaylo, E., and A. G. Snow, Jr.
   1959. Relation of soil nutrients, and light to prevalence of mycorrhizae on pine
      seedlings. USDA For. Serv., Northeast. For. and Range Exp. Stn., Stn. Pap. 125,
      13 p. Upper Darby, Pa.
Harrington, M. G.
   1977. The response of ponderosa pine seeds to light. USDA For. Serv. Res. Note
      INT-220, 8 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.
Hermann, R. K. (ed.)
   1970. Regeneration of ponderosa pine: symposium proceedings. 126 p. Sch. For.,
      Oreg. State Univ., Corvallis, Sept. 11-12, 1969.
Kelsey, R. G., and M. G. Harrington.
   1979. A search for potential phytotoxins influencing germination and early growth of
      ponderosa pine. USDA For. Serv. Res. Pap. INT-216, 28 p. Intermt. For. and
      Range Exp. Stn., Ogden, Utah.
Larson, M. M.
   1967. Effect of temperature on initial development of ponderosa pine seedlings. For.
      Sci. 13:286-294.
Larson, M. M., and G. H. Schubert.
   1969. Root competition between ponderosa pine seedlings and grass. USDA For. Serv.
      Res. Pap. RM-54, 12 p. Rocky Mt. For. and Range Exp. Stn., Ft. Collins, Colo.
Lawrence, W., N. Kverno, and H. Hartwell.
   1961. Guide to wildlife feeding injuries on conifers in the Pacific Northwest. 44 p.
      West. For. and Conserv. Assoc., Portland, Oreg.
Loewenstein, H.
   1970. Mineral nutrition and the drought resistance of ponderosa pine seedlings. *In*
      Regeneration of ponderosa pine: symposium proceedings, p. 77-81. Sch. For., Oreg.
      State Univ., Corvallis, Sept. 11-12, 1969.
McDonald, P. M.
   1976. Inhibiting effect of ponderosa pine seed trees on seedling growth. J. For.
      74:220-224.
Meyer, W. H.
   1938. Yield of even-aged stands of ponderosa pine. U.S. Dep. Agric. Tech. Bull. 630,
      p. 59.
Pearson, G. A.
   1934. Grass, pine seedlings, and grazing. J. For. 32:545-555.
Pearson, G. A.
   1936. Some observations on the reaction of pine seedlings to light. Ecology 17:
      270-276.
Pearson, G. A.
   1942. Herbaceous vegetation, a factor in natural regeneration of ponderosa pine in
      the southwest. Ecol. Monogr. 12:318-338.
Pfister, R. D., B. L. Kovalchik, S. F. Arno, and R. C. Presby.
   1977. Forest habitat types of Montana. USDA For. Serv. Gen. Tech. Rep. INT-34, 174 p.
      Intermt. For. and Range Exp. Stn., Ogden, Utah.
Rietveld, W. J., and L. J. Heidmann.
   1976. Direct seedling ponderosa pine on recent burns in Arizona. USDA For. Serv.
      Res. Note RM-312, 8 p. Rocky Mt. For. and Range Exp. Stn., Ft. Collins, Colo.
Roe, A. L., and A. E. Squillace.
   1950. Can we induce prompt regeneration in selective-cut ponderosa pine stands?
      USDA For. Serv., North. Rocky Mt. For. and Range Exp. Stn., Res. Note 81, 7 p.
      Missoula, Mont.

Roth, L. F.
   1970.   Disease as a factor in regeneration of ponderosa pine.   *In* Regeneration of
      ponderosa pine: symposium proceedings, p. 89-93.   Sch. For., Oreg. State Univ.,
      Corvallis, Sept.11-12, 1969.
Schultz, A. M., and H. H. Biswell.
   1959.   Effects of prescribed burning and other seedbed treatments on ponderosa pine
      seedlings.   J. For. 57:816-817.
Shearer, R. C., and W. C. Schmidt.
   1970.   Natural regeneration in ponderosa pine forests of western Montana.   USDA For.
      Serv. Res. Pap. INT-86, 19 p.   Intermt. For. and Range Exp. Stn., Ogden, Utah.
U.S. Congress, Senate Committee on Interior and Insular Affairs.
   1970.   A university view of the Forest Service.   U.S. Govt. Printing Off., Doc.
      91-115.
USDA Forest Service.
   1970.   Management practices on the Bitterroot National Forest: a taskforce appraisal.
      Northern Region, Missoula, Mont.
U.S. Department of Commerce, National Oceanic and Atmospheric Administration.
   1973.   Monthly normals of temperature, precipitation, and heating and cooling degree-
      days, 1941-1970.   Climatography of the United States No. 81.
VanSickle, F. S., and R. D. Hickmann.
   1959.   The effect of understory competition on the growth rate of ponderosa pine in
      north central Oregon.   J. For. 57:852-853.
Viro, P. J.
   1974.   Effects of forest fire on soil.   *In* Fire and Ecosystems, T. T. Kozlowski and
      C. E. Ahlgren (eds.), p. 7-45.   Academic Press, New York.
Vlamis, J., H. H. Biswell, and A. M. Schultz.
   1955.   Effects of prescribed burning on soil fertility in second growth ponderosa
      pine.   J. For. 53:905-909.
Vlamis, J., H. H. Biswell, and A. M. Schultz.
   1956.   Seedling growth in burned soils.   Calif. Agric. 10:13.
Vlamis, J., H. H. Biswell, and A. M. Schultz.
   1957.   Nutrient response of ponderosa pine and brush seedlings.   J. For. 55:22-28.
Wagg, J. W., and R. K. Hermann.
   1962.   Artificial seeding of pine in central Oregon.   Oreg. State Univ. For. Lab.
      Res. Note 47, 47 p.
Weaver, H.
   1943.   Fire as an ecological and silvicultural factor in the ponderosa pine region of
      the Pacific Slope.   J. For. 41:7-14.
Weaver, H.
   1951.   Fire as an ecological factor in the southwestern ponderosa pine forest.   J.
      For. 49:93-98.
Weaver, H.
   1955.   Fire as an enemy, friend, and tool in forest management.   J. For. 53:499-504.
Wellner, C. A.
   1970.   Regeneration problems in the Northern Rocky Mountains.   *In* Regeneration of
      ponderosa pine: symposium proceedings, p. 5-11.   Sch. For., Oreg. State Univ.,
      Corvallis, Sept. 11-12, 1969.
Wollum, A. G., II.
   1968.   Influence of nitrogen fertilization on ponderosa pine seedling growth.   Agron
      Abstr., p. 140.
Wollum, A. G., II.
   1970.   Utilization of soil and fertilizer nitrogen by ponderosa pine.   *In* Regenerati
      of ponderosa pine: symposium proceedings, p. 69-76.   Sch. For., Oreg. State Univ.
      Corvallis, Sept. 11-12, 1969.
Wright, E.
   1957.   Importance of mycorrhizae to ponderosa pine seedlings.   For. Sci. 3:275-280.

Headquarters for the Intermountain Forest and
Range Experiment Station are in Ogden, Utah.
Field programs and research work units are
maintained in:

Billings, Montana

Boise, Idaho

Bozeman, Montana (in cooperation with
Montana State University)

Logan, Utah (in cooperation with Utah State
University)

Missoula, Montana (in cooperation with
University of Montana)

Moscow, Idaho (in cooperation with the
University of Idaho)

Provo, Utah (in cooperation with Brigham
Young University)

Reno, Nevada (in cooperation with the
University of Nevada)

NUTRIENT LOSSES FROM TIMBER HARVESTING IN A LARCH / DOUGLAS-FIR FOREST

NELLIE M. STARK

NUTRIENT LOSSES FROM TIMBER HARVESTING IN A LARCH/DOUGLAS-FIR FOREST

Nellie M. Stark

THE AUTHOR

Nellie M. Stark is a forest ecologist with the Montana Forest and Conservation Experiment Station, University of Montana, School of Forestry at Missoula, Mont. She has studied nutrient cycling in temperate and tropical forest ecosystem for many years. She is the author of the direct-cycling theory and also the concept of the biological "life" of soils--a means of evaluating the rate of deterioration of the productivity of soil.

ACKNOWLEDGMENTS

RESEARCH SUMMARY

    Studies of the total amount of biologically essential nutrient
removed in logs and water through clearcutting, shelterwood cutting,
and group-selection cutting were conducted in a western larch (*Larix
occidentalis*)/Douglas-fir (*Pseudotsuga menziesii*) forest at the
Coram Experimental Forest near Glacier Park, Montana. Nutrient
removal by species was investigated under three intensities of
harvest. Results show that with the most intensive logging method
(clearcutting) less than 0.25 percent of the total content of eight
biologically essential cations in the effective root zone were
removed with wood and bark. This means that intensive harvest took
away an equivalent of 1/4 of 1 percent of the nutrients stored in
the soil and rock of the root zone. In theory, it would require
28,000 years of clearcutting on a 70-year rotation to exhaust the
total nutrients in the present root zone. Soil development will
slowly extend the root zone downward. Far more important than total
nutrients are those nutrients available in the soil. Harvest of wood
and bark removed an equivalent of less than 14 percent of most of
the available elements in the root zone. Harvest is a one-point-in-
time removal of nutrients that have been accumulated in the wood and
bark of trees over 70 years time. Removal of only 14 percent of
what is at one moment available in the soil is a small loss. Unfor-
tunately, we cannot yet measure the weathering rate so we cannot
estimate how rapidly the removed nutrients will be returned through
weathering. Harvest did remove from 14.8 to 91.7 percent of the
available zinc in the soil (accumulated over +70 years). Although
zinc is scarce in the parent material, this loss is not serious
because sufficient zinc is still available for seedling growth. In
most cases bulk precipitation alone will return all of the nutrients
removed in harvest within 70 to 100 years. Nutrient losses from
harvest on this relatively young, fertile soil is not a problem to
management in the absence of erosion.

    Nutrient levels in an intermittent stream were virtually
unchanged by all logging treatments. The skyline system did not
cause erosion. Because the area does not have a permanent stream
or impermeable bedrock, it is unsuited to typical watershed study
methods. Water samples taken below the root zone did show nutrient
losses as a result of harvest, but these were at levels not signif-
icant to management. The most severe treatment studied, clear-
cutting by skyline and light burning, did not cause serious nutrient
depletion from this forest ecosystem.

CONTENTS

INTRODUCTION

Modern logging methods are progressing toward complete utilization of wood fiber. With greater utilization comes increased removal of biologically essential nutrients. On rich soils, nutrient loss may do little harm, but on old or very young, poorly developed soils nutrient depletion caused by harvest may create either temporary nutrient shock or long-term nutrient deficiencies. In the case of nutrient shock (depletion of available nutrients), the soil contains adequate levels of biologically essential elements but they are in unavailable form. During shock, one or more of the essential elements is depleted from available form, and time is needed to allow weathering, precipitation, and organic decomposition to restore the available nutrient reserves. Long-term nutrient deficiencies result when not enough of one or more biologically essential elements remains in the root zone of the soil in either available or unavailable form to restore the soil to productivity (Stark 1977, 1978).

In western Montana, the greatest concern is for temporary nutrient depletion of young, undeveloped soils. Steep topography can accelerate nutrient loss through runoff, erosion, dust, or slump. In calculating nutrient losses resulting from harvesting, data are often not available for various species or different harvesting intensities.

This study has accumulated data on the elemental content of the harvestable portions of eight local tree species. Actual nutrient loss from the site was estimated from careful measurement of the volumes and weights of each species harvested. Harvest losses were related to the levels of available and total biologically essential elements in the soil to the limit of the root zone.

Land managers have also shown increasing concern over the possible loss of nutrients in soluble form from the root zone as a result of harvest. Erosion and solution losses below the root zone can detract from the ability of a soil to grow the next forest. Where logging activities approached streambanks too closely, there has been an increase in the sediment load and nutrients lost via streams. The Hubbard Brook study (Bormann and others 1968) showed the magnitude of nutrient loss associated with clearcutting. Few studies have attempted to quantify loss of soluble nutrients on drier western soils where the streams are intermittent and the bedrock fractured. Loss of soluble nutrients must be understood to allow ecologically sound land management.

Numerous studies have monitored the effects of logging and fire on stream water quality (Fredriksen 1971, Fredriksen and others 1975; Likens and others 1967; Moore 1974; Tiedemann 1974). Watershed studies are conventionally used to show changes in water quality as a result of treatment. But the stream studied in the Coram Experimental Forest is partly underground. It is ephemeral and the area does not have unfractured bedrock, making it unsuited to a conventional watershed study. For this reason, nutrient losses below the root zone were measured using lysimetry and tension soil water extractors. Nutrients lost below the root zone of a mature forest are almost as effectively lost to tree growth as if they were washed into a stream.

In 1973, the USDA Forest Service initiated a series of timber harvesting and utilization studies on the Coram Experimental Forest near Glacier National Park in western Montana (fig. 1). The overall objective of the project was to evaluate four levels of utilization and three silvicultural prescriptions, followed by burn and no-burn treatments, on the recovery of the above and below ground portions of the ecosystem. The study reported here, a portion of the total project, describes the impact of different levels of log removal and solution losses on the nutrient status of the ecosystem.
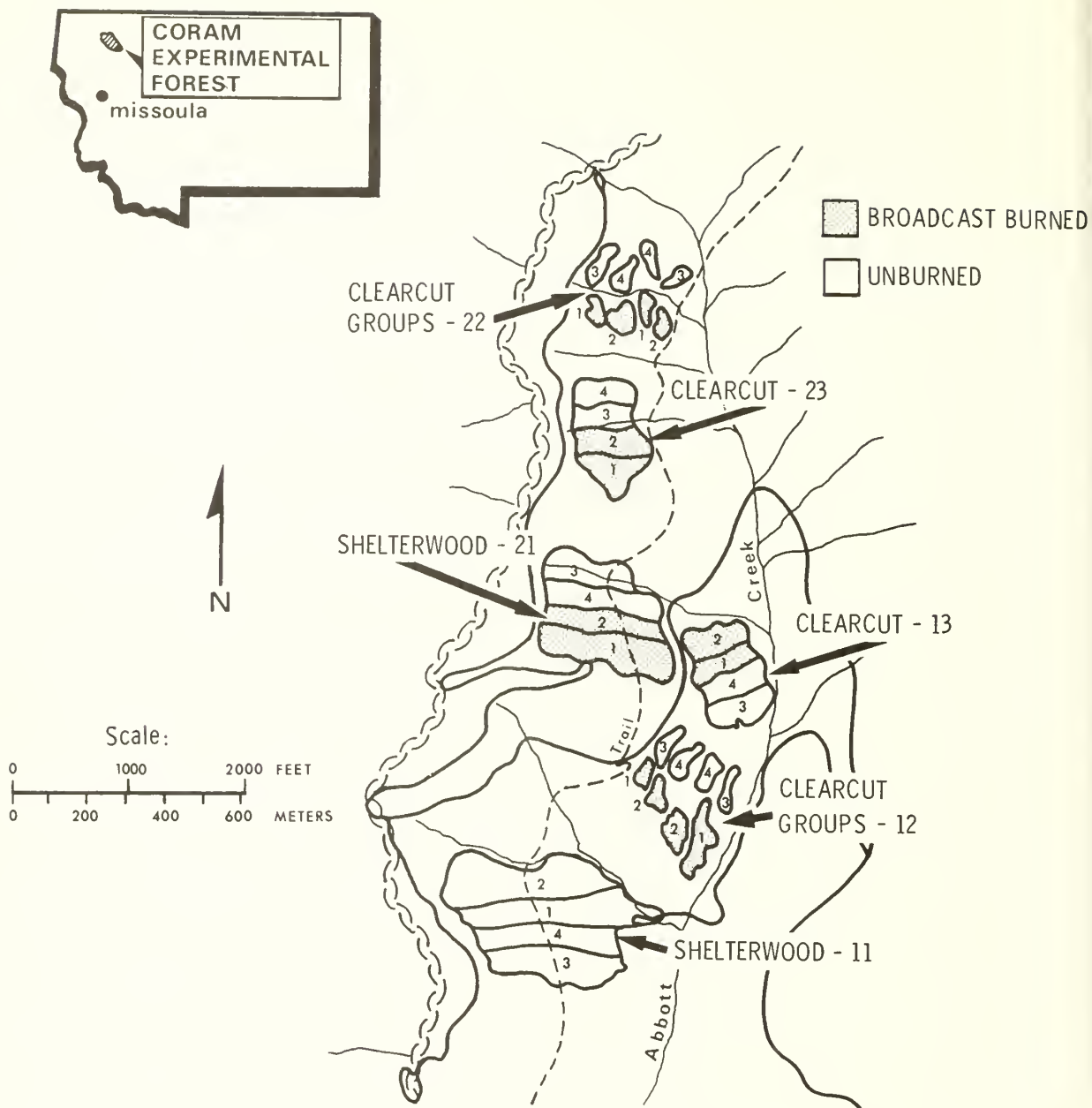
Figure 1.--Map of the Coram Experimental Forest logging study sites (from Artley and others 1978).

The treatments were designed to study the effects of different degrees of fiber utilization and burning 1 year after logging. The study involved 12 scientists and covered the period 1 year prior to logging (1973-74), logging (May-September 1975), burning (September 1975), and 2 years thereafter.

The forest is composed of larch/Douglas-fir (*Larix occidentalis* Nutt./*Pseudotsuga menziesii* [Mirb.] Franco) on steep slopes (35-45 percent) from 3,339 to 6,269 feet (1,018 to 1,942 m) elevation. The mean annual precipitation at the lower stations averages 31 inches (787 mm), with a mean annual temperature of 42.8°F (6°C). Much of the precipitation falls as snow. The snowpack lasts about 6 months. Appendix A includes a habitat type listing and a species listing for herbs and shrubs. Soils are derived from argillite, impure limestone, and quartzite, with some influence from glacial drift and in some areas volcanic ash (Klages and others 1976). Most are gravelly silt loams with up to 50 percent rock. Surface soil had a bulk density of 0.9 g/cm^3. The soils of the study area are primarily cryocrepts of the Felan series (possibly andeptic), and andeptic cryoboralfs, or eutroboralfs.

A portion of the main study included a complete inventory by the USDA Forest Service of all standing dead and live timber, as well as downed timber before and after harvest.[1] The difference constitutes the material removed from the site during harvest.

The silvicultural prescriptions included two replications of clearcutting, shelterwood, and group selection logged with a skyline yarding system. Treatments within each prescription were (descending order of intensity of utilization) as follows:

Silvicultural prescription	*Utilization standard*	*Remaining understory treatment*	*Postharvest site preparation*
Clearcut (CC) 1 and 2	1. Intensive log utilization (8 ft long, 3 in top, 2.4 m-7.6 cm) *all* trees live and dead.	Cut	Broadcast burn
	2. Conventional sawlog utilization of live and recently dead sawtimber.	Cut	Broadcast burn
	3. Heavy fiber utilization of all trees 1+ in dia. (2.54 cm), live and dead, including tops and branches 1+ in (2.54 cm).	Cut	None
	4. Intensive log utilization (8 ft, 3 in top, 2.4 m-7.6 cm) all sawtimber (7+ in dia., 17.8 cm), live and dead.	Uncut	None
Shelterwood (SW) 1 and 2	Same as for clearcuts for all categories		
Group selection (GS) 1 and 2	Same as for clearcuts for all categories		
Control (C) 1 and 2	Unlogged, unburned		

---

[1]Benson, R. E., and Joyce Schleiter. 1978. Volume and weight characteristics of a typical Douglas-fir/western larch stand. USDA Forest Service, unpublished report.

INFLUENCE OF LOGGING ON SOIL WATER NUTRIENTS

Methods

Skyline logging studies in Douglas-fir/larch forests at the Coram Experimental Forest in western Montana used clearcutting and shelterwood cuts, with three levels of utilization (reported here). Because the area does not have a permanent stream, nutrient loss was measured in the ephemeral Abbott Creek and through changes in the soil water quality below the root zone. The elements H, Ca, Cu, Fe, F, Mg, Mn, Na, NO_3, PO_4, and Zn were measured in soil and stream water, in precipitation, and throughfall whenever water was available before and after logging and 1 year after burning.

The study reported here covers only the nutrient cycling portion of the main research. Only the clearcut and shelterwood areas were studied for soil water quality and the fourth treatment (understory uncut, slash left, no burn) was omitted from consideration to focus attention on extreme treatments.

Changes in soil chemistry were studied by soil extraction using 0.002N H_2SO_4 and by soil water extracted from soil in the field using permanently placed tension extractors (Soil Moisture Corporation). Soil and water samples were from replicate plots on clearcutting and shelterwood treatments. Soil samples were obtained by digging a pit to 19.6 inches (50 cm) and removing 4,000 g soil samples at 0-3.9 inches (0-10 cm), 7.8-9.8 inches (20-25 cm), and 17.7-19.6 inches (45-50 cm) depth. The soil samples were then taken to the laboratory, sieved (1 mm), and 2 g subsamples were extracted with 0.002N H_2SO_4. The cations were analyzed on an atomic absorption spectrophotometer (Techtron AA-5). Phosphate was determined colorimetrically on the acid extract (Farber 1960). Soils were also tested for physical characteristics. Soil water samples were extracted from sites 3 feet (1 meter) from the soil pits (fig. 2) by placing a 1-1/2 inch (3.8 cm) plastic tube with a porous ceramic tip in a carefully augered 1-1/2 inch hole to 19.6 inches (50 cm). The porous ceramic tip was previously cleaned with acid and distilled water. The tip was seated in a slurry of mud from the bottom of the hole and sealed along the sides of the hole to prevent air leaks. After a period of 5-10 days for equilibration, the PVC tubing was sealed with a stopper and a vacuum was pumped on the tube, drawing soil water in through the ceramic tip. After 3-5 days, soil water was removed from the tubing using a clean pump and acid-cleaned Nalgene tubing and bottles. This water was taken in marked bottles to the laboratory for chemical analysis on the atomic absorption spectrophotometer and colorimeter.

The two methods, laboratory soil extraction and field soil water extraction, were used to compare results. Soil water removed under tension was by far the best indicator of changes in soil chemistry. The soil water is the solution in immediate contact with living roots and from which roots obtain nutrients. It is not an artificial extract. The soils vary greatly from point to point, so a soil water sample gives integrated results. Therefore, only soil water data will be reported here. Samples of soil water were withdrawn from above the tree root zone, within the tree root zone, and below the tree root zone whenever available soil water occurred. Fractured rock occurs at 19.6-21.7 inches (50-55 cm) depth. The data presented here represent the results from 200 soil water probes over 4 years. Bulk precipitation, stream water, and through fall were collected from the same areas. Abbott Creek is ephemeral and partly underground, so it could not be used directly in evaluating nutrient losses from the treatments. It surfaces above one of the treated areas, and then goes underground below the clearcut and emerges near the shelterwood cuts. Changes on the slopes could be reflect in the stream, in spite of its ephemeral nature.

Figure 2.--*Soil water probes set at three depths in the ground to collect soil water after the burns at Coram.*

Water samples had to be frozen because of the distance between the laboratory and field study site. The samples were normally frozen for 1 week, thawed at room temperature, and analyzed by a Techtron AA-5 atomic absorption spectrophotometer for Ca, Cu, Fe, K, Mg, Mn, Na, and Zn (Techtron 1974). Subsamples were tested for pH, F, and NO_3 by specific ion analyzer, and PO_4 by the most sensitive stannous chloride method reported in Farber (1960). Data from other portions of the study were used to aid in the final interpretation. Because water samples could rarely be brought from the field in winter without freezing, it was impossible to measure bicarbonates.

Statistical tests compared the changes in the elemental content of soil water means:

1.   By depths and treatments--total cations and anions

2.   By year and treatments--total cations or anions

3.   By silvicultural prescription and utilization standard--total cations or anions

4.   By all three methods above for individual cations and anions

5.   By control blocks versus test blocks and by test versus test blocks.

The F-statistic was used first to test for equal variances in each paired comparison. Where the variances were found to be equal, a regular t-test was used to test for the differences in the means; an "appropriate" t-test was used.

Results and Discussion

All results are expressed as significant at the 5 percent level. Data are reported for pretreatment (July 1973-April 1974, 237 collections), postlogging (May 1974-Sept. 1, 1975, 452 collections), and 1-year postburn (Sept. 1, 1975-June 30, 1976, 870 collections). About 510 collections were made in 1978.

The initial statistical tests showed that the replicates for each silvicultural prescription differed significantly in soil water quality so that the two clearcuts and two shelterwood treatments had to be considered separately. Comparisons were made between the test area and its nearest unlogged control (table 1). Appendixes B and C provide detailed soil physical and chemical data, which may be compared to soils elsewhere and which may be useful in management plans.

Table 1.--*Mean and standard deviation of total cations and anions in soil water after logging and after burning, Coram logging study (mg/ℓ)*

Study plot		Postlogging treatment			Postburn treatment		
		1	2	3	1	2	3
Total cations							
Control 1[1]	Mean	21.8	21.8	21.8	22.3	22.3	22.3
	SD	16.3	16.3	16.3	10.9	10.9	10.9
Control 2	Mean	7.1	7.1	7.1	9.0	9.0	9.0
	SD	3.2	3.2	3.2	3.9	3.4	3.9
Shelterwood 1	Mean	13.9	14.9	12.1	14.5	14.3	12.9
	SD	6.5	8.2	6.3	5.0	9.0	6.1
Shelterwood 2	Mean	19.4	9.2	15.1	17.3	10.8	11.4
	SD	10.2	4.4	15.6	7.5	5.3	9.1
Clearcut 1	Mean	17.2	34.3	19.6	25.1	41.5	22.1
	SD	10.7	26.7	12.8	13.5	28.4	17.6
Clearcut 2	Mean	17.3	7.9	11.9	17.2	16.2	11.9
	SD	10.7	4.9	6.7	11.9	11.9	6.7
Total anions							
Control 1	Mean	1.9	1.9	1.9	7.5	7.5	7.5
	SD	.9	.9	.9	5.2	5.2	5.2
Control 2	Mean	1.4	1.4	1.4	2.6	2.6	2.6
	SD	.6	.6	.6	4.9	4.9	4.9
Shelterwood 1	Mean	2.2	5.6	2.1	4.8	3.9	4.9
	SD	1.3	9.3	1.4	5.1	3.6	4.6
Shelterwood 2	Mean	1.9	1.3	1.3	6.4	7.1	3.8
	SD	.8	.7	.5	6.4	6.9	2.9
Clearcut 1	Mean	5.3	14.2	6.5	19.6	31.2	5.5
	SD	3.5	15.9	5.5	15.9	25.0	5.4
Clearcut 2	Mean	3.3	1.4	3.0	19.9	14.3	3.0
	SD	5.0	.5	2.6	19.4	12.3	2.6

[1]Controls 1 and 2 are the same plots for treatments 1, 2, and 3. Treatment 1 = heavy log utilization, light burn, Treatment 2 = conventional utilization, medium burn, Treatment 3 = heavy fiber utilization.

Shelterwood Logging--Cation Losses

The total cations in the soil water for shelterwood 1 were lower 1 and 2 years postlogging when compared to the closest control. Shelterwood 2, which was about 0.31 miles (0.5 km) from shelterwood 1, had higher cation levels in the soil water for treatment 1 postlogging, and treatments 1 and 2 (light and hot burns) postburn (table 1). The total soil water cations in shelterwood 1 probably result from unusually high levels of ions in the soil water of the control, which had unusually deep litter. Shelterwood 2 behaved more as expected (table 1), with higher cation loadings in the postlogging and postburn soil, compared to its nearest control (control 2, table 1). Standard deviations are sometimes high because data cover a full year's seasonal variation.

Clearcut Logging--Cation Losses

Clearcut 1 was the only block where a moderately hot burn treatment was possible. It produced a significant increase in the soil water cations, compared to its closest control (1). Logging left considerable needle debris on the slopes, which produced postlogging increases in the soil cations of clearcut 1, and postburn increases from nutrients added from ash. Clearcut 2 had higher total cation levels in the soil water following logging where the slash was removed and later burned (treatment 1) and where it was removed and not burned (treatment 3) but not in treatment 2. The removal of slash left a large amount of fine needle debris so that all sites had abundant fungal growths during the winter under the snow, regardless of whether the coarse slash (3 in, 7.6 cm) was removed or not. After burning, clearcut 2 had higher soil cation levels than its control for all treatments, heavy and light burning, and no burning (table 1).

Shelterwood Logging--Anion Losses

The total anions in the soil water of shelterwood 1 were higher 1 year postlogging on the heavy slash site (treatment 2, table 1), but lower than the control 2 years postlogging. In the case of shelterwood 1, "postburn" actually means 2 years postlogging, because this block was never burned. Shelterwood 2 was burned, and showed high levels of anions in the light burns but not the hot burns (postburn) and only in the heavy slash loading postlogging (compared to controls). High anion levels on the high utilization unburned site must come from the decay of excess needles.

Clearcut Logging--Anion Losses

Clearcut 1 had significantly higher levels of total anions in the soil water (mostly NO_3^-N) following logging in all three treatments, compared to the soil water from controls. This means that slash decomposition during the first year following logging resulted in an unusually high rate of nitrate release relative to the controls. Postburn, the anions were high in treatments 1 and 2 (light and heavy burns). Clearcut 2 showed elevated levels of anions only in treatment 3 (slash removed), but in all three treatments postburn (table 1). The main anion is again nitrate.

Total Cation and Anion Losses by Slash Treatment

The effects of the three slash treatments on total soil water cations can be seen by comparing treatment means within years. For total cations, all depths combined, treatment 1 (slash removed, burned) was different from treatment 2 (slash left, burned) in four out of eight possible cases. Treatments 1 and 3 differed in two out of eight cases, and treatments 2 and 3 differed significantly in three out of eight cases.

No one treatment produced predictable increases in soil water cations in more than 50 percent of the tests. This is partly the result of the moderate disturbance of the site from the logging method (skyline) and the relatively low burning temperatures (138°F, 59°C).

The total anions differed significantly between treatments 1 and 2, and treatments 1 and 3 four out of eight times (each) and between treatments 2 and 3 in six out of eight cases. The heavy burn did produce significant increases in the anions and particularly nitrate in soil water.

Results by Individual Ions

The analysis of the results for individual ions requires considerable space, therefore only a few main points will be presented in a year-to-year comparison. The elements NO_3, Mg, Cu, Na, Zn, and Mn were those most often influenced by logging and burning (table 2). Those most influenced by burning alone were NO_3^-, Cu, Mg, Mn, K, Fe, Zn, and PO_4. Those least influenced by the treatments were Ca, F, and Fe. These are strongly dependent on an acid soil solution for solubility. In most cases the alkali added to the soil through burning was inadequate to cause a greater increase in soil alkalinity as had occurred in a previous study (Stark 1977). If the burns had been hotter than 572°F (300°C), these elements, and particularly Fe, should have been significantly altered by the burning. The average ion concentrations in soil water are shown in table 3.

Table 3 shows the average levels of cations and anions present in soil water before logging and after burning. Unfortunately, during 1973-74, or prelogging, no data could be obtained from shelterwood 2, clearcut 2, and control 2. These results summarize the effects of increasing utilization for all four areas compared to the two controls (table 3). Most elements in the soil water do not show drastic differences between prelogging and postburn samplings. There is a tendency toward more NO_3^--N and PO_4 after burning, but only in a few cases are the differences great. Significant differences that appear in the raw statistics may not appear in these summaries. The summaries are included to show the low magnitude of chemical differences in soil water resulting from logging and light burning.

Shelterwood cutting caused the greatest changes in phosphate with the most important differences between postlogging and postburn treatments 1 and 2 for shelterwood 2. Shelterwood 1, which was not burned in 1975, had almost no significantly different soil water ion concentrations 2 years postlogging.

Clearcutting showed no definite pattern of elemental differences in the soil water following logging, but treatments 2 and 3 were most different (by seven elements on clearcut 1, but not on 2). Burning produced significant differences in 10 ions between the medium burn (treatment 2) and slash removal (treatment 3) postburn for clearcut 1 but not for 2. Clearcut 1 generally burned much hotter than did 2.

Ionic differences by depth were most prominent between 7.9-9.8 inches (20-25 cm) and 15.7-19.6 inches (40-50 cm) when all 3 years were considered collectively. This is surprising because the burning and logging should have caused the greatest change at 0-3.9 inches (0-10 cm). The importance of deep soil differences in ion content suggests a spotty but widespread influence of scattered limestone deposits beneath the soil surface.

The means in tables 1 and 3 are figured on a slightly different number of sample points, so they do not agree exactly.

Table 2.--*Summary of results of year-to-year statistical tests, combining over all soil depths and separating silvicultural practices, level of utilization, and site preparations*

Year[1]	Ca	Cu	Fe	F	K	Mg	Mn	NO₃	Na	PO₄	Zn	Cations	Anions
Years 1 vs 2													
Control 1		*[2]		*		*	*		*				
Shelterwood 1													
Heavey log util. light burn													
Conv. log util. med. burn			*			*	*	*	*		*	*	
Heavy fiber util.-no burn						*	*		*	*	*	*	
Clearcut 1													
Heavy log util. light burn													
Conv. log util. med. burn	*	*		*			*	*			*	*	
Heavy fiber util.-no burn		*	*			*		*	*		*		
Control 2													
Shelterwood 2													
Heavy log util. light burn													
Conv. log util. med. burn													
Heavy fiber util.-no burn													
Clearcut 2													
Heavy log util. light burn		*	*			*	*	*	*				
Heavy fiber util.-no burn													
Year 1 vs 3													
Control 1													
Shelterwood 1													
Heavy log util. light burn													
Conv. log util. med. burn	*		*			*	*			*		*	*
Heavy fiber util.-no burn		*				*	*	*	*				

See footnotes at end of table.

Table 2.--*Summary of results of year-to-year statistical tests, combining means for all soil depths and separating silvicultural practice, level of utilization, and site preparation--Continued*

Year[1]	Ca	Cu	Fe	F	K	Mg	Mn	NO$_3$	Na	PO$_4$	Zn	Cations	Anions
Clearcut 1													
Heavy log util. light burn													
Conv. log util. med. burn	*		*	*	*	*			*	*	*		
Heavy fiber util.-no burn		*	*	*		*			*	*	*	*	
Control 2													
Shelterwood 2													
Heavy log util. light burn													
Conv. log util. med. burn													
Heavy fiber util.-no burn													
Clearcut 2													
Heavy log util. light burn													
Conv. log util. med. burn													
Heavy fiber util.-no burn													
Years 2 vs 3													
Control 1					*	*	*	*	*				
Shelterwood 1													
Heavy log util. light burn	*	*		*		*					*		
Conv. log util. med. burn											*		
Heavy fiber util.-no burn	*					*					*	*	
Clearcut 1													
Heavy log util. light burn	*	*		*	*	*					*		*
Conv. log util. med. burn	*	*		*	*	*							
Heavy fiber util.-no burn	*							*					

See footnotes at end of table

(Cont.)

Table 2.--*Summary of results of year-to-year statistical tests, combining across for all soil depths on separating silvicultural practice, level of utilization, and site preparation--Continued*

Year[1]	Ca	Cu	Fe	F	K	Mg	Mn	NO$_3$	Na	PO$_4$	Zn	Cations	Anions
Control 2	*	*						*			*		
Shelterwood 2													
Heavy log util. light burn		*				*	*	*	*				
Conv. log util. med. burn				*		*	*	*	*				
Heavy fiber util.-no burn		*	*				*	*	*				
Clearcut 2													
Heavy log util. light burn	*	*				*	*	*	*		*		
Conv. log util. med. burn	*			*			*	*		*			
Heavy fiber util.-no burn	*					*	*		*		*		

[1]Year 1 - prelogging,
Year 2 - postlogging,
Year 3 - postburn.
-* indicates a significant difference at the 5 percent level.

11

Table 3.--Average elemental content of Coram soil water by silvicultural treatment before logging (1973-74) and after burning (1975-76)

Block	Treatment	H+ X10⁻⁶	Ca	Cu	Fe	F	K	Mg	Mn	NO₃	Na	PO₄	Zn	Total Cations	Total Anions
Prelogging															
Shelterwood 1	2	--	9.8	0.04	0.25	0.09	4.9	2.1	0.06	3.6	--	0.33	0.04		
	3	--	7.5	.03	.16	.10	3.4	2.1	.02	1.8	--	.23	.03		
Clearcut 1	2	--	12.3	.04	.15	.18	7.2	2.4	.03	5.4	--	.54	.04		
	3	--	12.9	.03	.27	.09	2.9	1.8	.02	2.9	--	.29	.04		
Control		--	14.2	.03	.19	.12	3.5	1.9	.02	2.5	--	.13	.03		
One Year Postburn															
Shelterwood 1	1	0.10	8.1	.06	.17	.15	4.4	1.7	.01	3.5	0.8	.94	.03	15.3	4.6
	2	.10	7.1	.03	.16	.09	4.2	1.5	.01	2.9	.8	.62	.03	13.7	3.6
	3	.09	8.3	.04	.12	.16	3.9	1.7	.01	4.4	.9	.49	.03	15.0	5.1
Shelterwood 2	1	.15	7.7	.06	.12	.11	7.2	2.5	.04	5.0	1.0	.74	.04	18.7	5.8
	2	.17	4.2	.04	.13	.06	4.7	1.4	.04	5.9	.6	.53	.02	11.2	6.5
	3	1.90	6.5	.04	.13	.10	3.6	2.3	.18	3.0	.6	.54	.03	13.5	3.7
Clearcut 1	1	.08	15.0	.04	.08	.38	5.2	2.3	.01	16.9	.7	.87	.02	25.4	17.9
	2	.03	24.3	.03	.04	.64	12.5	4.2	.01	28.6	.7	.75	.02	41.9	29.6
	3	.06	16.3	.04	.16	.31	2.2	2.1	.01	5.1	.5	.37	.03	21.4	5.7
Clearcut 2	1	.13	8.9	.05	.15	.08	5.9	2.5	.01	16.7	.7	.81	.06	18.3	17.6
	2	5.00	7.9	.05	.13	.21	5.5	1.8	.16	12.8	.8	.80	.05	16.3	13.8
	3	.39	5.3	.05	.14	.09	4.0	1.3	.01	6.8	.5	.55	.04	11.3	7.4
Control 1		.05	13.8	.04	.13	.12	5.0	2.4	.005	6.3	.8	.37	.02	22.2	6.8
Control 2		.35	4.7	.06	.19	.09	2.2	1.0	.009	2.3	.6	.27	.05	8.8	2.6

The total cations in the soil water showed few significant differences by year, but the total anions were significantly different between years 2 and 3 (logging and burning) in shelterwood 1, 10 out of 14 plots. Copper, potassium, magnesium, nitrate, sodium, and phosphate were the ions most influenced by burning between years 2 and 3. Logging, as measured by ion changes between years 1 and 2, produced fewer ionic differences than did burning. Those ions most affected by logging (based on annual comparisons) were F, Mg, Mn, NO_3, Na, and Zn. These were probably released from extremely active needle decay during the winter.

The exceedingly dry summer of 1977 complicated this study. Only a very few soil water samples could be extracted at all, and these were taken in the early spring. So few samples of soil water are available from 1977 that it is impossible to tell anything about nutrient movement for that year. It is quite certain that very little water or nutrients moved below the root zone in 1977.

In 1978, more than 450 soil water samples were collected during the spring. For purposes of comparison, data were taken from the months of May and June for 1978 and compared to data from May and June of 1976, the last year with collectable soil water. Data were combined for all depths within treatments for each block studied. Results are summarized in the following tabulation:

Block	Treatment	Significant ion	Year with greater quantity
Shelterwood 1	Unburned Light fuel	Ca	78
		Cu	78
		Zn	78
Shelterwood 1	Unburned Heavy fuel	Cu	78
		Fe	78
		F	78
		NO_3	76*
		Zn	78
Shelterwood 1	Heavy utilization No burn	Cu	78
		Fe	78
		F	78
		NO_3	76*
		Zn	78
Clearcut 1	Heavy fuel Burned	Cu	78
		Fe	78
		F	78
		NO_3	76*
		Zn	78
Clearcut 1	Heavy utilization Unburned	F	78
		K	76
		Mn	76
		NO_3	76*
		Na	76
Control 1	No treatment	Cu	78
		F	78
		NO_3	76*
		Zn	78

Continued

Block	Treatment	Significant ion	Year with greater quantity
Shelterwood 2	Light fuel Burned	Fe	78
		F	78
		NO_3	76*
		Zn	78
Shelterwood 2	Heavy fuel Burned	Ca	78
		Cu	78
		Fe	78
		F	78
		NO_3	76*
		Zn	78
Shelterwood 2	Heavy utilization	Cu	78
		Fe	78
		F	78
		Mn	76
		NO_3	76*
		Na	76
		Zn	78
Clearcut 2	Light fuel Burned	Fe	78
		F	78
		NO_3	76*
		PO_4	76
Clearcut 2	Heavy fuel Burned	Fe	78
		F	78
		Mn	76
		NO_3	76*
		Zn	78
Clearcut 2	Heavy utilization	Ca	78
		Fe	78
		F	78
		Mg	78
		NO_3	76*
		Na	78
		Zn	78
Control 2	No treatment	Ca	78
		Cu	78
		F	78
		Mg	78
		Mu	78
		Zn	78

----

*NO_3 consistently higher in 1976.

These results are extremely difficult to interpret because the 1978 soil water represents those nutrients freed from the surface and through weathering in 1977 and in 1978, minus what was taken up by plants. Normally, nutrient status is best evaluated year by year, but this is impossible with this method in dry soil. Theoretically, low available soil moisture during the growing season in 1977 should mean abnormally low nutrient uptake from the soil and slow growth. Increment borings of trees in the area do verify slow growth for 1977, but there is no proof of low uptake. If the roots did not take up their "normal" amount of water and nutrients in 1977, then there would be a natural excess of nutrients in available form at the start of 1978. These extra nutrients would appear in the extracted soil water in 1978 and we would not know if they were "a leftover excess" from 1977, or if they truly resulted from the treatments applied.

Soil moisture in July of 1977 was 7.8 percent and only 8.4 percent in the wettest period of the summer. Based on the -1/3 and -15 bar moisture contents for these soils, a summer moisture percentage of 7.8 percent would allow little or nothing for plant uptake and growth in July. Thus, most nutrient and water uptake had to occur in May and June of 1977. The trees apparently lost 1.5 months of growth water in 1977. From these results, it is fair to say that some nutrients were left in the soil after the 1977 growing season in excess of the "usual" levels after a full growth period. High nutrient levels in 1978 would be expected under these conditions. We still do not know for sure if nutrient levels were elevated in 1978 because of treatment inputs or not. The magnitude of differences in means from 1976 and 1978 is small enough to suggest that if treatment was also causing higher soil water nutrient levels, it was probably not a major addition of great significance to management. In a few cases the means for individual ions in the 1978 soil water were two to three times higher than for 1976, but in the majority of cases, the difference of means was much lower. Copper and zinc were often two or more times higher in the soil water in 1978 as compared to 1976. Because this difference appears in the control plots also, it is likely that the increase in these ions in soil water is the result of some widespread release after the soil became moist again and not of the treatments alone.

Not all ions were higher in 1978 than in 1977. Potassium and magnesium were only higher in a few cases. Potassium did not show up as significantly higher (5 percent) in the 1978 soil water from any of the hot or lighter burns, suggesting that burn treatment effects had disappeared. Sodium was higher in 1978 than in 1976 in only 3 out of 14 plots. Copper and zinc were higher in 1978 soil water in 8 out of 14 plots; zinc, in 11 out of 14 plots, respectively. PO_4 was highest in 1978 soil water in only 1 out of 14 plots (clearcut 2, light burn).

Nitrate was higher in 1976 soil water compared to 1978 soil water in 11 of 14 plots. Nitrate was often two to five times higher in 1976 than in 1978, which suggests treatment effects forcing the soil nitrate levels higher in 1976. Because nitrate is the only ion that is produced in the soil mainly by microbial activity, it could be expected to behave the opposite of ions weathered from rock. Ion release from organic matter is all microbial, but additions of nitrate to the system are dependent on both temperature and moisture. It is likely that the low soil moisture in 1977 resulted in less nitrogen fixation than would occur in a wetter year. Thus, the soil water would be readily depleted of available NO_3-N in 1978 when active plant growth began. Only the light burn area in clearcut 1 showed no significant ion differences in soil water between 1976 and 1978. Control 2 showed 6 out of 10 ions higher in 1978 than in 1976, again suggesting that these high ion concentrations were the result of drought rather than the treatments. Control 1 had fewer significant ions in the 1978 soil water as compared to control 2, but control 1 had much less litter and different soil moisture conditions than occur at higher elevation.

In general, the effects of logging and fire appear to be small 4 years after logging and 3 years after light burning.

Clearcutting had a greater impact on soil nutrients than did shelterwood cutting, although neither produced massive or serious nutrient losses. Burning, as expected, increased the concentration of most ions in the soil water, especially Cu, K, Mg, Na, NO_3, and PO_4. The low intensity of the burns did not significantly reduce soil water iron, as is known to occur in hot burns (Stark 1977). Logging temporarily increased soil water levels of F, Mg, Mn, NO_3, Na, and Zn. This is the result of the rapid winter decay of a heavy green needle loading on the surface of the soil following logging. Slash removal often did not reduce soil water ion concentrations because wood to 3 inches (7.6 cm) was mainly removed, leaving behind large quantities of fine branches and needles. The needles began decaying under the snow during the first winter, whereas the recently cut heavy wood would release very few nutrients during the first winter.

Direct analysis of soil water is a more reliable indicator of short-term changes in soil water chemistry, than are artificial soil extraction procedures.

In this ecosystem, total nutrient losses beyond the reach of roots were insignificant. The data suggest that minimal surface disturbance by skyline logging does not cause excessive nutrient losses from the ecosystem. Although clearcutting influenced soil water quality more than did shelterwood cutting, neither produced serious nutrient losses. Burning increased soil water ion loads for a year, but the generally low-intensity burns prevented massive nutrient losses below the root zone. A full evaluation of nutrient losses from harvest and slash treatment requires measurements of the nutrients removed in harvested wood and bark. These measurements are being reported separately. The study demonstrates that logging and slash disposal as practiced here are not damaging in terms of excessive soil nutrient losses beyond the root zone or through overland flow into streams. Different results can be expected with different, more erosive soils or logging methods that disturb the surface soil.

Abbott Creek

Abbott Creek runs underground for 0.12 mile (0.2 km) and may dry up or disappear in late summer. Samples taken from above and below the treated areas actually showed a reduction in ion content, which is probably the result of 0.12 mile (0.2 km) underground transit. For this area, a watershed-type study was impractical. For a week postburn, there was a slightly elevated level of ions in the creek, but statistically not significant. Other studies involving cutting have shown considerable export of nitrogen and other ions in stream water on watersheds with impermeable bedrock (Bormann and others 1968).

INFLUENCE OF WOOD REMOVAL ON NUTRIENT CYCLING

Methods

To estimate how much of the biologically essential nutrients were being removed from the site as a result of harvest, it was necessary to analyze wood and bark in their naturally occurring proportions. All three silvicultural treatments were studied in duplicate, and all utilization treatments except the heavy utilization treatment, which included wood, bark, needles, and branches.

During harvest, wood and attached bark were collected from eight tree species, living and dead, using increment borings and cross-sections. Nutrient removal was based on the weight of bole wood removed. Volumes of wood removed per plot by species were converted to weight (kg) of wood and bark removed.

All plant samples were dried at 149°F (65°C), finely ground to under 0.069 inch (1 mm) and ashed in a muffle furnace at 977°F (525°±5°C) for 2 hours (Jackson 1958). The elements Ca, Cu, Fe, K, Mg, Mn, Na, and Zn were analyzed by atomic absorption spectrophotometry (Techtron 1974) and phosphate was measured by colorimetry (Jackson 1958). Total nitrogen was measured by the modified microKjeldahl procedure (Hesse 1971).

Over a period of three summers, duplicate soil extractions were made from the study site on 600 samples each year, using $0.002N$ H_2SO_4 extractant and measuring the same elements as were analyzed in plant samples. Two hundred soil and rock samples were also digested in HF-$HCLO_4$ to determine total elemental content of the root zone. The percentage of rocks and the depth of the root zone were determined in the field. In addition, 500-800 soil water samples were extracted each year using soil moisture probes under tension, and were analyzed on the atomic absorption spectrophotometer with bulk precipitation, throughfall, and stream water for the same elements. An Orion specific ion analyzer was used for H^+, F^-, NO_3^--N, and a colorimeter for PO_4^--P by the most sensitive method for water (Farber 1960). These data constitute more than 500,000 measurements and are reported briefly in the first portion of this paper. They were used in calculating the actual amount of each element removed from the ecosystem during harvest.

Results and Discussion

The site index for western larch is 65 (SI 50-70, 50 years; Ray Shearer, personal communication, Forestry Sciences Laboratory, Missoula, Mont.) for the area and is reasonably uniform so that greater diameter usually means greater age. Wood of the same species varied considerably in elemental content with age and diameter (table 4). Sampling from increment borings made it possible to analyze the proper proportion of wood to bark for each diameter class. Elemental differences with size were the result of thicker bark with age, changing wood/bark ratios, and progressive storage of waste products in older wood. Often wood in the 6-12 inch (15.2-30.5 cm) size class was lower in elemental content than either the younger or older wood although there were exceptions (table 4).

Generally, western white pine (*Pinus monticola* Dougl.) and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) were low in calcium and copper compared to the other species (table 4). Harvest of alpine fir (*Abies lasiocarpa* [Hook.] Nutt.) and Engelmann spruce (*Picea engelmannii* Parry) wood and bark would remove the most calcium from the site (table 4). Alpine fir, Douglas-fir, western hemlock, and western larch were the highest in phosphorus. Engelmann spruce and western larch had relatively high levels of zinc while western redcedar (*Thuja plicata* Donn.) wood plus bark was low in zinc. Harvesting the wood of alpine fir and Douglas-fir would remove more nitrogen than would harvest of other tree species. The most magnesium would be lost in the wood and bark of Douglas-fir, western hemlock, and western white pine. Alpine fir, Douglas-fir, and Engelmann spruce wood and bark were high in potassium (table 4). Potassium is usually low in supply in western forest soils.

Obviously, harvesting practices cannot be built around those species that are lowest in total elements removed with wood and bark, but a knowledge of relative nutrient losses by species can be important if the site to be harvested is extremely low in the available form of one biologically essential element and the species to be removed contains high levels of that element. Figure 3 shows the lower group selection (left) clearcut (right) after logging.

Table 5 shows how much merchantable wood was removed from each silvicultural prescription and treatment. The amount removed is a function of the density and size of the original stocking, and the intensity of utilization. The data represent a summation of volumes of all species present. Nutrient removal was based on the species components of the total volumes. Shelterwood cuttings removed from 576 to 2,950 ft³/acre, while group selection cuts removed from 5,765 to 12,254 ft³/acre.

Table 4.--Average elemental content of bark plus wood for live commercial wood from the Coram Experimental Forest

Species	D.b.h. class (Inches)	(cm)	Ca	Cu	Fe	K	Mg	Mn	N	Na	P	Zn	Ash (Percent)
								µg/g					
Alpine fir[1]	< 6	<15.2	3406	9.1	72	1003	227	152	1089	29	527	12.1	1.5
	<12	2<30.5	3138	10.6	28	738	16	111	1610	25	659	8.4	1.0
	>12	>30.5	2467	9.2	39	1126	27	123	2602	20	406	10.2	0.9
Douglas-fir	< 6	<15.2	2100	9.6	29	1022	234	93	1208	21	716	14.5	0.5
	<12	<30.5	1125	7.7	17	305	394	43	884	18	657	9.3	0.6
	>12	>30.5	1586	9.3	26	517	91	71	1374	24	669	12.1	0.5
Engelmann spruce	< 6	<15.2	2100	8.8	179	878	137	81	805	20	323	21.4	1.2
	<12	<30.5	3330	9.0	36	1000	163	77	1009	22	473	23.9	0.8
	>12	>30.5	2900	10.9	24	933	126	115	653	30	454	11.3	0.9
Lodgepole pine	< 6	<15.2	1000	8.7	11	345	22	120	700	19	288	11.0	0.5
	<12	<30.5	1800	8.9	24	330	22	140	560	20	152	11.5	0.7
	>12	>30.5	777	5.8	31	253	185	75	630	28	310	11.6	0.5
Western larch	< 6	<15.2	1415	8.7	39	699	180	167	1176	24	673	12.7	0.8
	<12	<30.5	1071	9.5	56	374	64	71	607	17	486	42.4	0.6
	>12	>30.5	1186	9.0	33	392	132	81	476	23	350	9.6	0.2
Western white pine	< 6	<15.2	955	6.4	33	201	240	42	602	30	155	11.5	0.2
	<12	<30.5	765	5.9	37	270	170	31	607	25	149	7.4	0.2
	>12	>30.5	848	5.8	26	230	212	67	553	33	164	8.3	0.2
Western hemlock	< 6	<15.2	913	6.6	29	403	232	190	700	33	765	6.0	0.5
	<12	<30.5	783	6.3	36	423	174	153	707	36	541	5.6	0.5
Western redcedar	< 6	<15.2	1450	7.0	31	257	128	5	784	30	132	2.4	0.6
	<12	<30.5	1034	5.2	35	223	91	4	898	26	218	3.0	0.6

[1]See Appendix A for scientific names.
[2]The size category <30.5 cm (12 inches) covers samples from wood + bark from 15.2 to 30.5 cm (6-12 inches) in diameter.
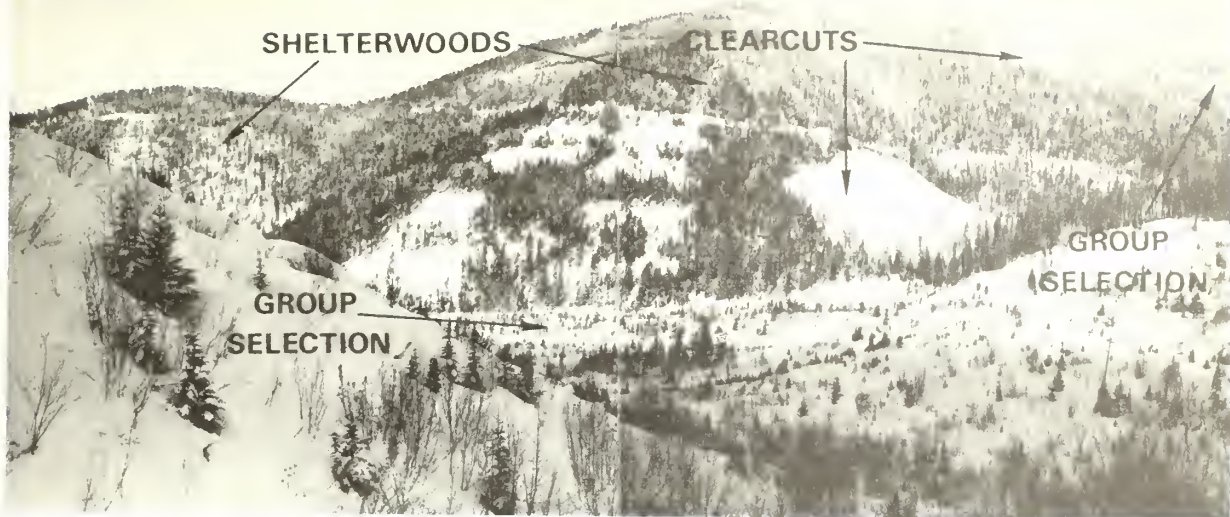
18

Figure 3.--*Lower group selection cut (left) and clearcut block (right) at the Coram Experimental Forest after logging. A portion of the upper clearcut shows in the upper right hand corner.*

Table 5.--*Total volume of wood 3-inch diameter and larger (7.6 cm) apparently removed in harvest*[1]

Block	Treatment			
	2	1	4	3
	- - - - - - - - - - - - Cubic feet - - - - - - - - - - - -			
Shelterwood 1	1,248	2,876	1,614	2,950
Group selection 1	5,765	7,586	8,607	7,655
Clearcut 1	4,323	6,426	5,895	4,962
Shelterwood 2	576	2,773	1,013	2,570
Group selection 2	12,254	6,214	9,009	6,241
Clearcut 2	4,519	6,387	4,035	5,533

[1]Derived by subtracting postharvest volume from preharvest volume, Benson and Schleiter (review draft). See tabulation for treatment definitions.

The data provide a rough estimate of the amount of nutrients likely to be removed with the three silvicultural prescriptions on these habitat types for mature forest.

Elemental losses from harvest can be evaluated in terms of the levels of available elements in the soil, or the available plus potentially available elements in soil, or the total elemental content of the ecosystem (soil + plants + animals + precipitation). Ideally, harvest losses should be evaluated against total ecosystem nutrient levels (available and stored, separately). This is a difficult comparison because of the problem of measuring animal biomass and elemental content on a unit area.

Data presented cover losses from logs only and do not reflect the losses from intensive fiber utilization. The calculations of nutrient loss from harvest relative to the total biologically essential elemental content to the limit of the root zone were based on a meter square surface area to the depth of 19.6 inches (50 cm), with a bulk density of 1.92 g/cm^3 (includes coarse rock fragments, not a typical andic soil).

The soils have moderate reserves of total calcium (5,240 g/0.5 m^3 root zone) but high levels of total iron (29,731 g/0.5 m^3), and high levels of potassium (19,573 g/0.5 m^3, table 6). Calcium and magnesium are the macroelements that are in shortest supply and most vulnerable to ultimate depletion. Phosphorus is quite low (1,621 g/0.5 m^3). The sampling sites did not include the calcareous material that underlies part of the Coram Experimental Forest.

In terms of available elements, calcium is relatively abundant (857 g/0.5 m^3), indicating that it is being readily released from the parent material and could easily be lost (table 6). Magnesium is available in low amounts (89 g/0.5 m^3) relative to calcium. Copper losses were high on a percentage basis because total soil copper is low. Low amounts of potassium (171 g/0.5 m^3) and iron (30 g/0.5 m^3) are available in the root zone. Phosphate (as PO_4-P) is available in large amounts relative to its total content in the soil as P (table 6).

Table 7 shows the amount of each element removed from the site through harvest, divided by the total elemental content (available + potentially available) of the soil expressed as a percent. The four treatments are discussed under the Introduction, but data are relative to log removal only (merchantable and unmerchantable dead and alive). These results show that clearcutting and group selection removed the most cations relative to the total potentially available cations in the soil (0.18-0.21 percent, table 7). Clearcutting removed total cations amounting to from 0.05 percent to 0.18 percent of all the measured essential cations stored in the soil. Shelterwood cutting removed from 0.03 percent to 0.17 percent of the total soil cations (eight of biological importance). In terms of the total cation content of the soil, clearcutting of the type of CC1 or group selection cuts of the type on GS2 removed the most cations relative to the soil total content. In absolute terms, neither of these logging methods produced serious nutrient losses in wood plus bark if viewed as a single treatment on a 70- to 100-year rotation.

The largest cation losses for CC2 and GS2 occurred in treatment 1 where trees were removed down to 3 inches d.b.h. (7.6 cm) and the understory was cut. Treatment 2 produced the largest total cation losses for SW1 and GS1. On clearcut 1, treatment 4 removed the most total cations (relative to total root zone cations). More total biomass was removed in treatment 3 than in 1. Treatment 3 included the removal of needles and branches, but no data are available at this time on the weights of slash removed (only bole wood), so that nutrient loss from slash removal is not reflected in the data. The actual losses of ions from any one site varied according to the intensity of harvest, the original species present, and stocking, so that similar treatments did not show the same cation losses.

Harvesting wood + bark produced low percentage losses of Fe, K, Mg, Na, and Zn (table 7). These elements were either low in the materials harvested or high in the soil in total content. Calcium losses were only 0.2 to 1.7 percent of the total calcium, so that little harm was done to this relatively scarce ion (total) from harvest. Magnesium losses were even lower (0.02 to 0.23 percent) than those for calcium. Even the phosphorus removed in wood was low (0.2 to 1.2 percent of total soil P) and of no serious immediate concern. On the basis of total elemental content, none of the logging methods or intensities used produced significant losses of essential cations from the total ion reserve in the soil through removal of wood or bark. A 0.2 percent loss of the essential cations means that 70-100 year rotations could continue for 28,000 to 40,000 years before most ions would be depleted from the soil. The highest cation loss was for total PO_4. If 1.2 percent of the total PO_4 were lost each 100 years, it would take 8,300 years for depletion of PO_4 from the soil and rocks. Deficiency conditions would reduce growth before 8,300 years. Microerosion would also expose the roots to freshly weathered soil during that time. Time spans in excess of 500 to 1,000 years are not realistic to management because of the innate change in forest ecosystems. Glaciation, volcanic action, speciation, climatic change, migration, invasion, and other factors will all too soon change the forest that we are trying to manage now.

Table 6.-- ... [faded]

Parameter	Element									
	N		Cu	Fe		Mg	Mn	Na		
Total µg/g	1,190	5,460	29	30,970	20,388	5,551	1,...	..,962	1,6..	..
Total g/0.5 m³	1,142	5,240	28	29,751	19,573	5,329	1,17.	6,684	1,6..	..
Available g/0.5 m³	--	857	2.8	30	171	89	44	1.	1,144	0.4

Table 7.--*Percentage of total elements removed from a 1 m² surface area in a single harvest (clearcut, selection cut, or shelterwood) on the basis of g/0.5 m³ feeder root zone, relative to total root zone*

Silvicultural practice	Treatment[1]	Elemental content										Percent total cations removed
		Ca	Cu	Fe	K	Mg	Mn	N	Na	PO₄	Zn	
Shelterwood 1	2	1.2	1.2	0.004	0.11	0.17	0.33	2.6	0.01	0.76	0.19	0.17
	4	.4	.5	.002	.04	.14	.10	1.2	.004	.43	.25	.07
	1	.9	1.0	.006	.05	.09	.17	2.4	.02	.25	.19	.12
	3	.6	.7	.003	.05	.07	.13	1.7	.006	.59	.12	.08
Group selection 1	2	1.1	1.1	.001	.12	.15	.23	2.7	.01	1.20	.20	.16
	4	.6	.8	.002	.07	.14	.16	2.1	.007	.63	.10	.09
	1	.5	.6	.002	.05	.06	.11	1.6	.006	.53	.09	.08
	3	.9	.9	.003	.08	.10	.18	2.2	.008	.67	.12	.12
Clearcut 1	2	.4	.5	.001	.04	.12	.10	4.5	.004	.21	.06	.06
	4	1.3	2.0	.004	.09	.23	.42	5.1	.02	.57	.26	.18
	1	.4	.4	.001	.03	.04	.08	4.2	.004	.43	.08	.05
	3	.3	.3	.001	.03	.03	.08	1.4	.004	.36	.05	.05
Shelterwood 2	2	.2	.3	.001	.02	.02	.05	1.2	.002	.26	.05	.03
	4	.4	.4	.001	.03	.03	.08	1.3	.003	.58	.06	.05
	1	.4	.4	.001	.03	.04	.08	4.2	.004	.43	.08	.05
	3	.3	.3	.001	.03	.03	.08	1.4	.004	.36	.05	.05
Group selection 2	2	1.2	1.2	.005	.09	.12	.26	3.0	.01	.87	.20	.16
	4	.8	.8	.002	.07	.08	.16	2.2	.007	.71	.11	.11
	1	1.7	2.9	.005	.11	.13	.25	4.5	.02	.95	.18	.21
	3	.7	.7	.002	.07	.08	.04	2.0	.006	.59	.09	.10
Clearcut 2	2	.9	.9	.002	.09	.09	.14	2.3	.008	.50	.12	.12
	4	.6	.7	.002	.07	.07	.16	1.9	.007	.52	.10	.09
	1	1.1	.9	.003	.09	.09	.22	2.6	.009	.71	.14	.15
	3	.6	1.4	.002	.06	.05	.13	1.6	.005	.12	.07	.08

[1]Treatments described under Methods, least severe to most severe = 2, 4, 1, 3.

When harvest losses are examined on the basis of the percentage of the *available* soil cations removed, larger percentages of ions were taken from the site, representing from 1.9 to 13.9 percent of all the available cations in the root zone at one point in time (table 8). Again, each site varied according to stocking and treatment. The largest percentage losses were for zinc (14.8-91.7 percent of immediately available Zn).

Table 8.--*Representative percentage of available soil elements removed by clearcutting, selective cutting, and shelterwood cutting*

Block	Treatment[1]	Ca	Cu	Fe	K	Mg	Mn	Na	P	Zn	Percent available cations removed
Shelterwood 1	2	8.6	13.5	4.7	14.1	11.6	9.9	5.7	1.25	62.7	9.5
	4	3.1	5.7	1.9	5.7	9.7	2.9	2.3	.71	80.1	4.0
	1	6.3	11.5	6.6	7.0	6.5	5.1	8.3	.41	62.6	6.4
	3	4.3	7.9	3.4	6.9	4.6	3.9	3.1	.96	40.3	4.6
Group selection 1	2	7.8	12.8	1.4	16.1	10.5	6.9	5.3	1.98	64.7	9.0
	4	3.9	9.2	2.4	9.3	5.9	4.9	3.8	1.03	33.6	4.9
	1	3.9	6.9	2.0	6.8	4.4	3.4	3.0	.88	29.6	4.3
	3	6.1	10.5	3.0	11.0	6.9	5.6	4.3	1.10	39.6	6.8
Clearcut 1	2	2.7	5.3	1.2	5.2	3.2	2.9	2.1	.34	19.1	3.0
	4	9.1	23.5	4.7	10.5	15.8	12.8	7.9	.94	84.3	10.1
	1	12.2	17.3	3.9	27.4	11.2	9.2	6.8	2.01	91.7	13.9
	3	5.8	13.9	2.8	9.8	8.8	7.5	5.5	.58	48.2	6.6
Shelterwood 2	2	1.7	2.9	1.1	2.6	1.6	1.6	1.2	.43	15.3	1.9
	4	2.5	4.1	1.5	3.9	2.4	2.4	1.7	.63	20.7	2.8
	1	2.6	4.5	1.6	4.1	2.5	2.6	1.9	.71	24.7	2.9
	3	2.3	3.6	1.7	3.7	2.3	2.5	1.9	.59	14.8	2.6
Group selection 2	2	8.3	14.2	4.0	11.4	8.2	7.9	5.6	1.43	65.4	8.9
	4	5.4	8.9	2.5	8.2	5.6	4.9	3.8	1.16	35.9	5.9
	1	11.7	34.2	5.9	13.4	9.3	7.7	9.2	1.57	59.0	11.8
	3	5.2	8.0	2.3	7.8	5.3	1.1	3.3	.96	29.8	5.5
Clearcut 2	2	6.3	9.6	2.6	10.1	6.1	4.4	3.9	.82	38.4	6.9
	4	4.6	8.1	2.4	8.1	4.6	4.9	3.4	.86	31.9	5.2
	1	8.0	11.2	3.1	10.8	6.3	6.5	4.6	1.21	44.4	8.3
	3	4.3	16.5	1.8	6.6	3.8	3.9	2.8	.68	23.2	4.6

[1]Treatments described under Methods.

Only in the case of Zn is there a possible problem with future zinc deficiency because weathering might not be able to replace the needed Zn fast enough to accommodate new growth. This deficiency will probably not occur because burning released added zinc on some treatments, and it will be 20 years or more before the young regeneration is large enough to make severe demands on the soil for zinc. Available nutrients were not actually removed at one time from the soil through harvest, but gradually over a long time (70+ years). Zinc removal to close to 100 percent does not mean that after harvest there was almost no available Zn left in the soil, but the amount of Zn removed in harvest is about what was available in the entire root zone at one point in time. The roots are never able to extract all of the available zinc present in any soil at one time. Some zinc is always present in excess of what is actually being used by roots.

22

Most other elements showed low percentage losses relative to the available soil cations, normally under 10-15 percent. Calcium losses ranged from 2.5 to 12.2 percent of available Ca, and magnesium from 1.6 to 15.8 percent. Potassium losses were 2.6 to 27.4 percent of available K. Phosphate losses were low (0.3-2.0 percent of available PO_4). Shelterwood showed markedly lower percentage losses of cations when compared to all other blocks. The reason for this is unknown. These data indicate that the system has lost low percentages of the available soil cation and anion pool, and that these ions will not be available after harvest to be recycled through decomposition. The replicate harvest plots were from soils that were somewhat chemically different.

Realistically, the levels of elements taken from the logged sites should be corrected for the elemental input from precipitation (table 9). When corrections are made for precipitation additions as me/m^2 (table 10) the importance of harvest losses is further reduced. This is particularly true if we assume a 70-100 year rotation, and multiply the average additions by 100. Over 100 years, approximately 37 g/m^2 of Ca, 1.3 g of Cu, 5.7 g of Fe, 45 g of K, 31 g of Mg, 2 g of Mn, 120 g of NO_3, 300 g of Na, 15 g of PO_4, and 3 g of Zn, or about 425 g of cations and 140 g of anions would be added to each meter square of the ecosystem. These data apply to only this area where there is enrichment of the atmosphere from an industrial stack (table 9). The harvest losses must be balanced against other liquid and solid elemental losses (smoke, dust, runoff) over the 100 years. At this time, we cannot make this type of prediction, but ultimately this should be possible. This area does not have a permanent stream so that elemental losses to running water could not be measured. Where logging triggers erosion, nutrient losses would be far greater than reported here where erosion was nonexistent.

Harvest data corrected for elemental additions from rainwater show a net gain over 100 years in copper, iron, potassium, magnesium, sodium, nitrogen, phosphate, and zinc (table 9). This means that for most elements studied and for a 100-year rotation, precipitation would restore all but the calcium and manganese removed by harvest in wood and bark. In most cases this holds for a 70-year rotation as well. Calcium and manganese harvest losses would, by calculation, be replaced in 100 years of precipitation for SW2, which had the lowest nutrient losses in the wood and bark harvested. This ecosystem shows high sodium replacement, which may be related to stack emissions from a nearby aluminum plant 11 miles (17.7 km) southwest at Columbia Falls. Clearcutting produced the greatest nitrogen losses, but these would be more than adequately replaced by precipitation and fixation. These results assume no drastic changes in precipitation amounts over 100 years (for calculation purposes).

Only a few studies have dealt with nutrient removal through harvest. Weaver and Forcella (in press) reported that nutrient losses from whole tree harvest reduced ecosystem nitrogen by about 3x, phosphorus by 6x, potassium by 4x, and calcium by 3x compared to conventional log removal.

Long and Turner (1975) have described the aboveground biomass of understory and overstory Douglas-fir stands by age class. Odegard (1974) discussed nutrient and biomass relationships following clearcutting of lodgepole pine forests. Ovington and others (1973) described the biomass and nutrient capital of old-growth Douglas-fir stands. Few studies have included information taken directly from harvest. Carlisle (1967) showed that for oak forests nutrient input from precipitation in 12 years replaced harvest losses for 60- or 120-year rotations.

Weetman and Webber (1971) concluded that full-tree logging would not damage the soil for the next crop of spruce, with the possible exception of calcium deficiencies. They felt that sites of marginal fertility should not be subjected to full-tree logging unless fertilizer is applied to the soil. This view was also expressed by Tamm (1969). Other data showed large inputs of nutrients from dust and precipitation. Wilde and others (1972) showed that red pine can grow on soils which by chemical analysis show low fertility. These and other data point to a growing belief that forest trees can extract more nutrients from soil than are reflected in chemical analysis (Bowen 1972).

Table 9.--*Average annual and 100-year expanded additions of ions to the forest ecosystem from bulk precipitation*

Ion		Time span			Ion		Time span	
		Average annual	100 years				Average annual	100 years
		- - - Grams/square meter - - -					- - - Grams/square meter - - -	
Ca		0.37	37.0		NO_3		1.20	120.0
Cu		.013	1.3		Na		3.0	300.0
Fe		.057	5.7		PO_4		.149	14.9
F		.055	5.5		Zn		.031	3.1
K		.453	45.3		Cations		--	425.0
Mg		.306	30.6		Anions		--	140.0
Mn		.019	1.9					

Table 10.--*Levels of elements removed in wood and bark from the Coram Experimental Forest, corrected for estimated 100-year elemental additions from bulk precipitation*

Block[1]	Treatment[2]	Ca	Cu	Fe	K	Mg	Mn	N	Na	P	Zn
						$g/m^2/100$ years					
Shelterwood 1	2	26	+0.9	+4.5	+25	+22	1.9	+91.3	+299	+2.6	+2.6
	4	+14	+1.2	+5.2	+37	+23	+ .8	+106.8	+300	+7.9	+2.5
	1	9	+1.0	+4.0	+35	+26	.02	+93.8	+299	+10.8	+2.6
	3	+6	+1.1	+4.8	+35	+27	+ .4	+101.2	+300	+5.4	+2.8
Clearcut 1	2	+18	+1.2	+5.4	+38	+28	+ .8	+70.2	+300	+11.5	+2.9
	4	30	+ .7	+4.5	+28	+18	2.9	+62.9	+299	+5.7	+2.4
	1	53	+ .9	+4.7	+5	+22	1.6	+32.9	+299	4.9	+2.4
	3	5	+ .9	+4.9	+31	+24	.9	+72.9	+299	+9.2	+2.7
Shelterwood 2	2	+24	+1.2	+5.4	+41	+29	+1.3	+107.2	+300	+10.6	+3.0
	4	+18	+ .3	+5.3	+39	+29	+1.0	+105.8	+300	+8.7	+2.9
	1	+18	+1.2	+5.3	+39	+29	+ .9	+73.3	+300	+7.9	+2.9
	3	+20	+ .4	+5.3	+39	+29	+ .9	+104.2	+300	+9.1	+3.0
Clearcut 2	2	10	+1.1	+5.0	+29	+29	.2	+94.4	+299	+6.8	+2.8
	4	+3	+1.1	+5.1	+32	+29	+ .01	+98.9	+300	+6.4	+2.8
	1	22	+1.0	+4.9	+28	+28	.6	+91.0	+299	+3.0	+2.7
	3	+5	+ .9	+5.2	+34	+29	+ .4	+102.2	+300	+8.2	+2.9

[1]No precipitation data are available for the group selection plots.
[2]Treatments described under Methods.

+ = additions of elements above levels removed on a 100-year rotation. Other figures represent amount by which precipitation fails to replace harvest losses.

Cole and others (1967) discuss the problem of determining accurately the quantity of nutrients released by geochemical weathering.

The nitrogen content of spruce slash was reported as 167 to 387 kg/ha. This constitutes a major source of the potentially mineralized organic N (Weetman and Webber 1971). This same study concluded that adequate nitrogen would be left in the litter and humus layer to support the next forest (initially), even with tree-length logging. Gessel and Cole (1965) found that the removal of vegetation resulted in a 6 percent loss of K below the root zone.

CONCLUSIONS

On the relatively fertile soils at Coram, none of the harvest intensities used (clearcut, shelterwood, or group selection) with varying degrees of site preparation removed nutrients in amounts that should affect growth for thousands of years. Nutrient losses did vary by treatment, but not in amounts significant to management. One unknown in evaluating the impact of land use on nutrient losses is our inability to determine accurately how fast rock weathers with depth. The weathering rate is the key interest rate at which nutrients are made soluble and available to plants. Leaching losses represent the permanent expenditure of biologically essential nutrients from the system. The amounts of nutrients removed in the harvest of logs, even with clearcutting, will normally be replaced by bulk precipitation in from 70 to 100 years. This should hold true when the harvested species are alpine fir, Douglas-fir, western larch, western white pine, western redcedar, lodgepole pine, Engelmann spruce, and western hemlock on similar soils. Unfortunately, we cannot put long-term dollar values on the nutrients lost.

Skyline logging did not produce serious erosion or soil losses. This is surprising in view of the steep terrain (45 percent) and the fire lines that had to be built. Certainly these results could not be extrapolated to any area of similar topography. The combination of a productive surface soil with abundant organic matter and a tremendously dense herb and shrub layer prevented erosion. The surface disturbance from this method of logging was minimal, and the vigorous regrowth of vegetation held both nutrients and soil in place.

This vigorous regrowth probably also explains the low levels of solution nutrient loss from the system. The ephemeral stream, Abbott Creek, was essentially unaltered chemically by the extensive logging of the watershed that feeds it. Part of this is the result of the underground transit of this stream, and part results from rapid regrowth of the vegetation preventing excessive nutrient losses from the slopes.

Clearcutting exported more nutrients below the root zone than did any of the other treatments. These nutrient losses were low and only slightly elevated above those of the controls. They were also relatively short-lived. Logging temporarily increased the levels of F, Mg, Mn, NO_3, Na, and Zn in the soil water. These nutrients appear to have come from rapid winter decay of needles under a deep, dense snowpack. Soil water appears to be the best and most dependable indicator of the levels of available nutrients in soil.

Burning increased soil water ion loads for a year, but the burns were of low intensity and the ion additions were all quite low. Data on the nutrient content of the vegetation suggests that the herbs and shrubs were taking up large quantities of the nutrients released from burning. This study demonstrated that skyline logging as practiced on these slopes with this soil did not result in massive solution or erosion nutrient losses. The harvest losses in wood and bark were also relatively low and will be replaced by precipitation if not by weathering during the next rotation.

APPLICATIONS

One important use of these results is to compare other areas to be logged to Coram Appendix B shows details of the soil characteristics of the area, and Appendix A provid an idea of species diversity. Appendix C shows the range of soil chemistry for the general study area. Areas that vary considerably from this area in terms of soil chemistry, soil physical properties, slope, aspect, or vegetation should be looked at carefully before extrapolating these results. Quite different results could be expected on steeper slopes, for example. An erosive soil, such as some silt loams, fine sands, or some loams or silts would produce potentially higher nutrient losses than occurred at Coram. Clay soils may cause accelerated surface losses. Also, older soils more highly weathered may lose fertility faster if exposed to this type of nutrient loss, even at low levels. Fertile soils will probably suffer less than very poor soils. Talus slope with low total soil depth, little weathered, and with extremely low levels of available nutrients may not be able to withstand this type of logging treatment without irreparab nutrient losses. A different system of removing logs will surely produce different degrees of surface disturbance and more or less nutrient loss as well as differences in erosion. Hotter fires would create a greater chance of nutrient losses and could alter the conclusions reached here. Even a south slope with sparse vegetation and different species will respond in an altered manner to logging, and would be expected to lose more nutrient in years of heavy precipitation. A permanent, aboveground stream will react differently to disturbance on the slope. Infiltration is also a big factor in nutrient loss. Soils that characteristically freeze deeply in winter or that have heav clay surfaces may well produce overland nutrient losses not encountered at Coram. Even the Coram slopes may alter their nutrient losses in a year of exceptionally heavy precipitation, or very light or heavy snowpack.

Different land use history may influence the response of an area to logging. Heavily compacted soils, or flat ground will release nutrients differently than occurre at Coram. Also important is stoniness or rockiness. The heavy stone content of Coram soils aided infiltration and percolation of water and made this soil more able to store the modest amounts of nutrients released from logging and burning. Certainly a change in vegetation type would alter the ability of a site to absorb and retain nutrients. Vegetation which sprouts and regrows rapidly should be best suited to logging disturbance, but not necessarily to regeneration of trees. The intensity and method of site preparation will alter a site's ability to retain nutrients. High water tables and moist sites will lose nutrients readily. Logging must be evaluated in terms of the holocoenotic environment, the whole that is influenced in many ways by all of its parts

Every area to be logged is a bit different. The greater the difference from the Coram study site, the greater the chances of more or less nutrient losses. Harvest wil probably not remove significant levels of nutrients from any but the poorest very old o very young soils. Solution losses are highly dependent on the depth of soil, amount of precipitation, amounts of carbonates and bicarbonates in the soil solution, soil textur and clay and organic content, and the cation and anion exchange capacities.

We are not yet ready to write prediction equations for any forest in terms of nutr ent retention for any treatment, but we do have a "feel" for the types of areas that wi suffer most from logging or fire. Current logging and burning studies on predominantly clay soils will add to this knowledge. We might not always be able to say how much dif ferent conditions need to be from those at Coram to be significant.

More work needs to be done on nutrient removal associated with heavy utilization. We need to answer the question, "How much fiber can be removed from a site before the ability of the soil to grow the next rotation is impaired?" We are working on this. Because the Coram study showed no serious nutrient losses, we cannot assume that any forest or soil will respond the same way. We are, however, in a good position to estimate the magnitude of losses on other sites.

PUBLICATIONS CITED

Artley, Donald K., Raymond C. Shearer, and Robert W. Steele.
   1978. Effects of burning moist fuels on seedbed preparation in cutover western larch forests. USDA For. Serv. Res. Pap. INT-211, 14 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.
Bormann, F. H., G. E. Likens, D. W. Fisher, and R. S. Pierce.
   1968. Nutrient loss accelerated by clear-cutting of a forest ecosystem. Science 159(3817):882-884.
Bowen, C. W.
   1972. Progressive acid dissolution as a technique for determining the potassium supply of forest soils. M.S. Thesis, Univ. Mont., Missoula.
Carlisle, A., and others (other authors unknown).
   1967. The nutrient content of rainfall and its role in the forest nutrient cycle. Proc. XIV IUFRO Congr. Munchen Pt. II, Sec. 21:1450158. S. P. Gessel and S. F. Dice, ed.
Cole, D. W, S. P. Gessel, and S. F. Dice.
   1967. Distribution and cycling of nitrogen, phosphorus, potassium and calcium in a second-growth Douglas-fir ecosystem. *In* Symp. on primary productivity and mineral cycling in natural ecosystems, p. 198-232. Univ. Maine Press.
Eron, Zati.
   1977. Heat effects on forest soil physical properties and subsequent seedling growth. (Microfilm) Ph.D. Dissert., Univ. Mont., Missoula, 184 p.
Farber, L., ed.
   1960. Standard methods for the examination of water and waste water. Am. Publ. Health Assoc. and Am. Water Works Assoc., New York, N.Y.
Fredriksen, R. L.
   1971. Comparative chemical water quality--natural and disturbed streams following logging and slash burning. *In* Forest and land uses and stream environment, p. 125-137. Oreg. State Univ., Corvallis.
Fredriksen, R. L., D. G. Moore, and L. A. Norris.
   1975. The impact of timber harvest, fertilization and herbicide treatment on stream water quality in western Oregon and Washington. *In* Forest soils and forest land management. Proc., 4th North Am. For. Soils Conf., Quebec, 1973, p. 283-313. B. Bernier and C. H. Winget, ed. Laval Univ. Press, Quebec.
Gessel, S. P., and D. W. Cole.
   1965. Influence of removal of forest cover on movement of water and associated elements through soil. J. Am. Water Works Assoc. 57:1301-1310.
Hesse, P. R.
   1972. A textbook of soil chemical analysis. 520 p. Chemical Publishing Co., New York.
Jackson, M. L.
   1958. Soil chemical analysis. 498 p. Prentice-Hall, Englewood Cliffs, N.J.
Klages, M. G., R. C. McConnell, and G. A. Nielsen.
   1976. Soils of the Coram Experimental Forest. Mont. Agric. Exp. Stn. Res. Rep. 91, 43 p.
Likens, G. E., F. H. Bormann, N. M. Johnson, and R. S. Pierce.
   1967. The calcium, magnesium, potassium, and sodium budgets for a small forested ecosystem. Ecology 49(5):772-785.
Long, J., and J. Turner.
   1975. Aboveground of overstory and understory in an age sequence of four Douglas-fir stands. J. Appl. Ecol. 12:179-188.
Moore, D. G.
   1974. Impact of forest fertilization on water quality in the Douglas-fir region--a summary of monitoring studies. Natl. Conv. Soc. Am. For. Proc., p. 209-219.

Odegard, G.
    1974. Nutrient and biomass distribution following clearcutting in a lodgepole pine
        forest ecosystem. Ph.D. Dissert., Colo. State Univ., Fort Collins, 182 p.
Ovington, W., D. Lavender, and R. Hermann.
    1973. Estimation of biomass and nutrient capital in stands of old growth Douglas-fir.
        In IUFRO biomass studies. H. Young, ed. Coll. Life Sci. and Agric., Univ.
        Maine, Orono, 532 p.
Pfister, Robert D., Bernard L. Kovalchik, Steven F. Arno, and others.
    1977. Forest habitat types of Montana. USDA For. Serv. Gen. Tech. Rep. INT-34,
        174 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.
Stark, N.
    1977. Fire and nutrient cycling in a larch/Douglas-fir forest. Ecology 58:16-30.
Stark, N.
    1978. Man, tropical forests, and the biological life of a soil. Biotropica 10(1):
        1-10.
Tamm, C. O.
    1969. Site damages by thinning due to removal of organic matter and plant nutrients.
        In Thinning and mechanization. Proc. IUFRO Manage., Sweden, 1975-1977.
Techtron, Ltd.
    1974. Analytical methods for flame spectroscopy. Varian-Techtron PTY. Ltd.
        Melbourne, Australia; Victoria.
Tiedemann, A. R.
    1974. Stream chemistry following a forest fire and urea fertilization in north
        central Washington. USDA For. Serv. Res. Pap. PNW-203, 20 p. Pac. Northwest
        For. and Range Exp. Stn., Portland, Oreg.
Weaver, T., and F. Forcella.
    In press. Biomass of fifty conifer forests and nutrient exports associated with their
        harvest. Great Basin Naturalist.
Weetman, G. F., and B. Webber.
    1971. The influence of wood harvesting on the nutrient status of two spruce stands.
        Woodland Rep. WR/33, 26 p. Pulp and Paper Res. Inst. of Canada, Montreal.
Wilde, S. A., J. G. Iyer, and G. K. Voigt
    1972. Soil and plant analysis for tree culture. 209 p. Oxford Publ. House, New
        Delhi.

APPENDIX A

Plant Species Found on Coram Forest

Table 11.—*Habitat type and phase codes, utilization study, Coram Experimental Forest*[1]

1974 map	1977 abbreviation	Scientific name
D/P-P	PSME/PHMA h.t.-PHMA phase	*Pseudotsuga menziesii/Physocarpus malvaceus* h.t., *Physocarpus malvaceus* phase
H/C-A	TSHE/CLUN h.t.-ARNU phase	*Tsuga heterophylla/Clintonia uniflora* h.t., *Aralia nudicaulis* phase
A/O	ABLA/OPHO h.t.	*Abies lasiocarpa/Oplopanax horridum* h.t.
A/C-C	ABLA/CLUN h.t.-CLUN phase[2]	*Abies lasiocarpa/Clintonia uniflora* h.t., *Clintonia uniflora* phase
A/C-A	ABLA/CLUN h.t.-ARNU phase	*Abies lasiocarpa/Clintonia uniflora* h.t., *Aralia nudicaulis* phase
A/C-X-P	ABLA/CLUN h.t.-XETE phase[2]	*Abies lasiocarpa/Clintonia uniflora* h.t., *Xerophyllum tenax* phase
A/C-M	ABLA/CLUN h.t.-MEFE phase	*Abies lasiocarpa/Clintonia uniflora* h.t., *Menziesia ferruginea* phase

[1]Jack Schmidt and Robert Pfister, Intermountain Forest and Range Experiment Station, Forestry Sciences Laboratory, Missoula, Montana.
[2]*Physocarpus malvaceus* well represented in undergrowth community.

Plant Species Found on Coram Forest*

Abies lasiocarpa
Acer glabrum
Actea rubra
Adenocaulon bicolor
Alnus sinuata
Amelanchier alnifolia
Antennaria spp.
Aralia nudicaulis
Arnica cordifolia
Arnica latifolia
Aster conspicuus
Aster laevis
Athyrium filix-femina
Berberis repens
Bromus vulgaris
Calamagrostis canadensis
Calamagrostis rubescens
Carex concinoides
Carex geyeri
Carex rossii
Chimaphila umbellata
Cirsium vulgare
Clematis columbiana
Clintonia uniflora
Cornus canadensis
Disporum hookerii
Disporum trachycarpum
Dracocephalum parviflorum
Elymus glacus
Epilobium angustifolium
Epilobium watsonii
Equisetum spp.
Festuca occidentalis
Fragaria vesca
Galium triflorum
Gentiana amarella
Geranium bicknellii
Goodyera oblongifolia
Gymnocarpium dryopteris
Hieracium albiflorum
Larix occidentalis
Linnaea borealis
Lonicera utahensis
Melica subulata
Menziesia ferruginea
Oryzopsis asperifolia

Osmorhiza chilensis
Pachistima myrsinites
Pedicularis bracteosa
Pedicularis contorta
Pedicularis racemosa
Physocarpus malvaceus
Picea engelmanii
Pinus monticola
Pseudotsuga menziesii
Pyrola asarifolia
Pyrola secunda
Ribes lacustre
Ribes viscosissimum
Rosa acicularis
Rosa gymnocarpa
Rubus parviflorus
Salix scouleriana
Sorbus scopulina
Smilacina racemosa
Smilacina stellata
Spirea betulifolia
Symphoricarpos albus
Taxus brevifolia
Tiarella unifoliata
Trillium ovatum
Tsuga heterophylla
Vaccinium membranaceum
Vaccinium myrtillus
Viola adunca
Viola orbiculata
Xerophyllum tenax
Anaphalis margaritacea
Apocynum androsaemifolium
Betula papyrifera
Calochortus nuttallii
Ceanothus sanguineus
Comandra umbellata
Cornus stolonifera
Habenaria dilitata
Polystichum munitum
Pteridium aquilinum
Senecio pseudaureus
Senecio triangularis
Shepherdia canadensis
Taraxacum officinale

*U.S. Forest Service list.

APPENDIX B

Soil Characteristics, Coram Forest

Table 12.--Soil description, *Coram Forest, lower slope, adapted from Eron 1977*

Horizon	Depth	Thickness	Color Dry	:Moist:	Field texture: analysis:	Structure	Consistency (moist)	Roots	Boundary	Reaction
		- - - cm - - - -								
01	7.0-3.0	4.0	--	--	--	--	--	fine few	clear smooth	--
02	3.0-0.0	3.0	--	--	--	--	--	fine common	clear smooth	--
A2	0.0-1.5	1.5	10 yr 6/1	4/2	silt loam	weak fine crumbly	very friable	fine common	clear smooth	--
B2	1.5-35.0	33.5	10 yr 6/3	4/4	silt loam	moderate fine crumbly	very friable	fine many	clear smooth	pH=6.3 %M=52.5 (14.5 cm depth)

Organic matter upper 5 cm: 11.8%-15.6%
Hydraulic conductivity: 8.2-11.3 cm/h
Water holding capacity: 5 cm, 22%; B_2, 11%
Infiltration rate: 4 in (10.2 cm)/h

Date: August 12, 1976
Soil type: gravelly silt-loam
Soil series: Sherlock (Klages and others 1976)
Soil subgroup: andeptic cryobonalf (Klages and others 1976)
Family: loamy-skeletal, mixed (Klages and others 1976)
Elevation: ~1800 m
Slope: ~5%-10%
Aspect: east
Parent material: glacial till (Klages and others 1976)
Habitat type: *Tsuga heterophylla/Clintonia uniflora* (Pfister and others 1977)

Table 13.--Soil description, Coram Forest, upper slope, adapted from Exum 197?

Horizon	Depth	Thickness	Color Dry	Color Moist	Field texture: analysis	Structure	Consistency (moist)	Roots	Boundary	Reaction
		-- cm --								
O1	3.0-2.0	1.0	--	--	--	--	--	fine few	gradual smooth - clear smooth	--
O2	2.0-0.0	2.0	--	--	--	--	--	fine few	gradual smooth - clear smooth	--
A2	0.0-1.0	1.0	10 yr 5/1	4/1	silt loam	weak fine crumbly	very friable - friable	fine few	gradual smooth - clear smooth	--
B2	1.0-40.0	39.0+	10 yr 7/1	4/5	silt loam	weak - moderate fine crumbly	firm	fine - medium common - many	gradual smooth - clear smooth	pH=6.1 %M=62.5 (at 14.5 cm depth)

Date: August 13, 1976
Soil type: gravelly silt-loam
Soil series: Felan (Klages and others 1976)
Soil subgroup: andic cryochrept (Klages and others 1976)
Family: loamy-skeletal, mixed (Klages and others 1976)
Elevation: ~1970 m
Slope: ~60%
Aspect: east
Parent material: limestone (Klages and others 1976)
Habitat type: Abies lasiocarpa/Clintonia uniflora
(Pfister and others 1977)

Average Cation Exchange Capacity of Coram Soils

Depth (cm)	Cation exchange (me/100 g)
0-5	13.10
5-10	9.05
10-15	9.63
15-20	8.78
20-25	9.23
25-30	8.23
30-35	9.08
35-40	9.63
40-45	13.53
45-50	6.25
Average	9.65

Table 14.--*Characteristics of Coram soils: particle density, particle size, organic content*

PARTICLE CHARACTERISTICS

Particle weight[1]		Particle size	
>1 mm	<1 mm	>1 mm	<1 mm
$- - - - - - - g/cm^3 - - - - - - -$		$- - - - - - Percent - - - - - -$	
0.830	0.451	64.55	35.45

ORGANIC CONTENT

Block	Soil depth		
	0-5 cm	20-25 cm	50-55 cm
11	14.59	3.57	1.94
	7.39	4.26	2.76
	12.74	5.06	1.96
	12.64	5.92	2.20
21	8.64	6.00	4.56
	9.41	7.33	4.93
	7.76	10.86	13.43
	17.73	5.16	3.23
13	9.15	3.62	2.60
	11.29	5.79	2.62
	5.33	3.87	3.80
	10.71	5.24	5.63
23	17.53	5.24	2.28
	10.98	7.91	2.34
	13.86	6.53	3.99
	12.12	7.45	3.09

[1]Average particle density = 2.56 g/cm^3.

APPENDIX C

Average Elemental Content of Coram Forest Soil Samples

Table 15.--*Average elemental content of 0.002 N H_2SO_4 soil extract from Coram, as µg/g, by depth and plot, all months combined (pretreatment)*

Plot	Sub	H^+	Ca	Cu	Fe	K	Mg	Mn	Na	N	PO$_4$	Zn
		Molar										

May and October 1973

0-5 cm

Plot	Sub	H^+	Ca	Cu	Fe	K	Mg	Mn	Na	N	PO$_4$	Zn
11	1	0.74^{-6}	1089	2	24	291	113	83	13	1766	101	3
	2	0.22^{-5}	914	2	23	282	124	166	18	1920	77	2
	3	0.66^{-6}	1283	3	33	375	144	93	19	2608	107	2
	4	0.12^{-5}	1166	2	25	329	114	100	23	2203	105	2
21	1	0.20^{-5}	991	3	29	234	102	96	12	1644	50	3
	2	0.12^{-5}	1124	3	26	251	127	103	17	1780	74	2
	3	0.12^{-5}	1160	2	25	285	147	81	12	1953	71	2
	4	0.64^{-6}	1257	2	20	319	153	89	12	2843	95	2
13	1	0.78^{-6}	1277	2	20	240	106	82	13	2280	84	2
	2	0.25^{-5}	1072	3	27	193	133	93	15	2313	94	2
	3	0.14^{-5}	1290	3	33	288	96	76	11	1825	74	2
	4	0.36^{-5}	1224	3	42	254	104	89	14	2016	86	2
23	1	0.39^{-5}	1082	3	20	257	103	141	14	3158	70	2
	2	0.17^{-5}	1098	2	17	255	91	132	14	2229	46	1
	3	0.53^{-5}	1035	2	18	208	105	194	16	2935	41	2
	4	0.34^{-5}	1058	2	27	240	117	133	9	2120	84	2
14	5	0.96^{-6}	1203	3	24	292	124	96	12	2471	56	1
24	5	0.29^{-5}	1281	2	19	228	127	115	14	2046	82	1

20-25 cm

Plot	Sub	H^+	Ca	Cu	Fe	K	Mg	Mn	Na	N	PO$_4$	Zn
11	1	0.99^{-6}	725	2	44	160	69	23	22	648	53	1
	2	0.19^{-5}	698	3	36	144	67	38	25	702	43	2
	3	0.11^{-5}	850	3	45	247	87	33	29	1023	29	1
	4	0.98^{-6}	857	3	30	196	78	27	31	827	25	1
21	1	0.18^{-5}	750	3	29	150	78	33	14	832	21	1
	2	0.14^{-5}	870	3	23	189	92	38	22	1285	21	1
	3	0.15^{-5}	931	3	31	172	126	21	14	973	30	1
	4	0.12^{-5}	775	3	27	180	105	26	15	962	25	1
13	1	0.10^{-5}	876	3	30	135	74	18	15	644	38	1
	2	0.26^{-5}	865	3	32	119	118	39	15	1140	43	1
	3	0.96^{-6}	1022	3	46	139	77	15	15	766	28	1
	4	0.26^{-5}	879	3	49	146	76	13	18	706	29	1
23	1	0.26^{-5}	827	3	20	157	63	51	19	1077	24	1
	2	0.20^{-5}	594	3	20	131	46	42	20	1154	5	1
	3	0.22^{-5}	757	2	25	131	62	44	21	1289	22	1
	4	0.44^{-6}	793	3	32	149	74	40	14	1012	45	1
14	5	0.17^{-5}	1041	3	46	185	103	18	14	1044	23	1
24	5	0.29^{-5}	853	3	26	149	92	33	17	932	34	1

(Cont.)

Table 15.--*Average elemental content of 0.02 N H₃SO₄ soil extract from ... trees, ..., by depth and plot, all months combined by treatment—(cont.)*

Plot	Sub	H$^+$	Ca	Cu	Fe	K	Mg	Mn	Na	N	PO$_4$	Zn
		Molar										

May and October 1973 (continued)

50-55 cm

Plot	Sub	H$^+$	Ca	Cu	Fe	K	Mg	Mn	Na	N	PO$_4$	Zn
11	1	0.71^{-6}	588	3	27	87	63	14	15	510	29	1
	2	0.14^{-5}	640	5	28	105	79	17	19	537	20	1
	3	0.96^{-6}	591	3	38	130	81	16	19	615	23	1
	4	0.10^{-5}	596	3	22	102	77	17	22	402	19	1
21	1	0.24^{-5}	694	3	25	147	84	19	16	485	20	1
	2	0.29^{-5}	682	3	22	102	75	15	12	556	18	1
	3	0.14^{-5}	778	3	39	120	153	14	11	719	22	1
	4	0.19^{-5}	656	3	26	130	78	15	14	486	15	1
13	1	0.75^{-6}	910	3	42	115	87	18	13	582	15	1
	2	0.10^{-5}	938	3	29	85	99	14	14	445	18	1
	3	0.59^{-6}	1372	3	54	102	82	10	13	648	12	1
	4	0.15^{-5}	976	3	67	107	68	8	13	631	21	1
23	1	0.13^{-5}	657	3	17	127	63	22	13	535	14	1
	2	0.37^{-5}	430	3	19	76	60	19	11	419	9	1
	3	0.31^{-5}	627	3	20	93	67	30	17	587	13	1
	4	0.24^{-5}	673	3	21	100	63	45	14	581	27	1
14	5	0.10^{-5}	1418	3	58	149	99	12	14	796	16	0
24	5	0.17^{-5}	806	3	23	86	105	21	15	593	16	0

May 1974

0-5 cm

Plot	Sub	H$^+$	Ca	Cu	Fe	K	Mg	Mn	Na	N	PO$_4$	Zn
11	1	0.63^{-6}	743	2	21	219	76	41	10	976	85	2
	2	0.16^{-5}	727	2	22	198	77	85	16	3150	54	2
	3	0.98^{-6}	1005	2	18	350	124	55	14	2081	70	1
	4	0.10^{-5}	995	2	15	282	96	42	16	1422	57	1
21	1	0.15^{-5}	1185	4	64	308	157	148	10	1554	174	6
	2	0.12^{-5}	1418	4	51	274	180	151	10	2303	168	4
	3	0.84^{-6}	1564	4	38	249	167	87	10	1982	82	2
	4	0.89^{-6}	1290	3	21	233	186	75	10	1885	68	2
13	1	0.38^{-6}	1105	2	27	431	160	63	16	1105	70	1
	2	0.46^{-5}	658	2	43	162	80	56	18	1051	61	2
	3	0.95^{-6}	1187	2	41	576	90	42	19	1439	63	1
	4	0.37^{-5}	1042	2	35	209	87	85	18	1709	43	2
23	1	0.69^{-6}	1198	3	23	257	133	127	15	2268	74	1
	2	0.67^{-6}	1204	3	27	241	96	79	15	2308	47	1
	3	0.27^{-5}	957	3	34	206	83	158	18	2791	39	2
	4	0.88^{-6}	1047	3	33	210	121	65	9	1441	71	2
14	5	0.15^{-6}	1185	2	44	279	109	72	11	1562	63	1
24	5	0.10^{-5}	957	2	40	215	109	62	15	1514	40	1

(Cont.)

39

Table 15.--*Average elemental content of 0.002 N H_2SO_4 soil extract from Coram, as $\mu g/g$, by depth and plot, all months combined (pretreatment)--Continued*

Plot	Sub	H^+	Ca	Cu	Fe	K	Mg	Mn	Na	N	PO$_4$	Zn
		Molar										
					May 1974 (continued)							
20-25 cm												
11	1	0.72^{-6}	746	2	36	155	79	10	15	598	41	1
	2	0.13^{-5}	647	2	24	129	65	19	21	927	18	1
	3	0.96^{-6}	809	2	15	190	90	10	17	706	16	1
	4	0.61^{-6}	856	2	15	237	90	8	20	823	14	1
21	1	0.95^{-6}	801	4	60	196	109	36	14	869	92	1
	2	0.11^{-5}	743	4	53	159	87	31	20	1100	105	1
	3	0.12^{-5}	1128	4	66	175	180	22	11	1014	40	1
	4	0.83^{-6}	673	4	50	201	123	21	13	882	46	1
13	1	0.97^{-6}	878	2	28	259	136	26	26	1460	26	1
	2	0.24^{-5}	722	2	34	119	92	27	19	710	32	1
	3	0.96^{-6}	1053	1	30	250	72	10	21	710	13	1
	4	0.18^{-5}	923	2	27	141	78	9	22	749	8	1
23	1	0.98^{-6}	707	3	31	162	60	27	17	904	26	0
	2	0.54^{-6}	593	3	27	136	47	18	17	925	7	0
	3	0.79^{-6}	821	3	32	95	61	18	21	1525	25	0
	4	0.62^{-6}	774	3	37	179	71	20	11	687	47	0
14	5	0.24^{-6}	1029	2	78	209	82	13	15	773	21	1
24	5	0.63^{-6}	716	2	31	165	98	33	19	897	18	1
50-55 cm												
11	1	0.70^{-6}	508	2	19	72	64	6	15	326	14	0
	2	0.14^{-5}	509	2	19	90	57	9	15	402	17	0
	3	0.63^{-6}	540	3	19	100	86	10	13	476	14	1
	4	0.70^{-6}	505	2	14	82	64	8	14	323	7	1
21	1	0.59^{-6}	530	5	36	86	88	13	11	426	33	1
	2	0.14^{-5}	483	4	26	85	61	14	11	425	26	1
	3	0.10^{-5}	911	4	97	136	221	13	11	960	23	1
	4	0.10^{-5}	482	4	25	101	74	12	10	459	19	1
13	1	0.89^{-6}	889	2	25	114	79	10	17	491	11	1
	2	0.11^{-5}	730	2	28	90	111	13	16	455	7	1
	3	0.80^{-6}	1577	1	40	106	76	8	20	799	7	0
	4	0.49^{-6}	1419	1	32	193	112	7	19	551	4	0
23	1	0.92^{-6}	572	3	27	98	63	13	13	442	19	0
	2	0.61^{-6}	451	3	19	73	68	7	10	292	11	0
	3	0.89^{-6}	642	3	24	84	88	16	17	540	19	0
	4	0.55^{-6}	619	3	24	93	61	23	11	389	35	0
14	5	0.29^{-6}	1407	2	85	169	92	7	15	769	13	1
24	5	0.52^{-6}	764	2	30	95	91	32	20	725	14	1

(Cont.)

Plot: Sub :	H^+		Ca :	Cu :	Fe :	K :	Mg :	Mn :	Na :	N :	PO_4 :	Zn
: :							Element					
: :	*Molar*											
			All depths, plots, and months combined									
Average	0.10^{-5}		895	3	36	184	98	38	15	1078	40	1
S.D.	0.14^{-5}		426	1	35	177	68	47	6	1035	54	1
Percent nutrient balance	--		70.43	0.21	2.85	14.50	7.70	3.00	1.21	--	--	0.08

Total cations = 1270
Total anions = 593

Stark, Nellie M.
1979. Nutrient losses from timber harvesting in a larch/
  Douglas-fir forest. USDA For. Serv. Res. Pap. INT-231, 41 p.
  Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Nutrient levels as a result of experimental clearcutting,
shelterwood cutting, and group selection cutting--each with
three levels of harvesting intensity--were studied in a larch-
fir forest in northwest Montana, experimentally logged with a
skyline system. None of the treatments altered nutrient levels
in an intermittent stream, nor were excessive amounts of nutri-
ents lost in soil below the root zone. Under conditions on
this site, skyline logging did not result in surface erosion or
nutrient losses that would affect forest management.

KEYWORDS: Harvest, nutrient cycling, nutrient loss, water
quality.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field programs and research work units are maintained in:

Billings, Montana

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

FOREST RESIDUES UTILIZATION
RESEARCH AND DEVELOPMENT PROGRAM

INVENTORY & PRODUCT POTENTIAL

WOOD RESOURCE UTILIZATION

ENVIRONMENTAL EFFECTS

TECHNICAL AND ECONOMIC FEASIBILITY

FIRE BEHAVIOR IN NONUNIFORM FUELS

WILLIAM H. FRANDSEN
PATRICIA L. ANDREWS

FIRE BEHAVIOR IN NONUNIFORM FUELS

William H. Frandsen
and
Patricia L. Andrews

THE AUTHORS

WILLIAM H. FRANDSEN is a Research Physicist stationed at the Northern Forest Fire Laboratory in Missoula, Montana. He received his B.A. in physics and mathematics from Lewis and Clark College in 1954, and his M.A. in physics from the University of Oregon in 1960. Frandsen was employed from 1955-1967 as a physicist at the Naval Weapons Center at China Lake, California. While there, he was involved in two fields of study: infrared detection systems and the effects of ultrasound on metals. Since 1967, Frandsen has been with the Fire Fundamentals research work unit at the Northern Forest Fire Laboratory, where he is responsible for the technical planning and execution of research concerned with the thermodynamics of the fire and its interaction with the fuel complex.

PATRICIA L. ANDREWS is a Mathematician stationed at the Northern Forest Fire Laboratory in Missoula, Montana. She received her B.A. in mathematics and chemistry from Eastern Montana College in 1970, and her M.A. in mathematics and computer science from the University of Montana in 1973. Andrews has been with the Fire Fundamentals research work unit at the Northern Forest Fire Laboratory since 1973.

ACKNOWLEDGMENTS

RESEARCH SUMMARY

Predicting fire behavior in nonuniform fuel arrays is a problem requiring:

1. A method of assessing fuel nonuniformity,
2. A method of simulating fuel nonuniformity, and
3. An algorithm governing fire spread through a simulated array.

Satisfying these requirements is the objective of this paper. The main concept is built around partitioning the fuel into a honeycomb array. Each cell is described independently according to its bulk fuel parameters (depth, load, average particle size, etc.). Field assessment is designed to meet the requirements of simulation. An algorithm simulates fire spread through the array by coupling predictions of heat flowing from a burning cell to predictions of the heat required for ignition of the adjacent cells. Ignition is allocated to the cell offering the least requirement for heat. Consequently, the fire moves nonuniformly through the array taking advantage of the path of least resistance. Methodology is emphasized.

A simulated fire is initiated from a line source. Distortions in the propagating front result from fuel nonuniformities giving rise to a distribution of rates of spread rather than a single value. Analysis is appropriate for an assessment of a distribution of the fireline intensities.

Examples are given for slash, residue after tree harvest, and a mixture of grass and sagebrush. Nominal windspeeds of 0 and 2 mi/h were chosen for the purpose of illustrating the technique for handling nonuniformity.

Comparisons show that the previous alternative of combining all fuel to an average depth and load does not allow the land manager to assess the chance that patches of high risk fuel arrangements might result in unacceptable fire behavior.

CONTENTS

INTRODUCTION

Fire behavior in a woody fuel array such as found in the forest is a complex physicochemical process that does not lend itself to a simple solution. The process is further complicated by the spatial nonuniformity of the fuels involved in the combustion process. A fire responds to fuel nonuniformity by changing its rate of spread and intensity. As a result there is a distribution in the rate of spread and intensity experienced by the fire as it spreads through the fuel array.

For the purposes of this study nonuniform fire behavior is predicted by modeling fire spread through a hexagonal network of fuel cells. Fire spread is assumed to be a process of contagious growth between cells. Fuel properties are allowed to vary from cell to cell in a prescribed manner but have uniform properties within the cell. Consequently, the nonuniformity of the actual fuel array is simulated through cell to cell variations and has a resolution limited by the cell size. Because of the nature of the modeling process it is necessary to devise a scheme for collecting data describing nonuniformity and a scheme for filling the hexagonal cell array in a manner that simulates the actual fuel nonuniformity.

Historically, it was necessary that uniformity be addressed first. This approach laid the groundwork for present development. Rothermel (1972) chose a path of research into fire behavior that allowed the result to be applied to the needs of the fire manager. Rothermel's variables were the fuels and the environment in which they were found. That same view exists here. The fundamental approach of the model described here is the assumption that small portions of a nonuniform fuel bed can be considered uniform. Nonuniform fire behavior then can be examined by following the progress of the fire as it changes speed while moving through different but uniform subunits of the area. This model was developed as part of an integrated effort for solving fire behavior problems at the Northern Forest Fire Laboratory. The model is not intended for direct simulation of actual fire situations but rather is offered as a means to develop simplified methods for solving fire behavior problems in the field.

Some aspects of fuel nonuniformity such as occasional absences of fuel have a direct effect on fire behavior. However, most often fuel nonuniformities are more subtle and must be viewed through another interpretive system, a model of fire behavior. Consequently, we define fuel nonuniformity in terms of fire nonuniformity through a model of fire behavior that responds to spatial variations of the fuel array.

Uniform fuel arrays and uniform fires do not occur. All fire behavior in woody fuel arrays is nonuniform. Fire behavior becomes uniform by definition. As a point of comparison, most people consider fire spreading over a sheet of paper as uniform. But, it may be viewed by some as nonuniform by focusing on the elemental combustion process. Certainly, fuel uniformity does not exist in natural woody fuel arrays. The arrays are comprised of separated particles. Fons (1946) described fire spread as a series of ignitions. Fire spread appears to follow this description on the scale of the fuel separation. The flame ignites the particle and then spreads along that particle until it reaches another particle. The flame may ignite the next particle by flame contact or the particle may ignite after radiation from the flame front has preheated the fuel sufficiently to drive off combustible gases that burn when in contact with flame.

A fire appears uniform when the particle separation is small compared to the flame size (or the range of influence of the flame). Individual flames coalesce into a solid moving front and the fire spreads in response to the bulk fuel properties of the array--load, particle size distribution, and depth. These properties are defined within a volume element, averaging out the small variations of particle separation. Averaging is not limiting so long as the volume element encountered by the flame is small compared to the size or range of influence of the flame. It is this level of nonuniformity that we address. Wind and slope can act to increase the size of the flame and orient it so that the spatial variation of bulk fuel properties is small compared to the area affected by the flame. Thus, a nonuniform fire can become uniform in the presence of wind or slope.

Although resolution is limited by the cell size, the introduction of wind alters the overall perspective of resolution. Wind increases the size of the area sustaining active combustion and therefore increases the error of locating the fire. Consequently, in the presence of wind, the size of the cell can be increased without altering accuracy in locating the fire.

The model is applied to two examples of nonuniformity: slash, residue left after tree harvesting, and a mixed community of grass and sagebrush. (Slash is more uniform than a mixed community of grass and brush.) The reader should expect to gain an appreciation for the problem of defining fire nonuniformity, developing a model of fire behavior that responds to fuel nonuniformity, and an appreciation of the kind and form of the results obtained from the nonuniformity model. Attempts are not made to validate the model. Consequently, the rigors of replication are replaced with a logical flow of fire behavior concepts--concepts derived from the uniform fire behavior model. The initial advantage is a consistent manner of handling field data that is applied to nonuniform fire behavior.

The response of a spreading fire to the bulk properties of woody fuel arrays-- as found in forest fuels--has been investigated by Fons (1946), Thomas and Simms (1963), Anderson (1968, 1969), Frandsen (1971), Steward (1971), and Rothermel (1972). Rothermel incorporated fuel parameters (load, size, depth) and the fuel interactions into a model of fire spread through a continuous fuel array. Although the fuel array is continuous, it may be heterogeneous in size and type. Live and dead fuel may be included if mixed in the same stratum.

Fuel parameters for the uniform fire spread model are categorized as living or dead, and averaged within a specific set of fuel size classes. The fuel array is assumed to be continuous. As a consequence, the model given by Rothermel (1972) predicts well for spatially continuous fuels and becomes increasingly less accurate as fuel discontinuity increases. To properly assess fire behavior, continuity must be included as an essential parameter in the mechanism of fire spread. Brown (1966) described the problem of continuity as follows:

Closely related to compactness but on a larger scale is continuity or patchiness of fuels. It represents the degree of change, horizontally and vertically, in the physical characteristics of fuels existing over a given area and is a measure of the uniformity of continuous combustion (for a constant set of weather conditions). At present, a meaningful quantitative description of continuity is lacking. Development of an objective description of continuity would be of benefit to continued fire research as well as fuel appraisal and fire control planning.

A discontinuous fuel array exhibits abrupt changes and is a unique example of nonuniformity. We employ a broad definition of nonuniformity that includes discontinuities.

A simple example of a nonuniform array is one in which only the depth varies. The fire cannot achieve a constant rate of spread throughout the entire fuel complex, but may achieve it for some uniform subunit of the larger nonuniform array. Consequently, fire will accelerate and decelerate as it moves through the array. An observer usually calculates the average rate of spread from the time it takes the fire front to travel some given distance, but the result may not be related to either the individual depths or to the average depth.

Nonuniform fire behavior implies more than one result for the rate of spread and intensity. Results should be expressed as a frequency distribution allowing the user more complete information on which to base a decision. The breadth of the distribution indicates the range of options to be considered in the management or control of a fire. Rothermel (1974) gives general accuracy requirements for the application of fire behavior models to fire management and control ranging from training aids to real-time fire predictions. As a training aid the new information will help emphasize the probabilistic nature of fire behavior. The impact on planning and management can be profound allowing a realistic assessment of the range of effects for alternative treatments of the land. The highest requirement for accuracy is predicting real-time fire behavior. A knowledge of fire nonuniformity at this stage is essential.

A method of collecting information from the field that represents fuel nonuniformity is not common to present fuel inventory systems. Use of average fuel parameters in the uniform model as an alternative produces less reliable results as the fuel array becomes more nonuniform. An averaging of the fuel parameters prior to processing by a fire behavior model ignores the variable nature of fire as it moves through a nonuniform fuel array. A change in the fuel does not imply a proportional change in the fire behavior. An improved estimate of fire behavior can be derived from an analysis of the distribution of fire characteristics produced by the model as the fire passes through the array.

Both rate of spread and intensity are implied in the frequency distributions of fire behavior results. Distributions of the rate of spread allow for a realistic assessment of the actual range of spread rates and area growth rates essential to prescribed burning and the control of wildfire. Distributions of the fire intensity provide insights for an assessment of the distributions of flame lengths and crown scorch heights to be expected on a site. As research into quantification of the heat pulse impinging on the site progresses and is related to the intensity distribution, assessment of the proportion of the burned area that will regenerate vegetation after a fire should be possible. Variation in regeneration is seen in the response of seedlings in the vicinity of pile burning. Davis (1959) writes:

It is common to observe that seedlings and other vegetation often
do not become established for several years where large slash piles
have been burned. A profusion of vegetation may fringe the area, but
the center may be bare.

These efforts also should provide inputs to hydrologic and soil stability impacts.

SIMULATING FIRE BEHAVIOR

We are concerned only with nonuniform fire spread in the horizontal plane.
Arrays with large vertical nonuniformity are not considered. The results of the
simulation must reflect the variability in fire behavior due to the spatial non-
uniformity of the fuel. Fire spread results are presented as a frequency distri-
bution of the rate of spread of the fire front at variable lapsed times from igni-
tion of the initial fire front. Intensity distributions are presented for those
lapsed times.

The simulated fuel bed consists of an array of cells. Each cell is described
by a set of basic fuel parameters (Rothermel 1972) that affect the rate of fire
spread. The time to move from cell to cell depends on the parameters of the two
adjacent cells. The fuel is assumed to be evenly distributed within each cell.

The fire begins as a line source and travels from cell to cell by contagious
growth through a series of ignitions and spreads at a rate based on a minimum delay
time (appendix I) within each individual cell (fig. 1). Hexagonal cells are used
because they do not have point contacts when arranged in an array and offer the
maximum number (six) of growth directions while maintaining a constant distance
between cell centers.

The delay time is the core of this analysis. Delay time is viewed as the time
it takes for the fire to spread through the cell. Thus it is the amount of time the
fire is delayed in a cell before it can attack an adjacent cell. The delay time is
the sum of two parts: the time to achieve the quasi-steady spread rate in the cell
and the time to spread the remaining distance at a steady rate of spread. The time
to reach the quasi-steady state is assumed to be the residence time of the cell and
the remaining time is the remaining distance divided by the quasi-steady rate of
spread for that cell. Consequently, the cell chosen must be of a size such that the
time for the fire to spread through the cell is equal to or greater than the resi-
dence time of the fire in the cell. An essential restriction of the model is that
the influence from a burning cell extend no further than its immediate neighbors.

After passage of the front, the fire will remain burning in the cell for a
period of time dependent on cell fuel properties, the properties of the cell it
was ignited by, and the size of the fuel cell. The delay time can be shortened
after ignition if heat from another adjacent cell has sufficient intensity to
offer a delay time less than the present waiting time.

Fire from one cell can ignite an adjacent cell after it has reached its es-
cape level, i.e. waited a time equivalent to its delay time. If the adjacent cell
is presently unignited, the fire moves in, delay time is assigned, and the fire be-
gins its waiting period to reach its escape level. If the adjacent cell is already
ignited and the proposed delay time is less than the present waiting time, then the
waiting time is replaced by the delay time. Otherwise the cell retains its waiting
time. A detailed discussion of the delay time appears in appendix 1.
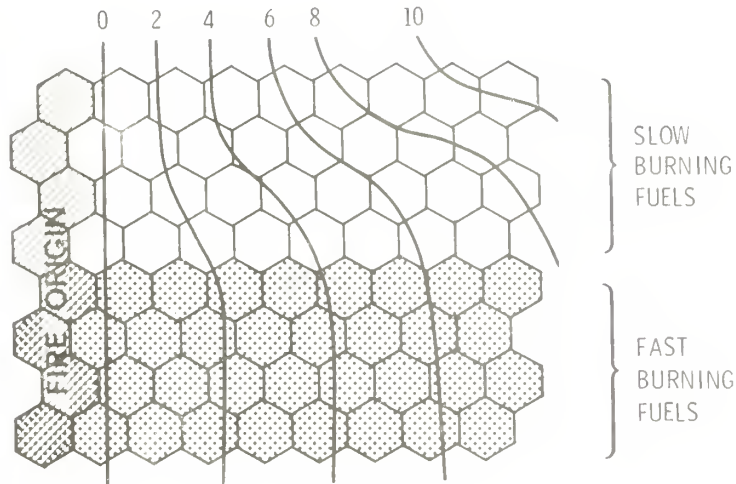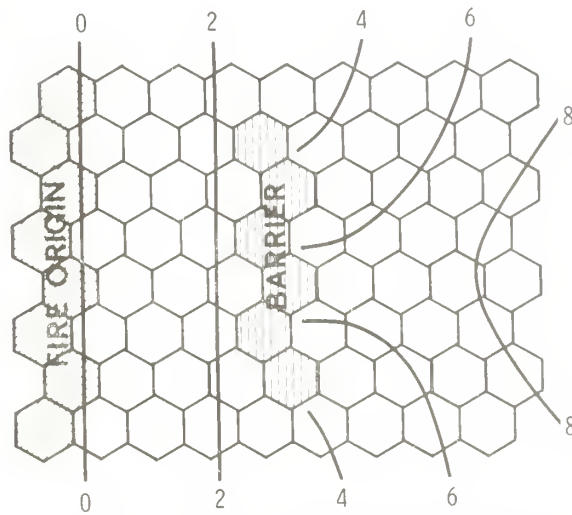
Figure 1.--Fire front progress through two nonuniform hexagonal fuel arrays.

The rate of fire spread also has a dependence on wind and slope. Rothermel (972) used only the maximum effect, i.e. wind and slope in the same direction. Fovision was not made for combining nonparallel wind and slope nor for the compu- ttion of rates of spread in the six spread directions required by the hexagonal aray. Albini,[1] however, developed a method for combining wind and slope that gve the resultant magnitude of rate of spread as a function of an angle relative t the directions of the wind and slope. With Albini's model, it was possible to cmpute potential rates of spread in all six directions in the presence of wind ad slope.

---

[1]Albini, Frank A. Memorandum, subject, Combining wind and slope effects on sread rate, to R. C. Rothermel, Northern Forest Fire Laboratory, Missoula, Mntana 59806, Jan. 19, 1976.

As a comparison, the Dijkstra (1959) algorithm employed in the Kourtz-O'Regan (1971) fire spread model locates the paths of least resistance based on delay times dependent only on the fuel descriptors of each individual cell, without dependence on an adjacent cell. As each cell is reached--ignited--by the fire, the lapsed time since fire starting time is recorded in the cell. Isochrones can then be drawn to illustrate the progress of the fire. The two models are similar except for the differences in delay time mentioned above. The Dijkstra model does not require up-dating since it maps the path of least resistance to fire spread. Presently the Kourtz-O'Regan model uses very large cells and average fuel parameters to describe the average rate of spread and thus the delay time to consume the fuel cell. The hexagonal model operating on cells that are subunits of the larger Kourtz-O'Regan cell then can provide a distribution of rate of spread values needed to compute the probable time a fire takes to consume a cell in the Kourtz-O'Regan model. Thus, data obtained from the hexagonal model could be used as input to the Kourtz-O'Regan model.

For a continuous fuel array the fireline intensity is the product of the reaction intensity and the combustion zone depth (Albini 1976) and assumes a constant reaction intensity throughout the combustion zone. For the nonuniform array the reaction intensity is assumed constant throughout the cell but may vary from cell to cell.

Following a suggestion by Frank Albini of the Northern Forest Fire Laboratory, the fireline intensity is obtained by summing the products of the reaction intensity and that portion of the cell contributing to the combustion process. Each column is scanned perpendicular to the initial fire front (fig. 1):

$$I_B = \sum_i (I_R)_i F_i D$$

where I_B is the column fireline intensity, $(I_R)_i$ is the reaction intensity of the ith cell, F_i (appendix II) is that fraction of the ith cell that is contributing to the combustion process, and D is the cell width. All column intensities then are grouped to form a frequency distribution.

The sum of the products, $\sum_i F_i D$, is the combustion zone depth if the fire is burning perpendicular to the initial line of fire. Occasionally, portions of the fire front may be burning to the side. Scanning down the columns would then give some combustion zone depths that are unreasonably high. This results in spikes in the distribution at high fireline intensities that can be easily located and disregarded.

Fuel Array Assessment

The geometric nature of the fire behavior model presented resulted in a fire spread algorithm coupled to a hexagonal array of fuel cells. However, application to the field is not possible unless we are able to fill the hexagonal array in a manner that preserves the horizontal stratification of the actual fuel array. Filling the hexagonal cells requires fuel array data (load, size, depth) that must be acquired in a manner that fills the needs of the cell filling algorithm. In general, we should look for some classifiable character to give the assessed non-uniformity a recognizable distinction related to its habitat type or other comparable classification, i.e., fuel type, and age. Habitat classification according to Daubenmire and Daubenmire (1968) is presently used by the USDA Forest Service in Idaho and Montana to classify vegetation and its associated environment. Fuels are a byproduct of the habitat type but may occur in different arrangements of load, particle size distribution, and depth, and thus are classified separately. Fuel models used in the U.S. National Fire Danger Rating System are obtained by grouping depth, particle size, and load into a classification scheme. Data gathered from sampling fuel arrays should characterize the horizontal pattern of differing fuel types as well as the spatial occurrence of the basic fuel properties (load, size, depth) within a fuel type. Other fuel properties--heat content, mineral content, and particle density--have little variation within the fuel type and are assumed constant. Fuel moisture is time-dependent responding to diurnal changes in humidity and temperature. However, these changes are sufficiently slow so that fuel moisture can be considered constant over the duration of the fire being examined. Although moisture can be introduced as a spatial variable, it is held constant so that the response to nonmoisture fuel variability can be emphasized. It is anticipated that experienced land managers will make adjustments for moisture changes.

Two methods of fuel assessment are presented: (1) sampling a specific size area at periodic intervals along transects, and (2) if components are random, evaluating the percent cover and describing the uniform fuel properties of each component.

SLASH

The first method stated was employed in slash owing to the absence of recognizable patterns in the spatial arrangement of the fuels. Transects were obtained from a slash area composed primarily of western larch and grand fir. The area was essentially a clearcut with only a few remaining trees. Trees were cut to an 8-inch (20 cm) unmerchantable top and the entire tree except the top skidded to the landing. Nonuniformity was assessed in terms of load and depth along a 100-foot (30.5 m) transect at 2-foot (0.61 m) intervals. The fuel load was estimated by size class from the number of intercepts through a vertical sampling plane (Brown 1974). The following size classes were assessed: 1h, 10h, and 100h.[2] Pieces greater than 3 inches in diameter were measured but not considered in the model because they do not significantly contribute to fire spread.

---

[2] Fuel size classes are characterized by the time lag constant related to their ability to respond to humidity by absorbing or desorbing moisture (Fosberg 1970). The 0-1/4 inch (0-0.63 cm) size class is called 1h, 1/4-1 inch (0.64-2.54 cm) the 10h, and the 1-3 inch (2.55-7.62 cm) the 100h.

Because of the roughness of the surface of slash, it was necessary to define a depth called the bulk depth. It is an estimated mean that retains the bulk density of the inventoried fuel load and is confined to a cylinder 1 foot (0.30 m) in radius whose central axis is perpendicular to the slope at the sample point. Four estimates are made within the cylinder, each representative of 25 percent of the area (not necessarily a quadrant). Vertical gaps of more than 1 foot are subtracted before each estimate is completed. Gaps less than 1 foot are assumed to maintain vertical continuity through the potential flame height. The average of the four estimates is recorded as the estimated mean depth.

Each logged unit was measured in two stages. A grid of approximately 30 sample plots was established for each unit. In the first stage, the load for each of the four size classes was measured at each plot according to Brown (1974). In the second stage, the unit was arbitrarily divided into four sections and a sample plot was chosen at random from each section. At the first sample plot, a 100-foot (30.5 m) transect was selected at random and oriented in one of three directions: (1) 60° counterclockwise to the uphill direction, (2) uphill, and (3) 60° clockwise from the uphill direction. A random selection of the two remaining orientations was made at the second plot. The last remaining orientation was made at the third plot. Orientation on the fourth plot was chosen at random from all three directions as in the first plot. Sample planes 2 feet (0.6 m) across were oriented first along the transect line and then perpendicular to this line with the sample point as the center. The bulk depth was recorded for each sample point (fig. 2). The 10h size class load was measured at both orientations of the sample plane at one-third of the sample points which were selected at random. The range of depths and loads obtained from transects are given in figures 3 and 4.

In stage two, only the 10h intercepts were counted. Data gathered in the first stage provide the information for relating the load in the 10h class to the other two classes (1h and 100h).

The resulting 2-foot sampling interval established a minimum cell size for the hexagonal array. A smaller size would seriously degrade the accuracy of the load estimate obtained from the planar intersect technique. If larger cells are required, they can be constructed by combining cells.

Three of the four transects taken on the slash area had similar cumulative depth distributions. The remaining transect was discarded leaving a data base of 150 bulk depths and approximately 50 10h-fuel load estimates. The unit was generally described as having a light slash load. Consequently, this unit should exhibit correspondingly low rates of spread and intensities.
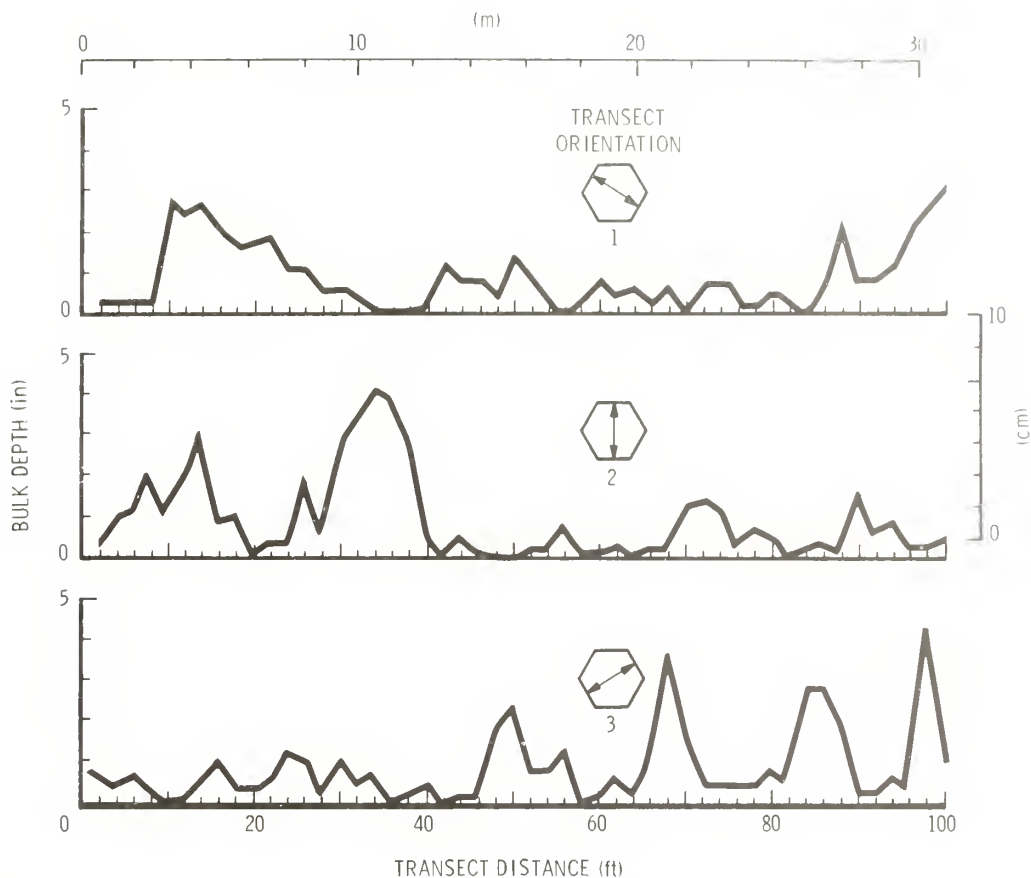
Figure 2.--A representative transect of the bulk depth evaluated every 2 feet. Three orientations are shown: (1) 60° counterclockwise to the uphill direction, (2) up-hill, and (3) 60° clockwise to the uphill direction.
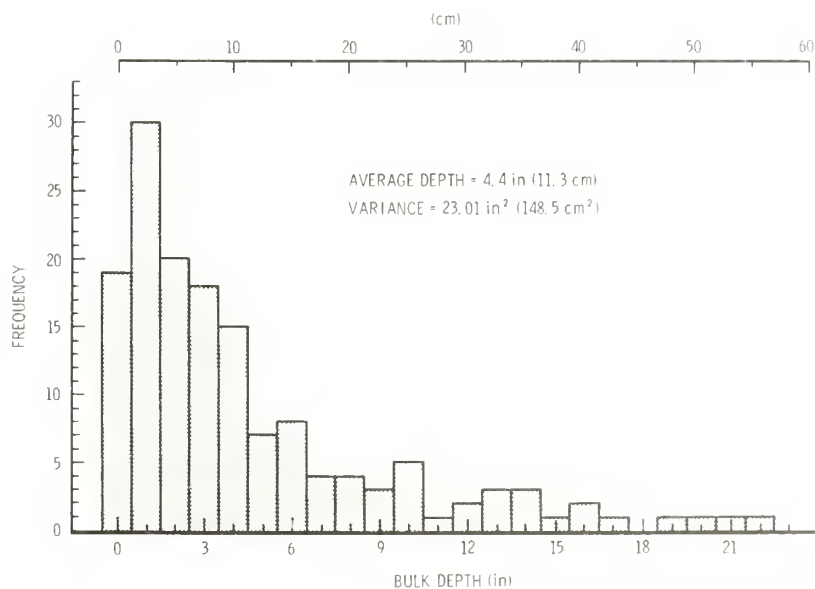
Figure 3.--Frequency distribution of the slash bulk depth. (All measurements were made at a resolution of 1 inch (2.54 cm).

9
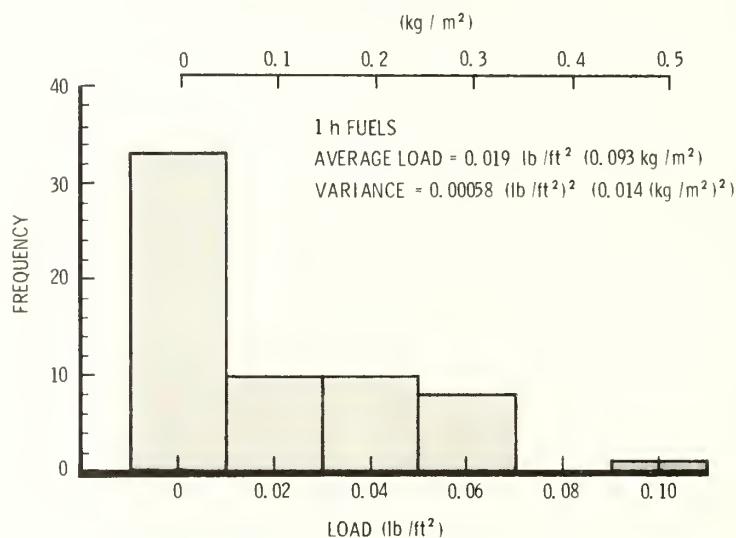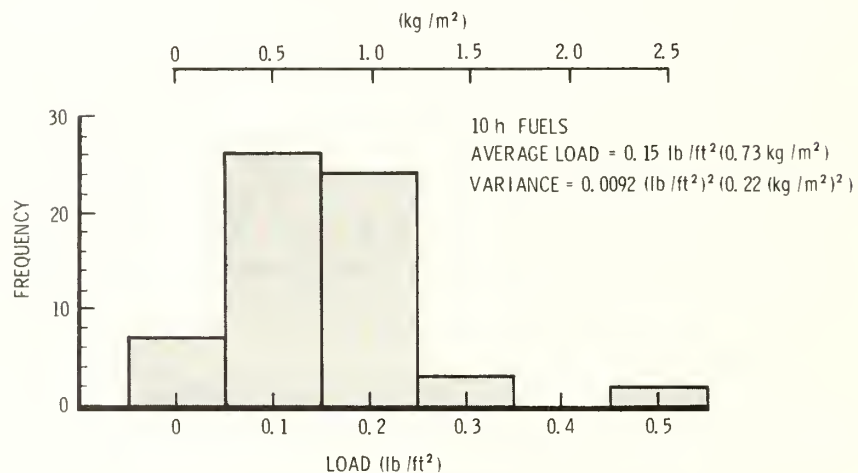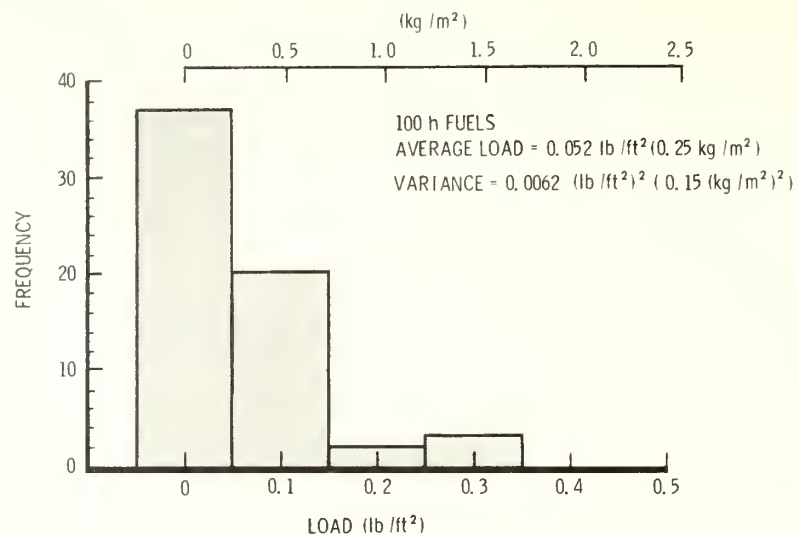
Figure 4.--Frequency distribution of the slash load. The upper distribution is for 100h fuels, the middle for 10h and the lower for 1h fuels. The implied negative load is artificial.

10

GRASS AND SAGEBRUSH

The second method, evaluating percent cover, was used for the mixture of grass and sagebrush because this mixture can be separated according to load breakdown by size class and depth, resulting in two components. Grass is predominantly made up of single sized particles. The bulk density, load divided by depth, varies from 0.028 to 0.085 lb/ft^3 (0.45 to 1.36 kg/m^3) with a mean of 0.05 lb/ft^3 (0.80 kg/m^3) according to data Sneeuwjagt (1974) collected from the Soil Conservation Service on Western United States grasses. A knowledge of either the load or the depth is sufficient to quantify the amount and arrangement of the grass fuel if the bulk density is known. For this example, we have considered all of the grass fuel to be dead.

Studies by Rittenhouse and Sneva (1977) and Brown (1976) allowed the evaluation of fuel loads for sagebrush according to height and largest planform diameter. The first study related the mass to the crown dimensions of the plant. The second study related the mass of single stems (including branches and foliage) to the basal diameter of the stem. But the second study (Brown 1976) went a step further to provide a breakdown of the mass by size class. Assuming that the sagebrush plant originated from a single stem. We were able to compare the two methods and obtain the load (mass per planform area) related to the crown dimensions of the plant.[3]

The following dimensions were chosen to represent sagebrush; an average height of 3 feet (91 cm) and an average diameter of 2.5 feet (76 cm). Table 1 lists the fuel parameters associated with these bulk dimensions. Fuels larger than 1/4 inch (0.64 cm) have been ignored in this analysis because they have only a minor impact on the spread rate and fireline intensity; these larger fuels are not consumed in the initial combustion process and therefore do not contribute to the spread process.

Table 1.--*Fuel parameters for grass and sagebrush*

Fuel description	Surface/volume ft^{-1}	cm^{-1}	Dry load lb/ft^2	kg/m^2	Moisture[1] content	Moisture of[2] extinction
Grass (fuel depth = 1.00 ft (0.30 m))						
	3000	98.4	0.0275	0.134	0.05	0.15
Sagebrush (fuel depth = 1.48 ft (0.45 m))						
Live foliage	1500	49.2	0.0538	0.263	1.00	2.00
Live 1h	677	22.2	0.0941	0.459	0.50	2.00
Dead 1h	677	22.2	0.0235	0.115	0.09	0.20

The values of fuel parameters common to all fuels discussed are:

Low heat value . . . . 8000.0 BTU/lb (18,595 kj/kg)
Particle density . . . . 32.0 lb/ft^3 (0.51 g/cm^3)
Fractional[1] mineral content 0.06
Fractional[1] effective mineral content 0.01

[1]Fraction of dryweight.
[2]A parameter involved in the computation of the moisture damping coefficient (Rothermel 1972). Higher values allow the fire to spread at higher moisture contents

---

[3]Data on file at the Northern Forest Fire Laboratory, Missoula, Montana.

Data collected and analyzed[3] according to Holgate (1965) shows sagebrush plants to have a random distribution. Consequently, the additional information required to fill the hexagonal fuel array is the number density of plants. The density, coupled with the average planform area, dictates the percent cover that must be achieved for a random filling of the array.

Fuel Array Generation

SLASH

Assignment of the bulk depth to each 2-foot hexagonal cell is the first step toward generating the slash fuel array. The fuel load then can be assigned to each cell through direct and indirect relationships to the depth (see appendix III).

After surrounding the area to be simulated by a boundary of depth values having the same distribution as the array but not the spatial order, the remainder of the area can be filled with depths using a linear model suggested by Mike Marsden of the Northern Forest Fire Laboratory:

$$Y = b_o + b_1 X_1 + b_2 X_2 + b_3 X_3 + e$$

where Y is the depth being assigned to a cell and X_1, X_2, and X_3 are the depths that have been assigned to three adjacent cells and e is the error.
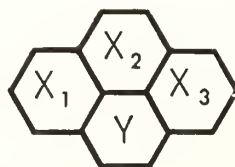
The dependent variable, Y, and independent variables, X's, change as the array is filled. A more extensive array using the same principle is shown below.
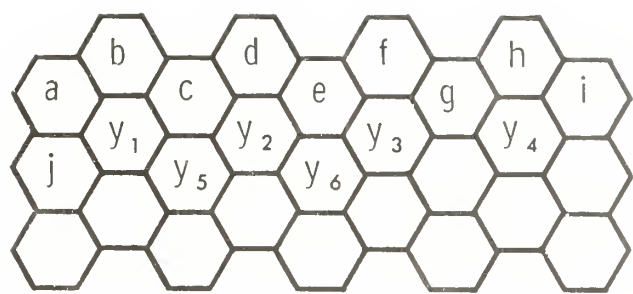
Y	: X_1	: X_2	: X_3
y_1	a	b	c
y_2	c	d	e
y_3	e	f	g
y_4	g	h	i
y_5	y_1	c	y_2
y_6	y_2	e	y_3

The coefficients b_o, b_1, b_2, and b_3 are derived from the mean bulk depth and serial correlations of lags 1 and 2 of the bulk depths along linear transects through the slash array (appendix IV) and not according to the cell filling format, shown above. The following data were obtained from field transects and are used to develop the array for the slash example.

Average depth = 4.44 in (11.3 cm)

Variance = 23.01 in^2 (148.5 cm^2)

| | Serial correlations | |
Orientation	Lag 1	Lag 2
1	0.45	-0.044
2	0.69	--
3	0.62	+0.38

Serial correlations are simply correlations of data pairs (Snedecor and Cochran 1967) obtained from sequential transect depths of lag 1 and 2. A lag of 1 designates a correlation of adjacent depths, whereas a lag of 2 designates a correlation of data pairs obtained by skipping one depth in the transect sequence. The numerical value of the correlation is the correlation coefficient that allows the user to quantify the similarity or dissimilarity of these data pairs.

The error, e, associated with each prediction of y is obtained through random access of the cumulative distribution of the bulk depth (see appendix V). Because of the error term, generated fuel arrays are not identical. This is in agreement with the goal to produce a pattern that has the essence of the array but is not an exact reproduction. An example is wallpaper design. Your eye recognizes a pattern, but may not find exact comparison.

The average fuel parameters of the simulated fuel array are given in table 2. A comparison with figures 3 and 4 shows the tabular load and depth values to be within one standard deviation of the averages given in the figures except for 100h fuels. The foliage load is not given as a distribution. The foliage load is a fraction of the sum of the 1h, 10h, and 100h fuel loads (appendix III). The simulated serial correlations of the depth for lag 1 were 0.12, 0.31, and 0.11 for orientations 1, 2, and 3, respectively. These correlations are reduced considerably from the original correlations used to generate the fuel array. However, these correlation data showed the best comparison while maintaining an average depth comparable to the original data. Other correlations can be obtained by manipulation of the error function, but this in turn causes unacceptable changes in the average depth and its variance. The average depth of the final simulated array is 5.45 inches (13.8 cm) with a variance of 18.03 in^2 (116.3 cm^2). These data are in good agreement with the original depth data used to generate the fuel array.

Table 2.--*Average fuel parameters for slash*

| Fuel description | : | Surface/volume | | : | Dry load | | : | Moisture[1] |
	:	ft^{-1}	: cm^{-1}	:	lb/ft^2	: kg/m^2	:	content
		Slash (fuel depth = 0.43 ft (0.13 m))						
Dead foliage		2000	65.6		0.118	0.576		0.05
Dead 1h		436	14.3		0.0363	0.177		0.05
Dead 10h		91	3.0		0.246	1.199		0.05
Dead 100h		29	1.0		0.190	0.926		0.05
		Moisture of extinction = 0.25						

[1]Fraction of dryweight.

GRASS AND SAGEBRUSH

Generation of the grass and sagebrush fuel array is less complicated than generation of the slash fuel array because of the random distribution of the sagebrush plants within the grass matrix. The cell size of the fuel array is chosen to approximate the average diameter of the sagebrush plant, 2.5 feet (76 cm). It is necessary then only to classify the cells randomly as grass or sagebrush from a distribution that reflects the percent cover of the sagebrush within the grass matrix. A value of 30 percent was chosen as representative of the percent cover of sagebrush. Cells were assigned a fuel type of either grass or sagebrush. The fuel descriptors are given in table 1. The fuel depth listed for sagebrush is an equivalent height that when divided into the fuel load gives a bulk density equivalent to the shrub crown.

RESULTS

Predictions of the fire spread rate and intensity were obtained for slash at 0 and 2 mi/h (0 and 3.2 km/h) and for the grass-sagebrush mixture in the absence of wind. Slope was 0 for both examples and the wind was perpendicular to the initial line source. The important difference from other forms of the result is that the predictions are presented as distributions.

The rate of spread distribution was obtained from the distance traveled in a specified time along each column of cells perpendicular to the initial fire front (fig. 1). Furthermore, the characteristic distance that the fire has traveled through a cell--and thus the fraction consumed--can be calculated at a given time (appendix II). Consequently, the accuracy of the overall distance traveled is not limited to the cell size.

The predicted intensity, Byram's fireline intensity, is presented as a distribution made up of the intensities from each column of the array.

SLASH

The distributions of the rates of spread at 0 windspeed and at a 2 mi/h windspeed and 0 slope are given in figure 5. A prediction of the rate of spread assuming a uniform fuel array having the average fuel parameters of the simulated array as given in table 2 is presented also for comparison to the distribution. The average spread rate of the uniform model lies 31 percent[4] below the nonuniform model (average of the distribution) at a 0 mi/h windspeed and 21 percent below at a windspeed of 2 mi/h. The overall range for both cases lies from 65 percent below to 76 percent above the nonuniform model average.

---

[4]The nonuniform model average was used as the base for all percentage calculations.
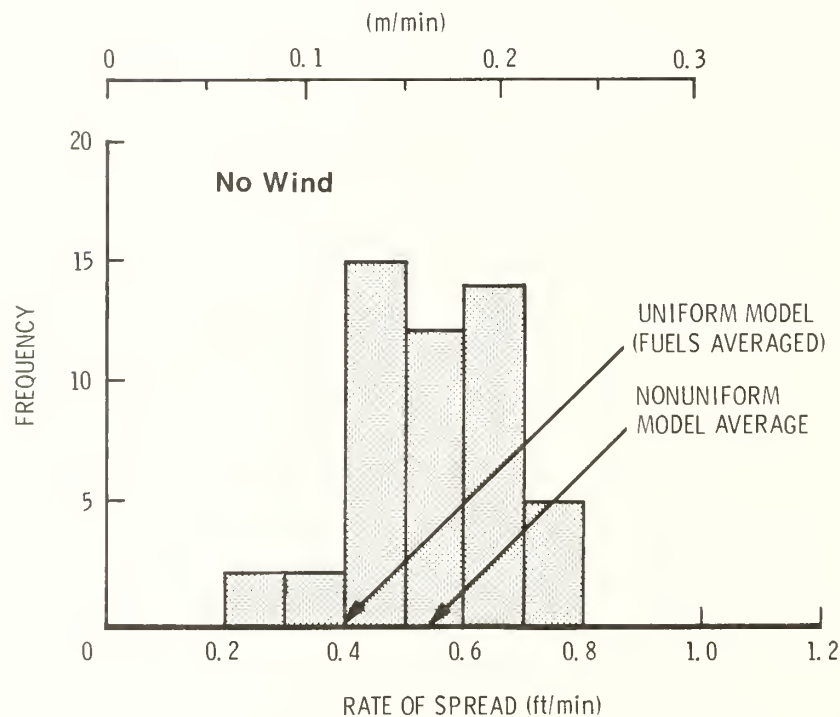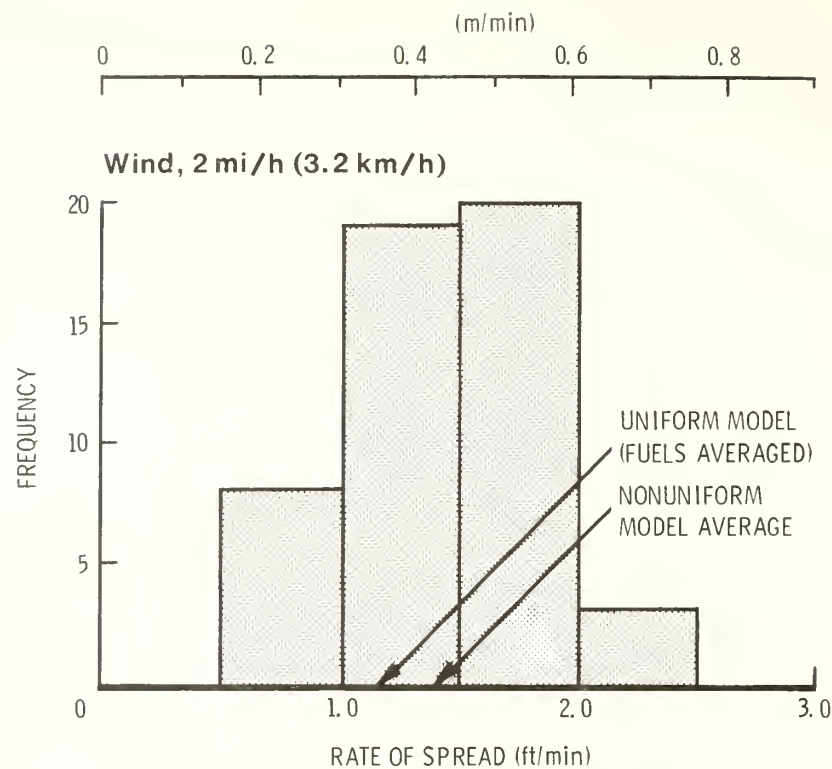
Figure 5.--Frequency distribution of the rate of spread in slash fuels at 0 windspeed and at a 2 mi/h windspeed. The average rate of spread is indicated for the uniform model (average fuel parameters from the simulated array) for comparison with the nonuniform model (average value of the distribution).

The distributions of the fireline intensities at 0 windspeed and at a 2 mi/h windspeed and 0 slope are given in figure 6. A prediction of the intensity from uniform fuel properties is again presented for comparison, similar to the presentation of the rate of spread prediction. The average intensity of the uniform model lies 43 percent above the nonuniform model at 0 mi/h windspeed and 29 percent above at 2 mi/h. Both distributions decrease monotonically with increasing intensity and are bounded on the low side by 0 intensity. The upper limit is 6 times the nonuniformity model average at 0 mi/h windspeed and 7 times that average at 2 mi/h.
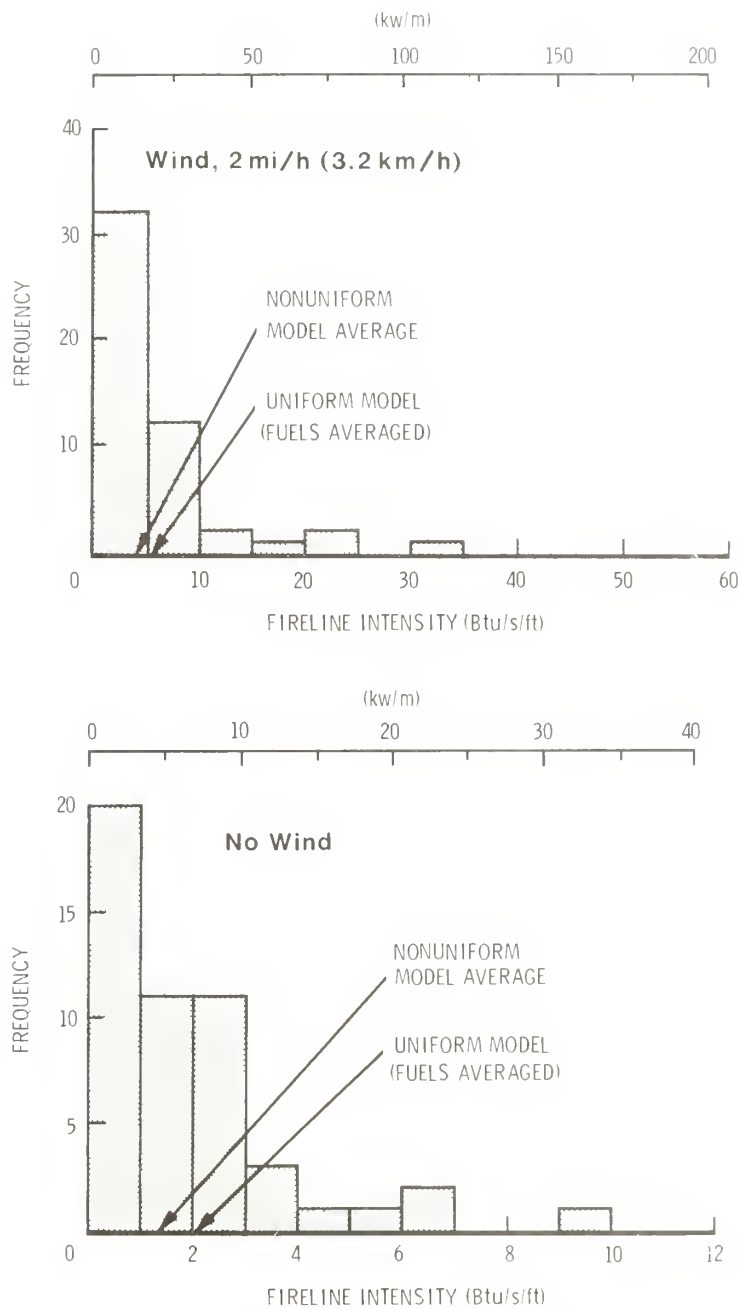
Figure 6.--Frequency distribution of fireline intensity in slash fuels (no windspeed and 2 mi/h windspeed).

GRASS AND SAGEBRUSH

The distribution of the rate of spread in the absence of wind and slope is given in figure 7. Uniform model predictions are obtained by averaging the fuels according to the percent area covered in the fuel array. In addition to the uniform model average and the nonuniform model average, the uniform rates of spread for grass and sagebrush are given individually along with their average weighted by percent area covered. The additional predictions are possible because the fuel array is made up of two distinct components.

In addition to the uniform and nonuniform model averages as presented in figures 5 and 6, the uniform results for grass and sagebrush are indicated separately along with the average, weighted by percent area covered.
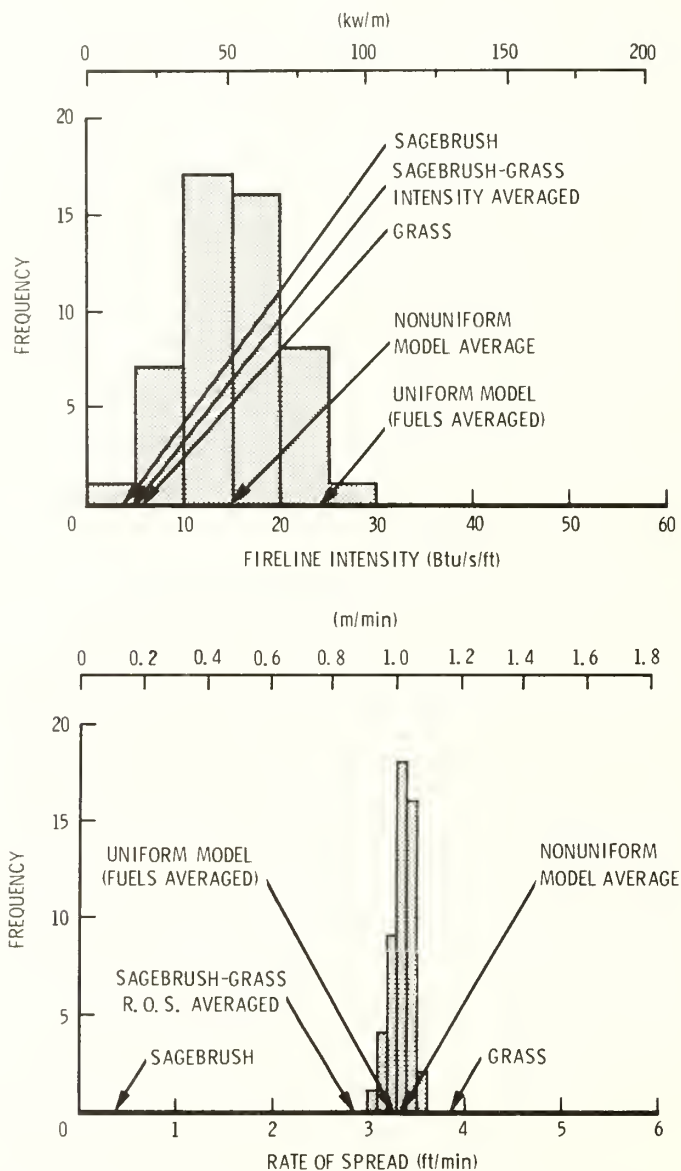
Figure 7.--Frequency distributions of rate of spread and fireline intensity in a 70 percent grass-30 percent sagebrush mixture (in absence of wind).

The rate of spread distribution lies in a narrow band near 5 ft/min. See figure 7. All values presented are less than 4 ft/min. All three averages--uniform, nonuniform, and weighted--lie within the extremes of uniform sagebrush and uniform grass.

The fireline intensity distribution extends from 0 to 30 BTU/s/ft and includes the uniform model averages. In contrast to the rate of spread, both the uniform and nonuniform model averages lie outside the extremes of uniform sagebrush and uniform grass--exceeding both values.

Fires were not simulated in the grass-sagebrush mixture at 2 mi/h windspeeds because the transition zone depth exceeded the cell size, 2.5 ft (76 cm). See appendix I. The grouping of cells into larger cells is possible but in this case the fundamental cell is the size of a sagebrush plant. Averaging such dissimilar fuel cells at this time does not serve the purpose of this paper--to illustrate the nonuniform modeling approach and the form of the result.

DISCUSSION

Fuel nonuniformities, and resulting nonuniform fire behavior, although recognized as a problem, have been ignored because of a general inability to handle nonuniformity both in its assessment and simulation and in the form of the result. Historically we have attributed a single rate of spread to a unit of land. This concept existed before the formulation of the uniform fire spread model (Rothermel 1972). The assumption of uniformity in the first attempts to describe firespread in wildland fuels was a logical first step. The assumption may have enforced our view of single valued results but is not the source of that viewpoint. The recognition of fuel nonuniformity carries with it the realization that fire exhibits nonuniform behavior. Consequently the result must be in the form of distributions, excursions about the average.

Two fuel arrays, slash and a grass-sagebrush mixture, are presented as examples for describing the nonuniform fire behavior model. Slash is a single fuel type with varying depth and load. The grass-sagebrush mixture is a mixture of fuel types. Unlike slash, most any location in the mixture has a dichotomous description as either grass or sagebrush.

All possible combinations of obtaining average fire behavior results using the uniform fire model were employed for comparison with the distributions. For slash, the average depth and fuel load were used. For the grass-sagebrush mixture, there were the additional results obtained from uniform grass, uniform sagebrush, weighted average of grass and sagebrush fuels, and the weighted average of the two results for uniform grass and uniform sagebrush.

In general, there is agreement among the averages of the uniform model (fuel parameters averaged) and the nonuniform model (distribution averaged). The trend indicates that the uniform model average is less than the nonuniform model for rate of spread but greater for fireline intensity. The higher frequency of zero fireline intensity in slash is attributed to the frequency of cells not having fuel. This is consistent with the grass-sagebrush mixture results where empty cells were not present.

The average fireline intensities of the slash are low values that suggest a minimum capability to spread fire. However, the distribution indicates that portions of the fire at a 2 mi/h windspeed would be comparable to a prescribed litter fire but would be easy to control. The last statement illustrates the importance of the distribution. Although the results are not alarming, a single average value even if correct does not indicate the upper limits of the intensity.

The upper limit on windspeed can be overcome by averaging cells into larger cells so that the influence of the fire from one cell does not extend beyond adjacent cells. This is in keeping with the relative reduction in the influence of spatial variations in fuel as the flame increases in response to wind. Future applications will likely employ general fuel models having flexibility in resolution as needs arise.[5]

The form of the result offers new ways of presenting alternatives to the land manager. With a distribution of results it is possible to ask what the probability is that a given range of rate of spread or intensity will occur. A high rate of spread or intensity although having a low probability may be intolerable. Viewing fire behavior in the form of probabilities gives a more accurate description of the probable fire behavior and a reasonable basis for management decisions.

PUBLICATIONS CITED

Albini, Frank A.
  1976. Estimating wildfire behavior and effects. USDA For. Serv. Gen. Tech. Rep. INT-30. Intermt. For. and Range Exp. Stn., Ogden, Utah.
Anderson, Hal E.
  1968. Fire spread and flame shape. Fire Tech. 4(1):51-58.
Anderson, Hal E.
  1969. Heat transfer and fire spread. USDA For. Serv. Res. Pap. INT-69, 20 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.
Brown, James K.
  1966. Quantitative description of the physical properties of forest fuels. Problem Analysis Fuels Science Project 2104, NFFL, Missoula, Montana.
Brown, James K.
  1974. Handbook for inventorying downed woody material. USDA For. Serv. Gen. Tech. Rep. INT-16. Intermt. For. and Range Exp. Stn., Ogden, Utah.

---

[5]Pursuing extended application of this model at this time detracts from the main purpose of explaining the model.

rown, James K.
   1976. Estimating shrub biomass from basal stem diameters. Can. J. For. Res.
      6(2):153-158.

aubenmire, R. and Jean B. Daubenmire.
   1968. Forest vegetation of Eastern Washington and Northern Idaho. Washington
      Agric. Exp. Stn., College of Agriculture, Washington State University Tech.
      Bull. 60.

avis, Kenneth P.
   1959. Forest fire control and use. McGraw-Hill.

ijkstra, E. W.
   1959. A note on two problems in connexion with graphs. Numer. Math. 1:269-271.

ons, W.
   1946. Analysis of fire spread in light forest fuels. J. Agr. Res.
      72(3):93-121, illus.

osberg, Michael.
   1970. Drying rates of heartwood below fiber saturation. For. Sci. 16:57-63.

randsen, William H.
   1971. Fire spread through porous fuels from the conservation of energy. Combus.
      and Flame 16:9-16, illus.

olgate, P.
   1965. Some new tests of randomness. J. of Ecol. 53:261-266.

endall, M. G. and A. Stuart.
   1967. The advanced theory of statistics. Vol. 2, p. 334-335. Hafner.

ourtz, Peter H. and William G. O'Regan.
   1971. A model for a small forest fire--to simulate burned and burning areas for
      use in a detection model. For. Sci. 17:163-169.

ittenhouse, L. R. and F. A. Sneva.
   1977. A technique for estimating big sagebrush production. J. of Range Mgmt. 30(1).

othermel, Richard C.
   1972. A mathematical model for predicting fire spread in wildland fuels. USDA
      For. Serv. Res. Pap. INT-115, 40 p. Intermt. For. and Range Exp. Stn., Ogden,
      Utah.

othermel, Richard C.
   1974. Concepts in fire modeling. Study Guide, Advanced Fire Management Training
      Course, National Wildfire Coordinating Group Training Center, Marana, AZ.

teward, F. R.
   1971. A mechanistic fire spread model. Combust. Sci. and Tech. 4:177-186.

homas, P. H. and D. L. Simms.
   1963. Report on forest research. Her Majesty's Stationery Office, London. 108 p.

NOMENCLATURE

Symbol	Definition	Units
I_R	Reaction intensity	kw/m^2
I_B	Fireline intensity	kw/m
F	Burning fraction of cell	none
D	Cell width	m
D'	Transition distance where fire is influenced by old and new cell	m
R	Rate of spread; or,	m/min
	Multiple correlation coefficient in statistical analysis location	none
t_d	Delay time	min
τ_r	Residence time	min
σ	Surface area-to-volume ratio	cm^{-1}
$\tilde{\sigma}$	σ value within cell weighted by total exposed surface area of each particle size	cm^{-1}
d	Particle diameter	cm
t	Time	min
R_T	Rate of spread in transition distance	m/min
ε	Effective heating number	none
Q_{ig}	Volumetric heat of preignition	kj/m^3
ξ	Propagating heat flux ratio	none
ϕ_w	Wind factor	none
ϕ_s	Slope factor	none
s	Distance fire has traveled in cell	m
$f(t)$	Time dependent decreasing influence from old cell	none
$h(t)$	Time dependent increasing influence from new cell	none
θ	Time since ignition of cell	min
e	Error term	none

APPENDIX I: DELAY TIME

The delay time of a cell is the time that must elapse from the time that the cell is ignited until it is able to ignite adjacent cells. In the simulation, we are concerned with fire behavior only at the resolution of the cell size. The fire is viewed as jumping into a cell at ignition and then waiting out the delay time before jumping into unignited adjacent cells. However, to develop a method of calculating delay time, the behavior of the fire within a cell must be considered.

After cell (i+1) is ignited by cell i, the fire spreads a transition distance, D', before it reaches a quasi-steady state. During the time that it takes the fire to spread this distance, the influence of cell i is decreasing and the influence of cell (i+1) is increasing. The fire spreads the remainder of the distance through (i+1) at a rate which is calculated according to the uniform fire spread model (Rothermel 1972).

The delay time is expressed as the sum of the residence time and the time that it takes the fire to spread the remaining distance (D-D') at a uniform rate:

$$t_d = (\tau_r)_{i+1} + (D - D')/R_{i+1}$$

where

$$(\tau_r)_{i+1} = \text{residence of cell (i+1)}$$

$$D = \text{cell width}$$

$$D' = \text{transition distance}$$

$$R_{i+1} = \text{quasi-steady state rate of spread in cell (i+1).}$$

The residence time, $(\tau_r)_{i+1}$, is the amount of time that fire exists at a given point as it spreads through a fuel array. Residence time is assumed to be a measure of the time that it takes a fire in cell (i+1) to achieve the quasi-steady state where it is no longer influenced by cell i and spreads at a rate dependent only on the fuel parameters of cell (i+1). Our goal in constructing the hexagonal fuel array is to choose the cell size such that the time for the fire to spread through the cell is greater than the characteristic residence time of the fuel particles in cell (i+1).

The residence time is expressed as the ratio of the combustion zone depth (approximately the horizontal region of active flaming) to the rate of spread. Anderson (1969) found the following approximation for the residence time in terms of the particle diameter d:

$$\tau_r = 3.15d$$

where τ_r is in minutes and d is in cm. The diameter, d, can be expressed in terms of the surface area-to-volume ratio:

$$d = 4/\sigma.$$

Therefore, residence time can be calculated from the characteristic surface area-to-volume ratio:

$$\tau_r = 12.6/\tilde{\sigma}$$

where $\tilde{\sigma}$ has the units of cm^{-1}.

Each hexagonal cell has a characteristic surface area-to-volume ratio obtained from the average particle diameter weighted by the total exposed surface area of each size class of fuels within the cell (Rothermel 1972). Thus, the residence time is an average property of the cell.

The values required for each cell for the delay time calculation are I_R, $\varepsilon \mathcal{Q}_{ig}$, ξ, ϕ_w, ϕ_s, and τ_r. These values are calculated in turn from measurable fuel properties. The reaction intensity, I_R, may be thought of as the "heat source" affecting adjacent cells. The second term, $\varepsilon \mathcal{Q}_{ig}$, is the product of the effective heating number, ε, and the volumetric heat of preignition, $\mathcal{Q}_{ig}$. This term may be thought of as the "heat sink," the absorption of heat required for the fire to advance into the cell. The propagating flux ratio, ξ, is the heat coupling coefficient operating on the reaction intensity to obtain the propagating flux. The wind and slope factors, ϕ_w and ϕ_s, are used along with the direction of spread in relation to the directions of the wind and slope to calculate a wind-slope factor, $g(\phi_w, \phi_s)$.[6] Calculation of I_R, $\varepsilon \mathcal{Q}_{ig}$, ξ, ϕ_w, and ϕ_s is described in Rothermel (1972).

The rate of spread in cell (i+1) is initially influenced by the cell i. The fire is assumed to have achieved a quasi-steady state when the residence time of cell (i+1) has elapsed. To smooth the change in rate of spread within cell (i+1), a gradual change is assumed. Two possible cases must be considered: I. $(\tau_r)_i \leq (\tau_r)_{i+1}$, and II. $(\tau_r)_i > (\tau_r)_{i+1}$. For case I the influence of cell i terminates at time $(\tau_r)_i$. The influence of cell (i+1) continues increasing until time $(\tau_r)_{i+1}$ when the fire reaches its quasi-steady state. For case II the influence of cell i is terminated at time $(\tau_r)_{i+1}$ rather than $(\tau_r)_i$. At $(\tau_r)_{i+1}$ the rear of the combustion zone leaves the boundary between the cells producing a burned out area between the cells whereupon cell i is assumed to no longer influence cell (i+1). Frank Albini of the Northern Forest Fire Laboratory suggested the following mathematical model for expressing these influences.

The distance, s, that the fire has traveled in cell (i+1) by time t is:

Case I: $(\tau_r)_i \leq (\tau_r)_{i+1}$

$$s = R_T \int_0^t f_1(t) \, dt + R_{i+1} \int_0^t h(t) \, dt \qquad (2)$$

[6]Albini, see footnote 1.

se II: $(\tau_r)_i \; \cdot \; (\tau_r)_{i+1}$

$$s = R_T \int_0^t f_2(t)\,dt \;+\; R_{i+1} \int_0^t h(t)\,dt \qquad (3)$$

ere

$$f_1(t) = \begin{cases} 1 - t/(\tau_r)_i & \text{for } t \underset{-}{} (\tau_r)_i \\ 0 & \text{for } t \cdot (\tau_r)_i \end{cases} \qquad (4)$$

$$f_2(t) = \begin{cases} 1 - t/(\tau_r)_{i+1} & \text{for } t \underset{-}{} (\tau_r)_{i+1} \\ 0 & \text{for } t > (\tau_r)_{i+1} \end{cases} \qquad (5)$$

$$h(t) = \begin{cases} t/(\tau_r)_{i+1} & \text{for } t \leq (\tau_r)_{i+1} \\ 1 & \text{for } t > (\tau_r)_{i+1} \end{cases} \qquad (6)$$

t = time since ignition of cell $(i+1)$

$(\tau_r)_i$ = residence time of cell i

$(\tau_r)_{i+1}$ = residence time of cell $(i+1)$

R_T = rate of spread as the fire passes from cell i to cell $(i+1)$

R_{i+1} = quasi-steady state rate of spread in cell $(i+1)$.

terms $f_1(t)$ and $f_2(t)$ are time dependent decreasing influences from cell i
le $h(t)$ is a time dependent increasing influence from cell $(i+1)$.

A graphical representation of the "influence" factors $f_1(t)$, $f_2(t)$, and $h(t)$
given in figure 8.
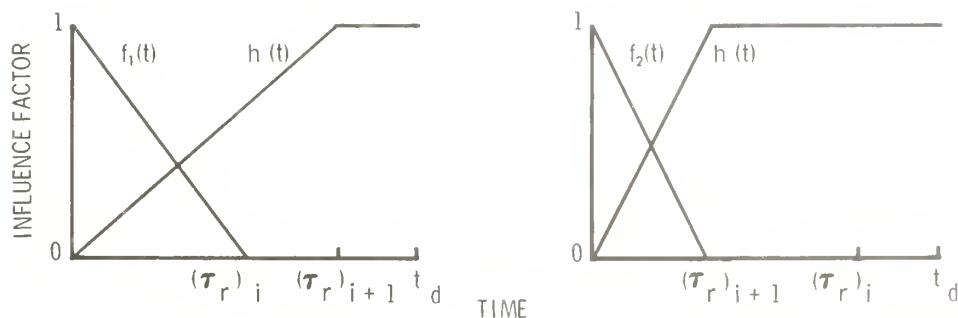
Figure 8.--Influencing factors governing fire transition from cell i to cell i+1

The quasi-steady rate of spread for cell (i+1) is calculated as described by Rothermel (1972):

$$R_{i+1} = (I_R)_{i+1} g_{i+1} (\phi_w, \phi_s) \xi_{i+1} / (\varepsilon Q_{ig})_{i+1}. \qquad (7)$$

The transition rate of spread as the fire moves from cell i into cell (i+1) is calculated from the heat source terms of cell i and the absorption terms of cell (i+1):

$$R_T = (I_R)_i g_i (\phi_w, \phi_s) \xi_{i+1} / (\varepsilon Q_{ig})_{i+1}.$$

This can also be written as:

$$R_T = CR_{i+1} \qquad (8)$$

where

$$C = (I_R)_i g_i (\phi_w, \phi_s) / (I_R)_{i+1} g_{i+1} (\phi_w, \phi_s).$$

Substituting equations (7) and (8) into equations (2) and (3) and evaluating the integrals over the intervals illustrated in figure 8, the distance that the fire spreads into a cell in a given time is as follows:

Case I: $(\tau_r)_i \leq (\tau_r)_{i+1}$

$$s = \begin{cases} CR\left(t - t^2/2(\tau_r)_i\right) + R\left(t^2/2(\tau_r)_{i+1}\right), & \text{for } 0 < t \leq (\tau_r)_i & (9a) \\ CR(\tau_r)_i/2 + R\left(t^2/2(\tau_r)_{i+1}\right), & \text{for } (\tau_r)_i < t \leq (\tau_r)_{i+1} & (9b) \\ D' + \left(t - (\tau_r)_{i+1}\right)R, & \text{for } (\tau_r)_{i+1} < t < t_d & (9c) \end{cases}$$

Case II: $(\tau_r)_i > (\tau_r)_{i+1}$

$$s = \begin{cases} CR\left(t - t^2/2(\tau_r)_{i+1}\right) + R\left(t^2/2(\tau_r)_{i+1}\right), & \text{for } 0 < t \leq (\tau_r)_{i+1} & (10a) \\ D' + \left(t - (\tau_r)_{i+1}\right)R, & \text{for } (\tau_r)_{i+1} < t \leq t_d & (10b) \end{cases}$$

where $R = R_{i+1}$.

The transition distance, D', can be obtained by solving equations (9b) and (10a) at $t = (\tau_r)_{i+1}$.

Case I: $(\tau_r)_i \leq (\tau_r)_{i+1}$

$$D' = R\left(C(\tau_r)_i + (\tau_r)_{i+1}\right)/2 \qquad (11)$$

Case II: $(\tau_r)_i > (\tau_r)_{i+1}$

$$D' = R(\tau_r)_{i+1}(C + 1)/2. \qquad (12)$$

Equations (9) and (10) can be solved for t to obtain the time that it takes the fire to spread a distance, s, in the cell.

Case I: $(\tau_r)_i \leq (\tau_r)_{i+1}$

$$t = \begin{cases} \left[-C + \sqrt{C^2 + 2B\left(1 - C(\tau_r)_{i+1}/(\tau_r)_i\right)}\right] \Big/ \left[1/(\tau_r)_{i+1} - C/(\tau_r)_i\right], & (13a) \\ \quad \text{for } (\tau_r)_i < (\tau_r)_{i+1} \text{ or } C \neq 1 \\ \quad \text{and } 0 < s \leq R(\tau_r)_i\left[C + (\tau_r)_i/(\tau_r)_{i+1}\right]/2 \\ s/R, & \text{for } (\tau_r)_i = (\tau_r)_{i+1}, \; C = 1 & (13b) \\ \quad \text{and } 0 < s \leq R(\tau_r)_i \\ \sqrt{2s(\tau_r)_{i+1}/R - C(\tau_r)_i(\tau_r)_{i+1}}, & (13c) \\ \quad \text{for } R(\tau_r)_i\left[C + (\tau_r)_i/(\tau_r)_{i+1}\right]/2 < s \leq D' \\ (s - D')/R + (\tau_r)_{i+1}, & (13d) \\ \quad \text{for } D' < s \leq D \end{cases}$$

Case II: $(\tau_r)_i > (\tau_r)_{i+1}$

$$t = \begin{cases} \left[-C + \sqrt{C^2 + 2B(1 - C)}\right] \Big/ \left[(1 - C)(\tau_r)_{i+1}\right], & \text{for } 0 < s \leq D' & (14a) \\ (s - D')/R + (\tau_r)_{i+1}, & \text{for } D' < s \leq D & (14b) \end{cases}$$

where

$$R = R_{i+1}$$

$$B = s/R(\tau_r)_{i+1}.$$

If the fire reaches its quasi-steady state in a cell, equation (13c) or (14b) for s = D is equivalent to finding the delay time as described in equation (1).

As stated earlier, the cell size should be large enough for the fire to achieve a quasi-steady state in every cell. Otherwise, the influence of cell i would extend beyond cell (i+1). At present the algorithm does not handle this situation. Increasing the cell size excessively may result in averaging out the nonuniformities we originally intended to examine. It is essential to design the array so that a high percentage of the hexagonal cells achieve a quasi-steady state rate of spread and accept the small error resulting from the few exceptions. If the calculated transition distance is larger than the cell size (D' > D), the delay time is calculated as the time that it takes the fire to travel the distance D.

The following is a general procedure for obtaining the delay time. If $(\tau_r)_i \leq (\tau_r)_{i+1}$, substitute D for s, select the equation having the correct limits from equations 13a, b, or c, and solve for t. If $(\tau_r)_i > (\tau_r)_{i+1}$, proceed in the same manner using equation 14a or b.

APPENDIX II: CELL BURNING FRACTION

The fraction of a cell that is burning at time θ since its ignition is evaluated from the distance equations for s in appendix I. Initially the front of the burning zone spreads into the cell as described by s with $t = \theta$. The rear of the burning zone follows in the same manner but with $t = \theta - \tau_r$, where τ_r is the residence time in the cell. During passage of the fire, the front and the rear of the burning zone may exist in the cell together, separately, or be absent. The following equations account for all cases:

$F = 0$	for $\theta \leq 0$	The cell has not been ignited.
$F = s(\theta)/D$	for $D' \leq D$ and $0 < \theta \leq \tau_r$	The fire front is in the cell. There is no burned out area.
	or for $D' > D$ and $0 < \theta \leq t_d$	
$F = (s(\theta) - s(\theta - \tau_r))/D$	for $D' \leq D$ and $\tau_r < \theta \leq t_d$	Both the fire front and rear are in the cell.
$F = 1$	for $D' > D$ and $t_d < \theta \leq \tau_r$	The entire cell is burning.
$F = 1 - s(\theta - \tau_r)/D$	for $D' \leq D$ and $t_d < \theta \leq t_d + \tau_r$	The fire front has passed the cell.
	or for $D' > D$ and $\tau_r < \theta \leq t_d + \tau_r$	There is a burned out area.
$F = 0$	for $\theta > t_d + \tau_r$	The cell is burned out.

where

F = fraction of the cell that is burning at time θ

D = cell size

D' = transition distance

t_d = delay time

τ_r = cell residence time

$s(\theta)$ = distance the front of the burning zone has spread at time $t = \theta$ according to equation 9 or 10

$s(\theta - \tau_r)$ = distance the rear of the burning zone has spread at time $t = \theta - \tau_r$ according to equation 9 or 10.

28

APPENDIX III: CELL LOAD EVALUATION

The 10h load is assigned through a relationship between the load and depth. The 1h and 100h are then assigned through two separate relationships of each of these loads to the 10h load derived from the first stage inventory. The necessary relationships are expressed in figure 9 as cumulative distributions of the following ratios: (upper) 10h load to bulk depth, (middle) 1h load to 10h, and (lower) 100h load to 10h load. For each cell in the depth array, the 10h load can be obtained by random access of the upper distribution in figure 9. The other two loads are determined in the same manner using the 10h load as a base and accessing the middle and lower distributions.

An estimate of the foliage load was made based on the dominant species composition of slash, foliage retention by these species, and a knowledge of the foliage load relative to the sum of the 1h, 10h, and 100h slash load.

Dominant species composition of the slash was western larch and grand fir. Because larch loses its needles quickly compared to grand fir and the slash had gone through one winter, it is reasonable to assume that western larch had lost all of its foliage while grand fir retained its foliage. Brown (1978) found that the grand fir foliage load was approximately 50 percent of the sum of the 1h, 10h, and 100h loads. Depending upon the relative amounts of western larch and grand fir, the foliage load could vary from zero to 50 percent of the overall sum of the 1h, 10h, and 100h slash load. An average of 25 percent was chosen. After 1h, 10h, and 100h loads are determined for each cell, 25 percent of the sum is used to represent the foliage load.

APPENDIX IV: EVALUATING b_0, b_1, b_2 AND b_3

Evaluation of the coefficients b_0, b_1, b_2, and b_3 of the multiple linear regression equation:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + e$$

is obtained by using serial correlation data and the mean and variance of the bulk depth distribution obtained from linear fuel array transects. The location of cell Y relative to cells X_1, X_2, and X_3 in the cell filling model is:
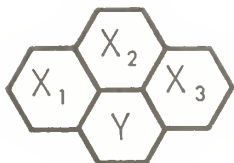
where the dependent variable, Y, is the cell being filled, and the independent variables, X_1, X_2, and X_3 are the cells already filled. It is important to distinguish between the data collected from the linear transects and the requirements of the cell filling algorithm.

Constants are added to the denominator of each ratio to avoid
dividing by zero. Appropriate corrections are later made upon
assignment to the cell. Metric conversion of these histograms
is not given because the histograms are working tools and do
not lend themselves to easy conversion.
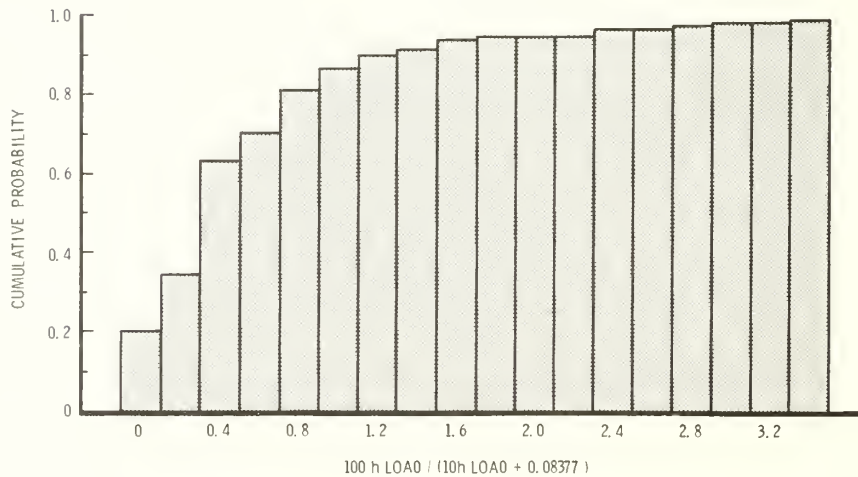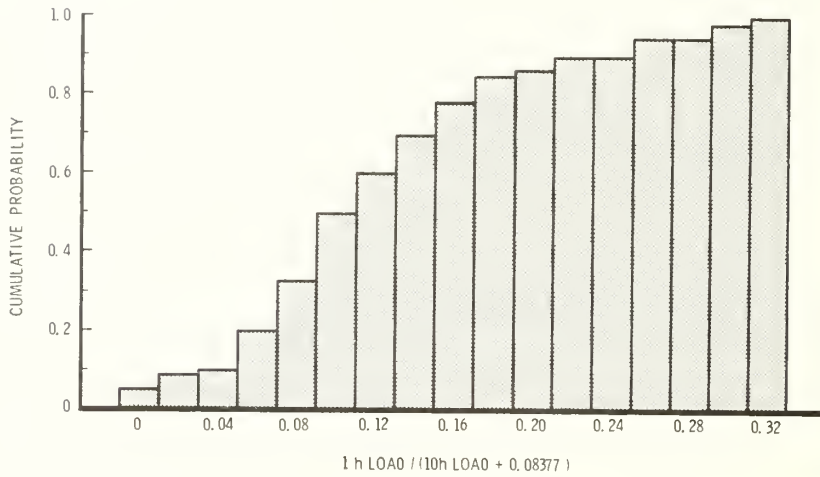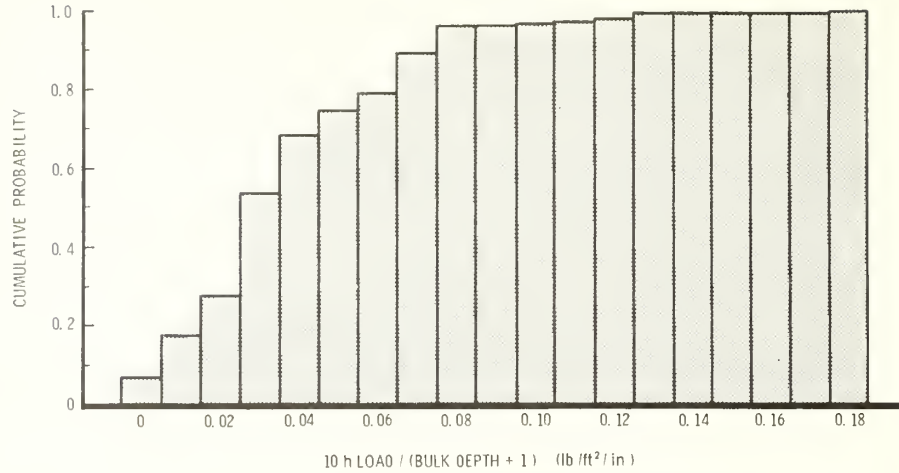
Figure 9.--*Cumulative probability distributions for assigning 1h, 10h, and 100h fuel
loads to each cell given the bulk depth.*

The principles of multiple regression analysis are used to estimate Y from X_1, X_2, and X_3.

The following analysis is simplified by transforming X's and Y's to deviations from the mean:

$$x = X - \overline{X}$$

and

$$y = Y - \overline{Y}.$$

Normal set of equations for $Y = f(X_1, X_2, X_3) + e$ is

$$\sum x^2_{1i} b_1 + \sum x_{1i} x_{2i} b_2 + \sum x_{1i} x_{3i} b_3 = \sum x_{1i} y_i$$

$$\sum x_{2i} x_{1i} b_1 + \sum x^2_{2i} b_2 + \sum x_{2i} x_{3i} b_3 = \sum x_{2i} y_i$$

$$\sum x_{3i} x_{1i} b_1 + \sum x_{3i} x_{2i} b_2 + \sum x^2_{3i} b_3 = \sum x_{3i} y_i$$

and

$$\sum Y_i - \sum (X_{1i} b_1 + X_{2i} b_2 + X_{3i} b_3) = n b_o.$$

Note that the variables in the fourth equation are uncorrected for deviations from the mean.

The serial correlation coefficient obtained from the bulk depth transect is related to the product mean and has this relation:

$$r_{ab} = \mathrm{cor}(x_j, x_{j+a})_b = \left[\frac{\mathrm{cov}(x_j, x_{j+a})}{\sqrt{\mathrm{var}(x_j)\, \mathrm{var}(x_{j+a})}} \right]_b$$

where a is the lag and b is the orientation and have values $a = 1, 2; b = 1, 2, 3$. The above expression can be written:

$$r_{ab} = \left[\frac{\overline{x_j x_{j+a}}}{\sqrt{\overline{x_j^2}\ \overline{x_{j+a}^2}}} \right]_b$$

Thus

$$\left[\overline{x_j x_{j+a}} \right]_b = r_{ab} \left[\sqrt{\overline{x_j^2}\ \overline{x_{j+a}^2}} \right]_b.$$

31

x's and y's are interchangeable (see p. 13) as we move through array filling cells. Thus

$$\overline{x_j^2} \simeq \overline{x_{j+a}^2} \simeq \overline{x^2}$$

and

$$\left[\overline{x_j x_{j+a}}\right]_b \simeq r_{ab}\overline{x^2}.$$

The following diagram is used to determine orientation and lag of the correlation.
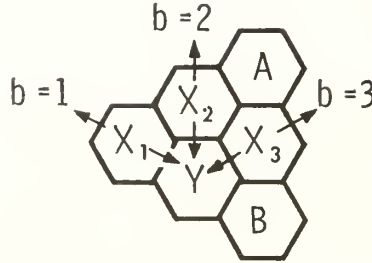
As examples, it can be seen that the correlation of cells x_2 and x_3 have orientation 1 and lag 1. The correlation of cells x_1 and A have orientation 3 and lag 2. Cells A and B are included to help in evaluating $\overline{x_{1i}x_{3i}}$. The correlation, $\overline{x_{1i}x_{3i}}$, is estimated by averaging the correlations of lag 2 illustrated by cells A and B in relation to cell X_1, because a direct estimate from the linear transect does not exist.

Since cells A and B are adjacent and directly above and below X_3, we define $\overline{x_{1i}x_{3i}}$ as:

$$\overline{x_{1i}x_{3i}} = (r_{21} + r_{23})/2.$$

Also, we can make the following observation:

$$\overline{Y}_i \simeq \overline{X}_{1i} \simeq \overline{X}_{2i} \simeq \overline{X}_{3i} \simeq \overline{X}$$

and

$$\overline{x_{1i}^2} \simeq \overline{x_{2i}^2} \simeq \overline{x_{3i}^2} \simeq \overline{x^2}.$$

We can now transform the coefficients of the b's of the normal set of equations with information gained from serial correlations along the three principle axes.

The transformed normal set of equations are below:

$$\overline{x^2}b_1 + r_{13}\overline{x^2}b_2 + \left(\frac{r_{21} + r_{23}}{2}\right)\overline{x^2}b_3 = r_{11}\overline{x^2}$$

$$r_{13}\overline{x^2}b_1 + \overline{x^2}b_2 + r_{11}\overline{x^2}b_3 = r_{12}\overline{x^2}$$

$$\left(\frac{r_{21} + r_{23}}{2}\right)\overline{x^2}b_1 + r_{11}\overline{x^2}b_2 + \overline{x^2}b_3 = r_{13}\overline{x^2}$$

and

$$b_o = \overline{X}(1 - b_1 - b_2 - b_3)$$

where

$\overline{x}$ = estimate of the mean bulk depth

$\overline{x^2}$ = estimate of the variance of the bulk depth.

Note that although $\overline{x^2}$ cancels in the above equations, it is retained for clarity.

Transects oriented in directions 1 and 3 should have equivalent parameters be-cause of their symmetry about the uphill orientation (orientation 2). The following changes have been made to insure this symmetry:

$$r'_{11} = r'_{13} = (r_{11} + r_{13})/2.$$

Primes pertain to transformed new values. Theoretically, the serial correlation of lag 2 should be the square of lag 1. To insure that the two matrix elements (1,3) and (3,1) that have correlation of lag 2, $(R_{21} + R_{23})/2$, are influenced by this re-lation, the following change has been made:

$$(r_{21} + r_{23})/2 + \left[(r'^2_{11} + r^2_{12} + r'^2_{13})/3\right]/2 = \left[(r_{21} + r_{23})/2\right]'$$

where the second term is the mean of the squares of the three correlations of lag 1. Note that r'_{11} and r'_{13} are the new values as expressed above.

Solving the three simultaneous equations gives:

$$b_1 = b_3 = R_1(1 - r_{12})/(R_2 - 2R_1^2 + 1)$$

$$b_2 = r_{12} - 2R_1b_1$$

where

$$R_1 = (r_{11} + r_{13})/2$$

$$R_2 = (r_{21} + r_{23})/2 + (2R_1^2 + r_{12}^2)/6.$$

Rewriting for completeness

$$b_o = \overline{X}(1 - b_1 - b_2 - b_3)$$

where $\overline{X}$ is the mean bulk depth.

The coefficients of the regression equation, b_1, b_2, and b_3, depend only on the serial correlation coefficients of the slash transects (all three orientations at lag 1 and orientations 1 and 3 at lag 2). The coefficient b_o has an additional dependency on $\overline{X}$, the mean bulk depth.

APPENDIX V: ERROR TERM

The error term is derived by random access of the cumulative distribution of the bulk depth (fig. 10). Random access is achieved by entering on the y-axis of the distribution with a random number from 0 to 1. The mean bulk depth is then subtracted from the accessed bulk depth to obtain the first estimate of the error, e'. The error is further modified by taking into consideration the relation of the variance of the estimate of y, $\hat{y}$, given x, to the variance of y (Kendall and Stuart 1967):

$$s^2_{\hat{y}|x} = (1 - R^2)s^2_y$$

where R = multiple correlation coefficient.

We can write the following expression for the error by recognizing the similarity of the variance to the square of the error:

$$e = \sqrt{1 - R^2}\ e'.$$
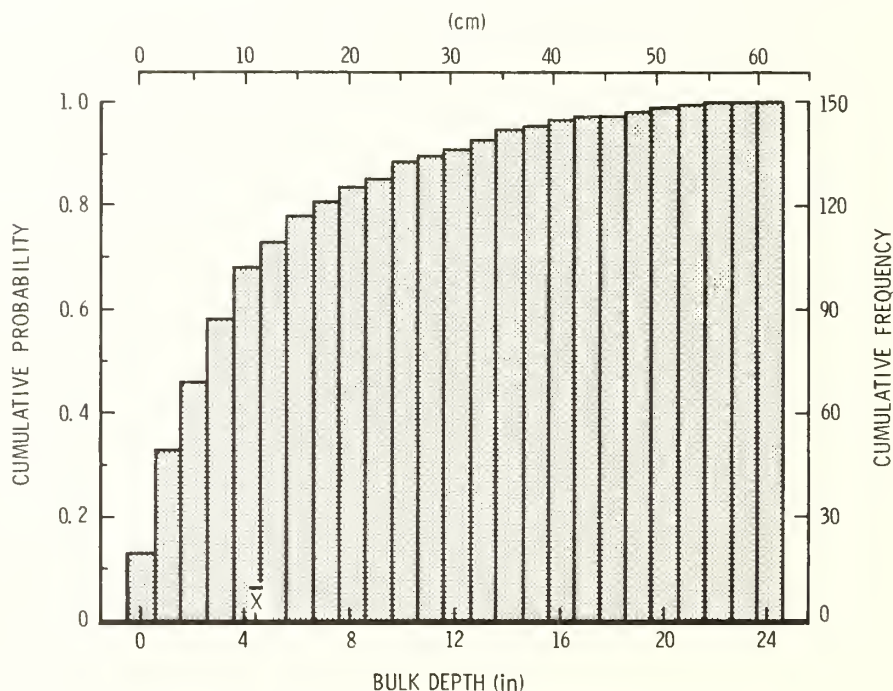
Figure 10.--Cumulative probability distribution of the bulk depth.

34

Frandsen, William H., and Patricia L. Andrews.
1979. Fire behavior in nonuniform fuels. USDA For. Serv. Res. Pap.
INT-252, 34 p. Intermt. For. and Range Exp. Stn., Ogden, Utah
84401.

Predicting fire behavior in nonuniform fuel arrays is a problem re-
quiring: (1) a method of assessing fuel nonuniformity, (2) a method
of simulating fuel nonuniformity, and (3) an algorithm governing fire
spread through a simulated array. The bulk fuel properties (load,
depth, average particle size, etc.) are partitioned into a honeycomb
array. An algorithm simulates fire spread through the array by
coupling predictions of heat flowing from a burning cell to predic-
tions of the heat required for ignition of its adjacent cells.
Multiple results of fire behavior are displayed as distributions
in contrast to previously generated singular values. Methodology is
emphasized.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field programs and research work units are maintained in:

Billings, Montana

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

VARIATION IN COLD HARDINESS AMONG POPULATIONS OF *PSEUDOTSUGA MENZIESII* VAR. *GLAUCA*

Gerald E. Rehfeldt

THE AUTHOR

GERALD E. REHFELDT is a plant geneticist at the Forestry Sciences
    Laboratory, Moscow, Idaho. His research includes studies
    of the ecological genetics of Northern Rocky Mountain conifers,
    primarily Douglas-fir.

ACKNOWLEDGMENT

VARIATION IN COLD HARDINESS AMONG POPULATIONS OF *PSEUDOTSUGA MENZIESII* VAR. *GLAUCA*

Gerald E. Rehfeldt

RESEARCH SUMMARY

Freezing tests were conducted to follow cold acclimation in seedlings representing 51 populations of *Pseudotsuga menziesii* var. *glauca*. For each of six dates between August and December, twigs from 2-year-old seedlings growing in a common environment were frozen to each of six test temperatures. Injury from freezing was scored by leaf discoloration.

Hardiness developed at a rate associated with the minimum temperature. During the early stages of cold acclimation, variation in the hardiness of populations was related to geographic and ecologic factors of the seed source. Multiple regression analyses accounted for 38 percent of the variance among populations and showed that populations of greatest hardiness in early autumn were from relatively high latitudes and high elevations. But, during late stages of cold acclimation, variation in hardiness among populations could not be related to factors of the seed source.

CONTENTS

INTRODUCTION

Cold acclimation in woody plants from temperate zones typically develops in two phases (Weiser 1970). The first phase is associated with the cessation of growth and development. In most tree species of the northern temperate zone, this phase coincides with the onset of winter dormancy or rest period that cannot be broken until chilling requirements have been satisfied (Glerum 1973). The second phase of cold acclimation results in the development of tolerance to extreme cold (Weiser 1970). This phase is triggered by the first frost, and hardiness develops in general response to the minimum temperature (Levitt 1972). Autumn frost injuries occur during the first phase of cold acclimation when phenological events are not synchronized with the local climate; injuries occur during the second phase when dormant tissues have failed to harden sufficiently to withstand the minima of autumn and winter.

The actual levels of hardiness that develop in response to given environmental stimuli are under genetic control. For example, geographic races of *Cornus stolonifera* (Smithberg and Weiser 1968), *Liquidambar styraciflua* (Williams and McMillan 1971) and *Quercus rubra* (Flint 1972) acclimate differently. Throughout cold acclimation, progenies of the coastal variety of Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) are of lesser hardiness than those of the Rocky Mountain variety (*P. m.* var. *glauca*) (Rehfeldt 1977). And for the Rocky Mountain variety, genetic variation in hardiness exists among populations and among trees within populations (Rehfeldt 1979).

Cold acclimation in populations of Douglas-fir from northern Idaho and eastern Washington is the primary concern of the present research. In this area, tolerance to cold temperatures is required for survival. Freezing temperatures can occur during any month, and temperatures as low as -40°C are not rare. Previous research has shown that tolerance to freezing is generally greater in Douglas-fir seedlings from western Montana than in those from northern Idaho and eastern Washington (Rehfeldt 1979). Differentiation of populations in cold hardiness may reflect ecological adaptations that should be considered in limiting seed transfer for reforestation. The present study emphasizes the effects of variation in hardiness on the delineation of seed zones for northern Idaho and eastern Washington.

MATERIALS AND METHODS

Cold acclimation was studied in 2-year-old seedlings from 51 populations of Douglas-fir (fig. 1). Each population was represented by seeds from at least 10 trees. Most of these populations were from northern Idaho and eastern Washington, but populations from northeastern Oregon and north central Washington were also included. Populations were selected to fully represent the geographic distribution and ecological amplitude of the species in the region of study; longitude, latitude, elevation, and habitat type were variables used to characterize a seed source. Habitat type was classified according to the system of Daubenmire and Daubenmire (1968).

About 100 seedlings from each population were grown for 2 years in plastic containers (150 cm^3) in a shadehouse at Moscow, Idaho. In order to promote branching, seedlings were decapitated during the first growing season.
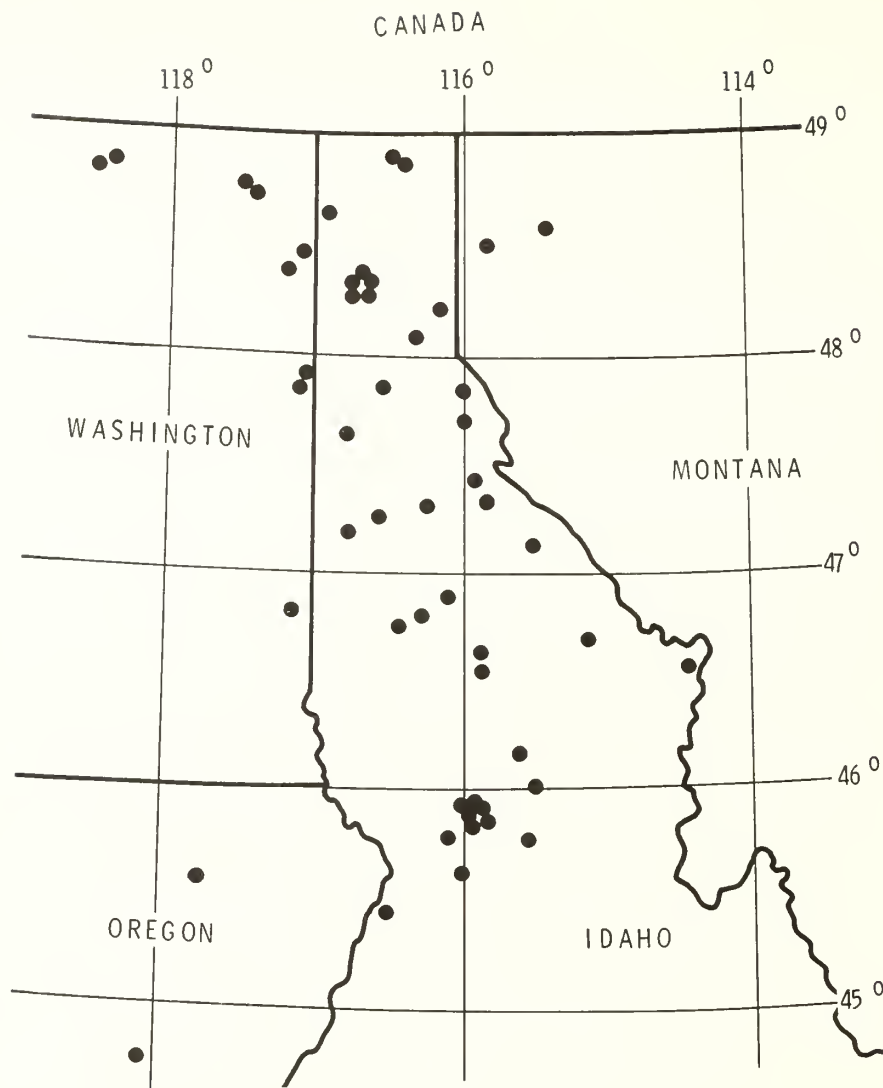
Figure 1.--Location of populations (dots).

Freezing tests were made to determine levels of hardiness of each population for six dates between August and December of the second growing season. These tests generally followed the procedures outlined by Levitt (1972). For each sampling date, six sets of 10 lignified twigs (5 to 10 cm in length) were cut from the current growth of seedlings representing each population. Twigs in each set were moistened and packaged in a plastic bag. Although each set contained twigs from 10 different seedlings, all sets did not necessarily contain twigs from the same 10 seedlings. About 15 seedlings from each population were needed to supply sufficient twigs for a single sampling date.

Twigs were stored overnight at 5°C. The following morning, one set of twigs from each population was frozen at a rate of 5°C/h to one of six test temperatures. The six test temperatures for a given date spanned a temperature range of 10° to 12°C. Each test temperature was maintained for 1/2 hour; twigs were thawed for 24 hours at 2°C, and basal portions of twigs were placed in water within plastic drinking cups. After 5 to 7 days, freezing injury to each twig was scored according to discoloration of leaves. For each population, the number of twigs exhibiting leaf injury was recorded for each test temperature.

Tolerance of populations to freezing was assessed by regression analyses that were made for each population according to the logistic model. This model, suitable for proportional data between values of zero and one (Johnson and Kotz 1970), is of the form:

$$Y_{ij} = \frac{1}{1 + be^{-rX_j}}$$

which is represented by the linear model:

$$\ln\left(\frac{1}{Y_{ij}} - 1\right) = -rX_j + \ln b$$

where:

Y_{ij} = proportion of twigs injured for population i in treatment severity j,

X_j = index of freezing severity = percentage of twigs from all populations injured in freezing treatment j,

$b = \frac{1}{y_0} - 1$ where y_0 is the predicted damage if no freezing treatment is applied ($X_j = 0$),

r = rate of increase in damage associated with an increase in severity index.

Separate analyses were made for each population on data obtained before the first frost (phase one of cold acclimation) and after frost (phase two). Since there were only two sampling dates before the first frost, regressions for phase one were based on 12 observations, and those for phase two were based on 24 observations.

Tolerance of each population to freezing during both phases of cold acclimation was expressed as the injury predicted from the logistic model when freezing severity (X_j) was 50 percent (50 percent of the twigs from all populations exhibited injury). In fact, throughout this paper, these estimates of injury are used as expressions of the hardiness of populations during cold acclimation.

Differentiation of populations in relation to latitude, longitude, elevation, and habitat type was assessed by multiple regression analyses. These analyses were made to relate differentiation to geographic and ecologic variables of the seed source so that hardiness could be used as a variable in delineation of seed zones for northern Idaho and northeastern Washington. However, the tests included populations from the Okanogan Mountains in north central Washington and from the Blue Mountains in northeastern Oregon. Since these populations could represent adaptive provinces that differ from the northern Idaho province in manners similar to the differentiation of the latter province from those of western Montana (Rehfeldt 1979) and southern

Idaho (Wright and others 1977), the four populations of greatest longitude (fig. 1) were excluded from the following analyses.

The hardiness of 47 populations for each phase of cold acclimation was used as a dependent variable in the following model:

$$Y_i = b_0 + b_1 X_{i1} + \ldots + b_7 X_{i7}$$

where:

Y_i = predicted injury for population i,

X_{i1} = degrees latitude at the origin of population i,

X_{i2} = degrees longitude at the origin of population i,

X_{i3} = meters (1×10^{-2}) elevation at the origin of population i,

X_{i4} to X_{i7} = constant terms (values of zero or one) that respectively code the *Pseudotsuga menziesii*, *Abies grandis*, *Thuja occidentalis*, and *Tsuga heterophylla* series of habitat types.

Under this model, effects of the *Abies lasiocarpa* series of habitat types are contained within the intercept (b_0). Consequently, values of regression coefficients for constant terms (b_4 to b_7) are deviations from the mean value for seedlings from *Abies lasiocarpa* habitat types.

Because multiple regression models are partially interpretable from inter-correlations among independent variables, it is instructive to note that significant associations were apparent between latitude and longitude (r = 0.56) and between longitude and elevation (r = -0.32). For the populations represented, habitat types account for significant proportions of variance in none of the other independent variables.

In accordance with the techniques of Morgenstern and Roche (1969), concepts of selection were used to estimate population change associated with the geographic and ecologic variables. This technique uses the expression for genetic gain:

$$R = i h \sigma_A$$

where:

R = selection response,

h^2 = heritability,

σ^2_A = additive genetic variance,

i = selection intensity.

The selection intensity is estimated by assuming that h^2 = 1, σ_A is estimated by the standard error of regression ($s_{y \cdot x}$), and R is estimated by the regression coefficie[nt] (b). Because the intensity of selection depends only on the proportion of the population in the selected group, the proportion of a population that is similar to a neighboring population one geographic unit distant is estimated directly from the selection intensity (fig. 11.3, Falconer 1960).

RESULTS

In order to relate cold acclimation to weather at Moscow, the temperature associated with injury to 50 percent of the twigs was estimated for each sampling date. That cold acclimation is closely related to the minimum temperature (Levitt 1972) is well illustrated in figure 2. Low levels of hardiness developed after the first frost on October 3. Hardiness increased little during a relatively warm period in late October, but increased greatly after the first cold wave in mid November.
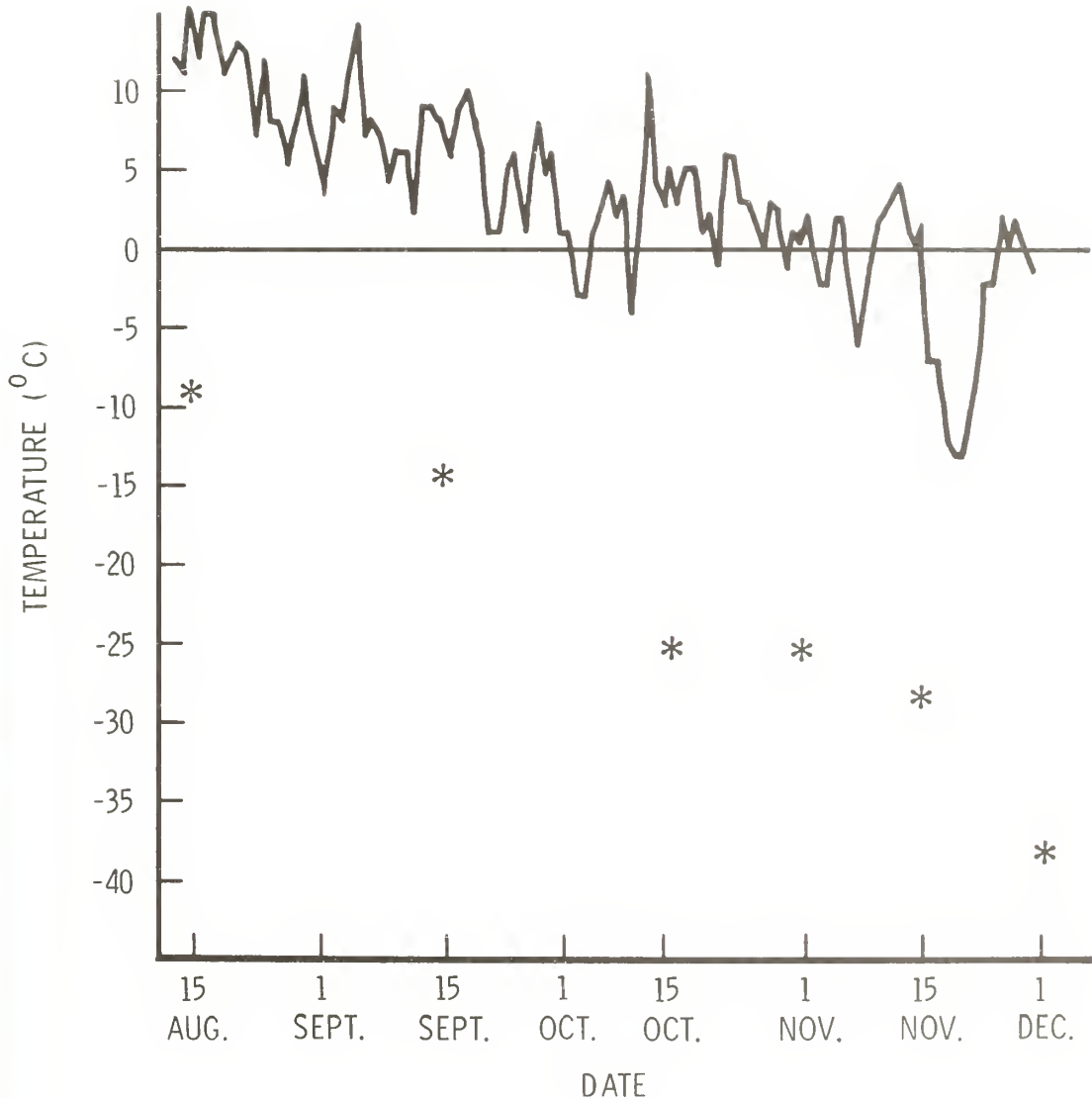
Figure 2.--Development of hardiness in relation to daily minimum temperatures. Stars denote the temperature associated with injury to 50 percent of the twigs at each sampling date.

5

Regressions of freezing tolerance for data from phase one of cold acclimation were statistically significant (1 percent level) for all populations and accounted for 64 to 96 percent of the variance. Response curves for three populations illustrate the variety of observed responses to freezing severity (fig. 3). Each of the curves presented in figure 3 differs significantly (5 percent level) from each other for either r or b in the regression equation.
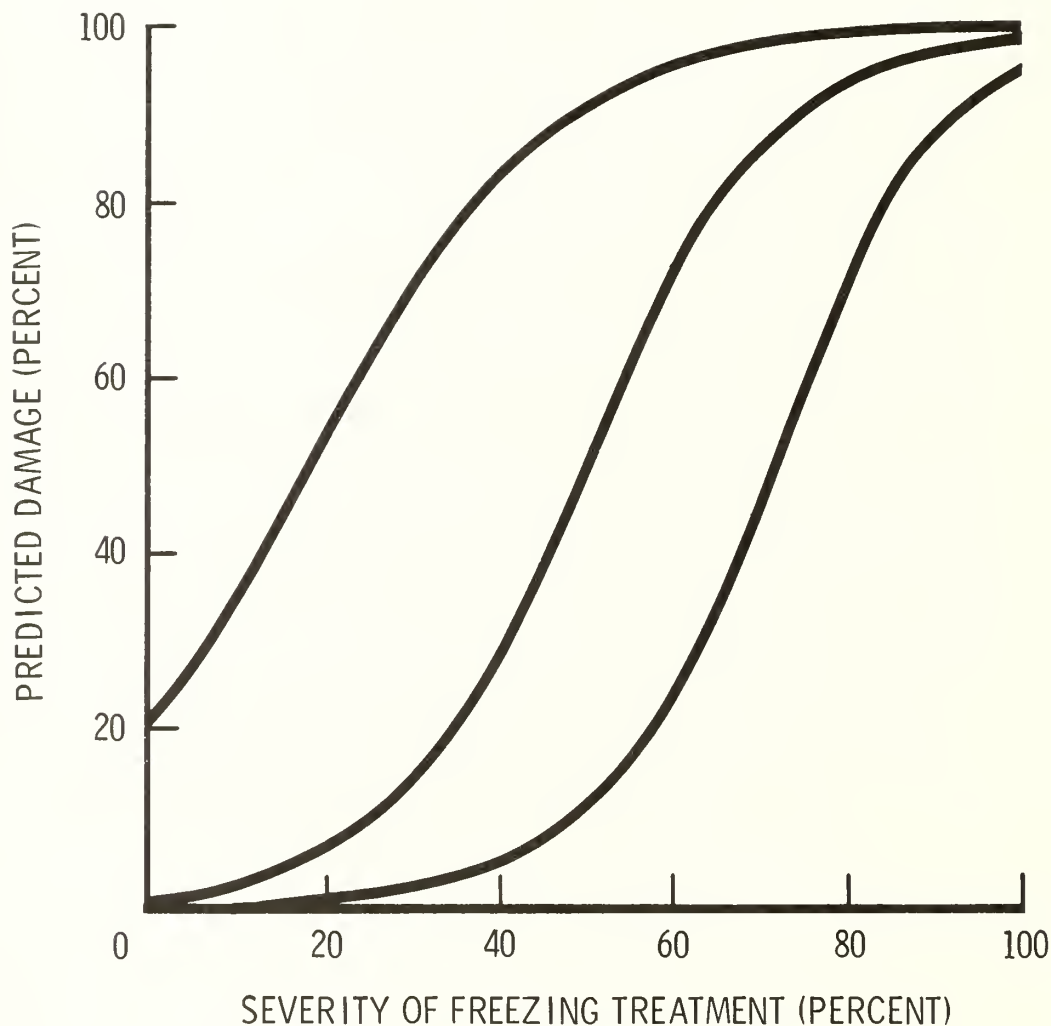
Figure 3.--Response curves of freezing damage according to severity of the freezing treatment for three populations during the first phase of cold acclimation.

Regressions of freezing tolerance for phase two were also significant (1 percent level) for each population. Values of R^2 ranged from 0.45 to 0.81. Figure 4 illustrates the variety of observed responses; but, only the response curves of maximum contrast differ significantly (5 percent level) for either p or b.
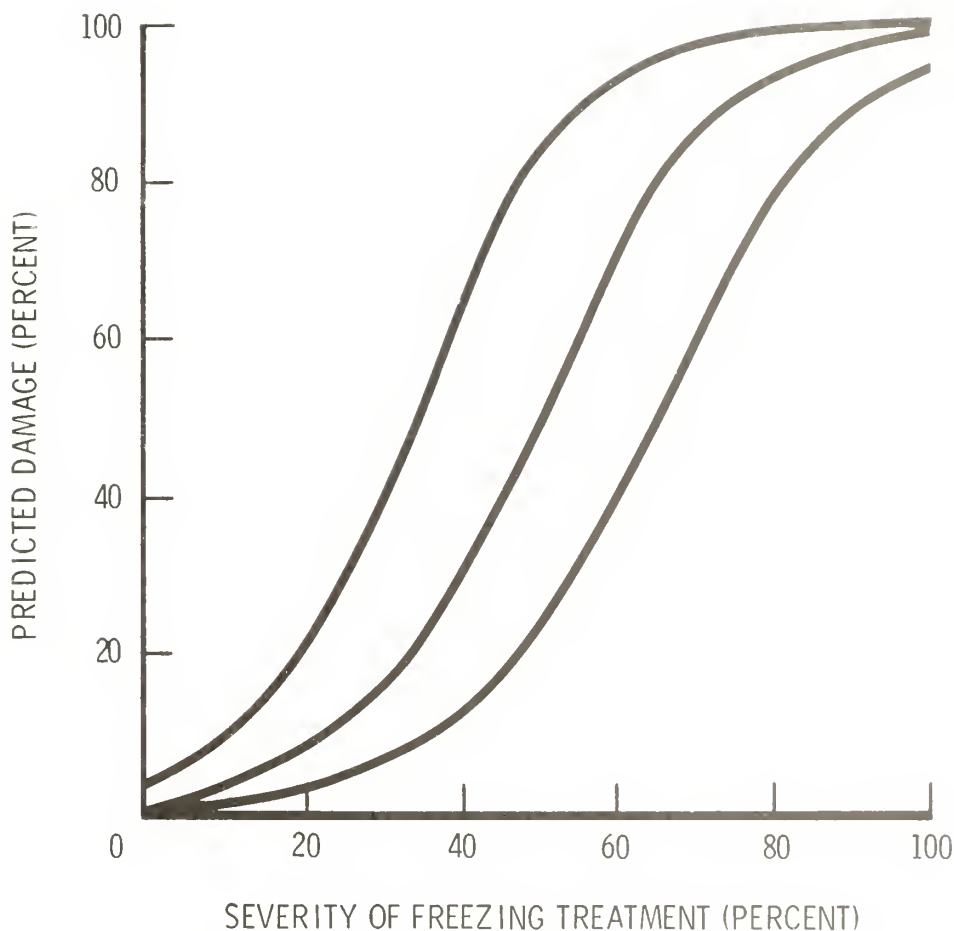
Figure 4.--Response curves of freezing damage according to severity of the freezing treatment for three populations during the second phase of cold acclimation.

The curves in figures 3 and 4 express a greater range in response and a consequent higher variance among populations for cold tolerance during phase one than during phase two. Previous studies (Rehfeldt 1979) have also suggested that population differentiation is readily detected for acclimation during autumn, but that relatively little genetic variance exists among populations for hardiness during deep winter dormancy. In concurrence with previous studies (Rehfeldt 1979), the curves in both figures that illustrate maximum tolerance to freezing depict populations from cool subalpine environments at relatively high elevations (above 1,500 m).

7

Multiple regressions for assessing the effects of geographic and ecologic variables on the hardiness of populations were made separately for data from two phases of cold acclimation (table 1). Whereas the regression for phase one accounted for a statistically significant (1 percent level) 38 percent of the variance, that for phase two accounted for a nonsignificant 15 percent. In accordance with relatively little variance among populations, variation in hardiness during the second phase of cold acclimation could not be related to geographic or ecologic variables of the seed source.

Table 1.--*Results of multiple regression analyses of hardiness during phases one and two of cold acclimation on geographic and ecologic variables. Variables are defined in the text. Results are presented in terms of regression coefficients (b) and standardized partial regression coefficients (b')*

| | Hardiness during: | | | |
| | Phase one | | Phase two | |
Variable	b	b'	b	b'
Latitude X_1	-9.27	-0.59	0.51	0.03
Longitude X_2	2.03	.08	-2.96	-.12
Elevation X_3	-3.05	-.37	.82	.11
Habitat type:				
Pseudotsuga menziesii X_4	.96	-.02	14.74	.41
Abies grandis X_5	-4.66	-.13	21.60	.64
Thuja occidentalis X_6	-.62	-.02	20.92	.64
Tsuga heterophylla X_7	-2.09	-.04	11.91	.28
b_0	111.40		29.26	
R^2	.38		.15	
$s_{y \cdot x}$	14.35		15.18	

By contrast, a comparison of standardized partial regression coefficients reflects the relative importance of the continuous independent variables in predicting hardiness during phase one. Elevation and latitude control differentiation (table 1). Longitude has little influence. Since regression coefficients for the constant terms (b_4 to b_7) are deviations from the intercept b_0, under the present model the constants reflect deviations in mean hardiness of seedlings representing the indicated habitat types from that of seedlings from the *Abies lasiocarpa* habitat types. None of the coefficients for the constant terms are statistically significant.

The multiple regression analyses pertaining to hardiness during phase one have direct application in delineating seed zones that reflect adaptive differentiation in the cold hardiness of populations. Methods described by Morgenstern and Roche (1969) were used to obtain estimates of selection intensity (i) for latitude (0.65), longitude (0.14), and elevation (0.21). The resultant percentages of similarity among populations various units of distance involving one degree latitude, one degree longitude, or 0 meters elevation are:

Units of geographic distance	Percent similarity for		
	Latitude	Longitude	Elevation
0.5	82	98	96
1	63	95	90
2	28	88	75
3	8	75	60
4	--	56	50

Morgenstern and Roche (1969) show that their assumptions ($h^2 = 1$ and $s_{y \cdot x} = s_A$) troduce bias that maximizes estimates of the selection intensity (i). Accordingly, e percentages of similarity presented above are minimal estimates.

DISCUSSION

Freezing tests showed variation in hardiness among populations of Douglas-fir ring the two phases of cold acclimation. Yet hardiness of populations during the rst phase (autumnal dormancy) was not related ($r = -0.05$) to hardiness during the cond phase, which is characterized by low levels of cold hardiness. Moreover, gression models accounted for significant proportions of the variance in hardiness r only phase one. Consequently, it appears that selective differentiation of pulations is systematically related to geography and ecology for physiological nditioning to the first frost (phase one). Little variance differentiates populations cold acclimation after the first frost (phase two), and most of that variance ems to be random. As such, the variation could be related to random events within e history of the population rather than to environmental conditions systematically lated to geography and ecology.

The latitude and elevation of the seed source seemed to control differentiation populations for hardiness during phase one. Longitude and habitat type had little fect. For habitat types to have little influence on differentiation is contradictory previous results (Rehfeldt 1974, 1979) that related population differentiation to *es lasiocarpa* habitat types. However, one of the populations in the present study oresented an *Abies lasiocarpa* habitat type from a small frost pocket at a relatively a elevation (980 m). Contrary to a previous report (Rehfeldt 1974), levels of rdiness for this population corresponded to those of populations from similar aitudes and elevations rather than to those from subalpine environments at relatively jh elevations. Finally, that none of the regression coefficients for constant ems (table 1) were statistically significant also suggests a lack of effects of aitat types on genetic differentiation in cold acclimation.

Populations from areas peripheral to the central area of study were also included in the present tests. The Okanogan Mountains in north central Washington (longitude 118.5°) were represented by two populations. Both populations were from relatively high elevations (1,460 m). Cold hardiness of these populations evidently approached maximum values in mid-November. Unlike populations from farther east, hardiness in populations from the Okanogan Mountains failed to develop greatly in response to the cold temperatures of late November. On the other hand, populations from the Blue Mountains in northeastern Oregon (longitude 118°) hardened similarly to populations from northern Idaho.

Current and previous studies on the hardiness of Douglas-fir populations have direct application in delineating seed zones in northern Idaho and eastern Washington that reflect adaptive variation in cold acclimation. In contrast with previous results (Rehfeldt 1979), present data provide no evidence that the cold *Abies lasiocarpa* series of habitat types should represent a seed zone that is independent of elevation. However, development of seed transfer guidelines associated with continuous variables requires acceptance of a level of genetic similarity that minimizes risk of maladaptation but that remains economically and administratively practical. For the present data, a 50 percent genetic similarity implies that seeds transferred 1-1/2 degrees latitude or 400 m elevation have a probability of only 0.5 of producing seedlings as cold hardy the alien site as seedlings derived from local seeds. Thus, it seems intuitively sound biologically to limit seed transfer by 75 percent genetic similarity, even though the associated probability of maladaptation is 0.25. However, it should be recalled that the estimates of similarity derived by the techniques employed represent minimal estimate (Morgenstern and Roche 1969). Consequently, probabilities of maladaptation are maximal

If a 75 percent genetic similarity limits seed transfer, seed for reforestation of northern Idaho and northeastern Washington should not be transferred more than 1 degree latitude, 3 degrees longitude, or 200 m elevation. However, seed zones must be based on numerous adaptational features. Consequently, this paper is one of a continuing series on the ecological genetics of Douglas-fir in the Northern Rockies.

PUBLICATIONS CITED

Daubenmire, R., and J. B. Daubenmire.
1968. Forest vegetation of eastern Washington and northern Idaho. Wash. Agric.
Exp. Stn. Tech. Bull. 60, 104 p.

Falconer, D. S.
1960. Introduction to quantitative genetics. 365 p., Oliver and Boyd, Edinburgh.

Flint, H. L.
1972. Cold hardiness of twigs of *Quercus rubra* L. as a function of geographic
origin. Ecology 53:1163-1170.

Glerum, C.
1973. The relationship between frost hardiness and dormancy in trees. IUFRO
Symp. on Dormancy in Trees, Kornik, Poland, Sept. 1973, 9 p.

Levitt, J.
1972. Responses of plants to environmental stresses. 697 p. Academic Press, New
York.

Johnson, N. L., and S. Kotz.
1970. Distributions in statistics: continuous univariate distributions -2. 306 p.
Wiley & Sons, New York.

Morgenstern, E. K., and L. Roche.
1969. Using concepts of selection to delimit seed zones. Food and Agric. Organ.
U.N. 2nd World Consul. For. Tree Breeding Proc., 1:203-215. FAI, Rome [Washington,
D.C., Aug. 1969].

Rehfeldt, G. E.
1974. Genetic variation of Douglas-fir in the Northern Rocky Mountains. USDA
For. Serv. Res. Note INT-184. Intermt. For. and Range Exp. Stn., Ogden,
Utah.

Rehfeldt, G. E.
1977. Growth and cold hardiness of intervarietal hybrids of Douglas-fir. Theor.
Appl. Genet. 50:3-15.

Rehfeldt, G. E.
1979. Adaptive genetic differentiation of Douglas-fir populations from the Northern
Rocky Mountains. Ecology 59:1264-1270.

Smithberg, M. H. and C. J. Weiser.
1968. Patterns of variation among climatic races of red-osier dogwood. Ecology
49:495-505.

Weiser, C. J.
1970. Cold resistance and injury in woody plants. Science 169:1268-1278.

Williams, G. J. III, and C. McMillan.
1971. Frost tolerance of *Liquidambar styraciflua* native to the United States,
Mexico and Central America. Can. J. Bot. 49:1551-1558.

Wright, J. W., F. H. Kung, R. A. Read, W. A. Lemmien, and J. N. Bright.
1977. Genetic variation in Rocky Mountain Douglas-fir. Silvae Genet. 20:54-60.

Rehfeldt, Gerald E.
  1979. Variation in cold hardiness among populations of *Pseudotsuga
     menziesii* var. *glauca*. USDA For. Serv. Res. Pap. INT-233, 11 p.
     Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

     Cold hardiness in 2-year-old seedlings representing 51 populations
of *Pseudotsuga menziesii* var. *glauca* developed at a rate associated with
the minimum temperature. During the early stages of cold acclimation,
variation in the hardiness of populations was related to geographic and
ecologic factors of the seed source. Multiple regression analyses
accounted for 38 percent of the variance among populations and showed
that populations of greatest hardiness in early autumn were from rela-
tively high latitudes and high elevations. But, during late stages of
cold acclimation, variation in hardiness among populations could not be
related to factors of the seed source.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

QUAKING ASPEN —
SEED GERMINATION AND
EARLY SEEDLING GROWTH

W. T. McDONOUGH

THE AUTHOR

WALTER T. McDONOUGH, Plant Physiologist on the Ecology
and Management of Aspen Lands research unit at Logan,
Utah, joined the staff of the Intermountain Station
in 1966. Degrees include a B.S. in Biology from
CUNY, an M.S. in Plant Ecology from Rutgers Univer-
sity, and a Ph.D. in Plant Physiology from the
University of Maryland.

RESEARCH SUMMARY

Although freshly dispersed aspen seeds germinate
quickly and nearly completely over a broad range of
temperatures, early growth of seedlings is highly
sensitive to availability of water, temperature, and
physical and chemical conditions of the seedbed.

QUAKING ASPEN — SEED GERMINATION AND EARLY SEEDLING GROWTH

W. T. McDonough

CONTENTS

INTRODUCTION

The suckering of aspen (Populus tremuloides Michx.) as a highly effective means of vegetative propagation is well known and has been widely studied (Baker 1918; Day 1944; Maini 1967; Schier 1974). Less is known about seed propagation, sometimes viewed as having only minor importance because early research (Baker 1918) had indicated that rare seedling establishment was due to low or nonexistent germinability.

However, numerous seedlings have been found in nature (Faust 1936; Larson 1944; Barnes 1966). These findings, in conjunction with pot culture and laboratory studies (Faust 1936; Moss 1938), show that aspen produces abundant germinable seeds that have no dormancy, but have a critical requirement for adequate soil water through the period of germination and early seedling growth. There is also a somewhat less critical requirement for the onset of these conditions soon after dispersal, because exposure of dry seeds to higher temperatures and humidities leads to rapid loss of germinability.

Reproduction by seed probably has several important consequences relative to successful establishment and spread of the species. Genetic variability in a changing environment, widespread dissemination, and new colonization by wind-dispersal of the seed are assured. Yearly production of seed by a mature tree is estimated at 1.6 million (Maini 1968). Even if the probability of any one successful establishment is low, reproduction by seed in aggregate could be important. The probabilities warrant further investigation of the environmental conditions that promote or inhibit germination and early growth. Also of interest are possible differences in germinability and seedling growth from seeds of clones varying in vigor. Specific information is needed on responses by seeds and seedlings to important environmental variables. Then, with appropriate management practices at particular sites, the probability of reproduction and spread by seed may be increased.

MATERIALS AND METHODS

General Procedures

Capsules were collected in the spring of 1976 and 1977 in Logan Canyon (Wasatch National Forest in northern Utah) from four clones, two of which had been classified as vigorous and two as declining, by criteria described by Schier (1974). The physical and topographical characteristics of the sites occupied were similar. Seeds were cleaned in a separator, air-dried for 2 days at 68°F (20°C), and, unless noted otherwise, stored in vapor-tight bottles at 25°F (-5°C).

Normal germination was identified as perceptible geotropic curvature of the hypocotyl and root, and incipient germination as bulging of the root-hypocotyl junction without further growth. In aged seeds and seeds under conditions of stress, abnormal germination was observed--hypocotyl elongation without concomitant root growth.

Tests were run separately on seeds from each of the four clones for effects of temperature on germination and growth of seedlings. Otherwise, seeds from the three clones that produced highest germination were bulked for the determinations. The standard temperature for germination, emergence, and growth was 68°F (20°C) unless noted otherwise.

Germination and Seedling Growth

For germination and growth, respectively, 9 cm petri dishes and 0.29 gal (1.1 liter) plastic pots were used. There were 25 seeds from each clone per dish with four replications and five seedlings from each clone planted individually in 20 pots. Substrates were distilled water-saturated filter paper and sieved aspen top soil held near field capacity. Early postgerminative growth was measured on 20 seedlings with an

ocular micrometer and binocular microscope. For periodic measurements of root growth, the main roots from additional sets of seedlings were excavated, washed, blotted, and laid out on blotting paper. The significance of differences was evaluated at the 5 percent level by variance analysis and multiple range tests (Goldstien 1964).

Seed germinators and environmental chambers were used for temperature and light control: 8 h photoperiods (102 lumens/ft^2 - 1100 lumens/m^2) for germinations and 16 h photoperiods (1859 lumens/ft^2 - 2 x 10^4 lumens/m^2) for growth. Germination counts were made daily and terminated 3 days after the last observed germination. Since standardized germination tests specify light treatment for species of *Populus*, possible light effects were tested by wrapping additional sets of dishes in double thicknesses of aluminum foil. These dishes were uncovered for counts 3 days after maximum germination under illumination.

Substrate Water

Seeds were allowed to imbibe on double circles of filter paper in thermocouple psychrometer chambers. Microliter volumes of distilled water were added for a series of substrate water potentials of approximately zero to -7.9 atm (-8 bars). There were 10 chambers with 10 seeds per chamber for each level of water potential. Equipment and procedures have been described elsewhere (McDonough 1975a).

The effect of pronounced variations in soil water content near the surface on germination and early growth was evaluated by passing sets of seeds through diurnal cycles of wetting and drying. In each cycle, seeds were allowed to imbibe on 0.2 in (0.5 cm) layers of sieved aspen topsoil at field capacity in 3.5 in (9 cm) petri dishes for 4, 8, or 12 h. There were 25 seeds per dish with 10 replications. The dishes were then partially uncovered to permit slow drying during the remainder of the 24 h period. This process was repeated for five cycles before a final 72 h wet phase to allow for continued growth of still viable seedlings.

Seedbed Conditions

There were plantings at the periphery of aspen woodland during late spring and early summer in two blocks of four squares (1.6 ft; 0.5 m), 100 seeds per square. The soil surface was raked free of litter and stones before planting. After initial irrigation of all squares to promote germination, squares were irrigated daily as required or left unirrigated.

Twenty-five seeds were planted in each of 10 pots and covered with 0.08, 0.16, or 0.24 in (2, 4, or 6 mm) of lightly compacted soil or left uncovered. Emergence in relation to depth of planting was monitored over a 20-day period at controlled temperatures of 50°, 68°, and 86°F (10°, 20°, and 30°C).

Similarly, seeds were planted on the surface of potted sand, clay, or on aspen topsoil with the litter layer left intact or sieved to remove all debris. Soil with intact surface litter was collected in and around the aspen sites where selected associated species predominated--cheatgrass (*Bromus tectorum* L.), coneflower (*Rudbeckia occidentalis* Nutt.), groundsel (*Senecio serra* Hook.), and tarweed (*Madia glomerata* Hook.).

Possible effects of allelopathic substances in litter as inhibitors of seedling growth were tested with solutions of compounds chemically representative of natural inhibitors in plants and soil (Rice 1974)--catechin (flavonoid), coumarin, gallic acid (tannin), and parahydroxybenzoic acid (phenol). Filter paper in petri dishes (25 seeds per dish in five replications) was saturated with solutions of 0.6 to 11.7 grains/gal (10 to 200 p/m), or to maximum solubility in water.

Seed Longevity

Air-dried seeds were stored in open containers under heated room conditions--68°to 77°F (20° to 25°C) and 20 to 40 percent RH, in cold storage, or in filter paper packets surrounded by air-dried soil in sheltered containers on an aspen site. Germinability following 4 to 8 weeks under these conditions was tested in petri dish germinators at six controlled temperatures-- 36°, 50°, 68°, 77°, 86°, and 95°F (2°, 10°, 20°, 25°, 30°, and 35°C). There were 25 seeds per dish in five replications.

RESULTS

Germination and Growth

Normal germination at various incubation temperatures in the 36° to 86°F (2° to 30°C) range was uniformly high (fig. 1), but declined precipitously at higher temperatures to 104°F (40°C). Abnormal germination as a percentage of the total became appreciable--24 percent at 95°F (35°C) and 100 percent at 104°F (40°C). Constant darkness did not inhibit germination. There was no evidence that seeds from declining clones (1 and 3 in fig. 1) had reduced germinability. The significantly lower germination of vigorous clone 4 was probably due to presence of a small percentage of defective seeds; microscopic examination of 100 showed 9 to be undersized or shriveled.
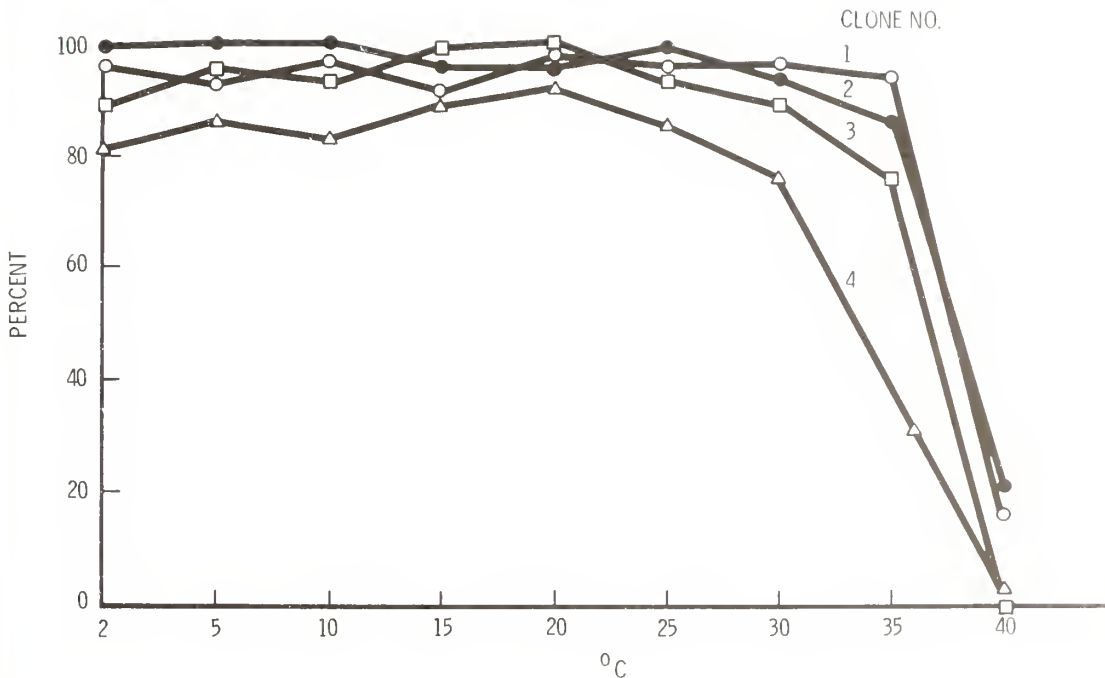
Figure 1.--Percentages of germination of seeds from vigorous (2, 4) and declining (1, 3) clones.

Onset of germination was rapid at all but the lowest temperatures (fig. 2). Rates of germination (days required to reach 10 percent of the total) increased from 36° to 68°F (2° to 20°C). The differences at yet higher temperatures were not significant.
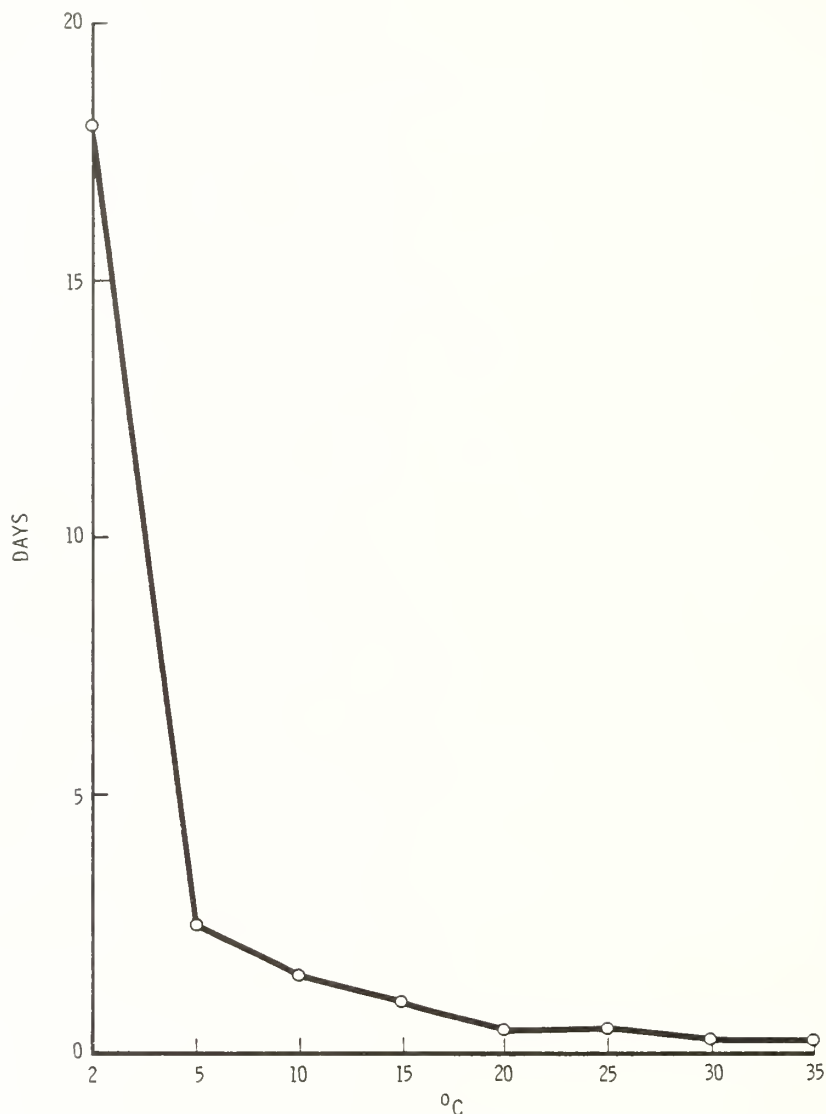
Figure 2.--Germination rates in days to 10 percent of total.

In postgerminative growth of seedling parts (fig. 3), incipient root protrusion, elongation and curvature of the hypocotyl, and greening of the cotyledons were earlier observed events. Development of a crown of root hairs at the root-hypocotyl junction, enlargement and unfolding of the cotyledons, and extension of the plumule followed. During this period, growth of hypocotyl and root hairs was rapid; the root hairs quickly attained final length. Root growth slowed perceptibly after an initial spurt. The plumule grew no more during the first week.

4
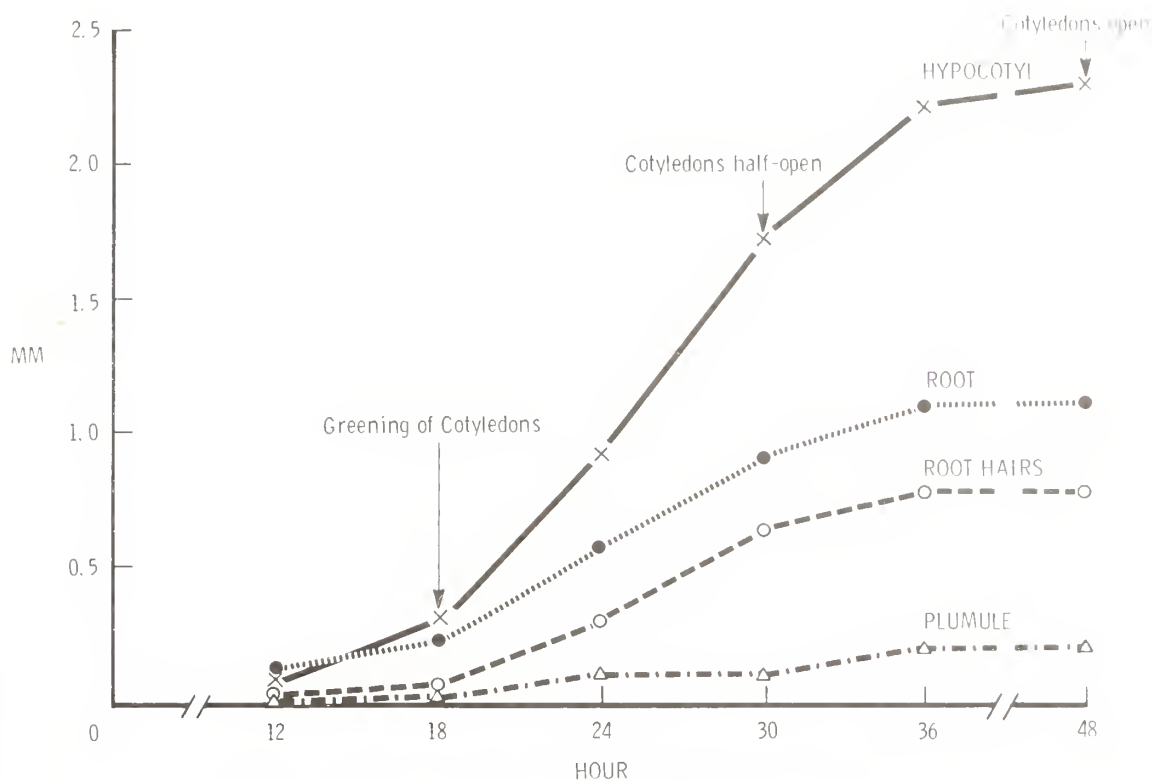
Figure 3.—Post-germination growth of seedling parts.

For seeds germinated at 68°F (20°C) and grown for a month at four temperatures (fig. 4), there was a trend toward best stem growth at 68°F (20°C), and root growth at 50° to 68°F (10° to 20°C). The data used in figure 4 are combined from the four source clones. Separately evaluated differences in growth of stems between seedlings derived from vigorous and declining clones were not significant. Axis elongation at 36°F (2°C) was very slow, although seedlings remained viable and showed accelerated growth when transferred to 68°F (20°C). Growth at 86°F (30°C) was rapid initially but fell off quickly. Root elongation, which amounted to approximately half that of the stem, began slowly and accelerated after the second week.

Substrate Water

Normal germination declined significantly at substrate water potentials of -2.3 atm (-2.3 bars) and was completely inhibited at -7.7 atm (-7.8 bars), as shown in table 1. As water potentials lowered, successively fewer seeds progressed beyond incipient germination.

Inhibition of germination and growth by wet-dry cycling depended upon the duration of phases and number of cycles (table 2). Because of the differing lengths of the drying phases, soil water potentials at the end of each drying cycle averaged -3.0, -10.9, and 17.8 atm (-3, -11, and -18 bars) for progressively longer drying phases. Longer wetting phases allowed more germination early in the cycling and more seedling development, but they impaired growth and survival. The extent of root tip necrosis and reduced hypocotyl length shows this (table 2). With 4 h wetting phases, germination
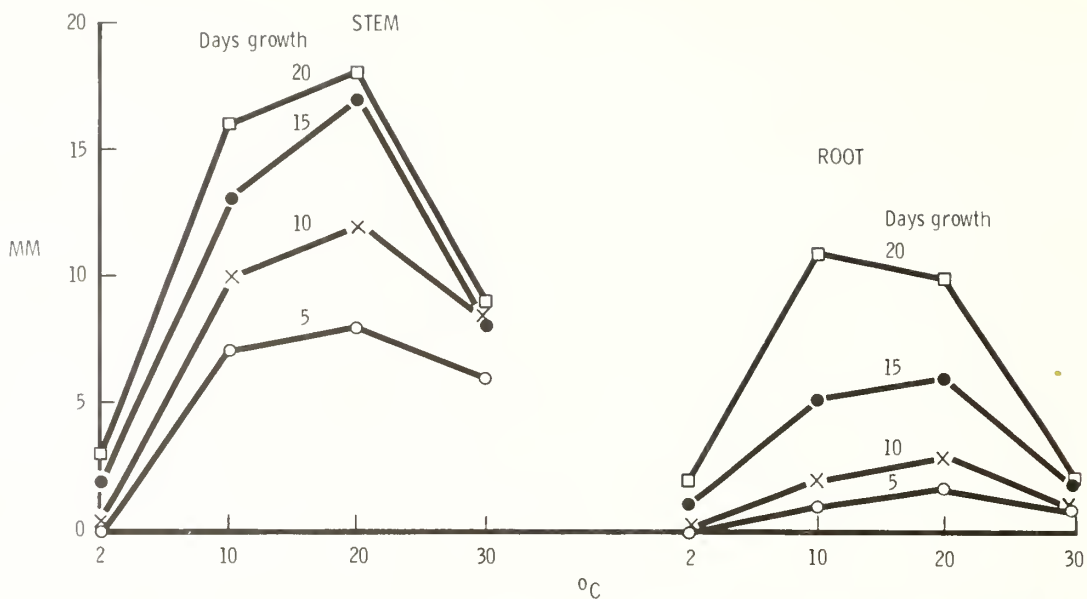
Figure 4.--Growth of shoots and main roots at 36° to 86°F (2° to 30°C) and during intervals of 5 to 20 days.

Table 1.--*Seed germination in relation to substrate water potential*

Water potentials atm (bars)	:	Germination		
	:	Incipient :	Normal :	Incipient/total
		- - - - - - - - - *Percent* - - - - - - - - - - - -		
-0.6 (-0.6)		0	97	0
-2.3 (-2.3)		11	77	13
-4.4 (-4.5)		21	48	30
-7.7 (-7.8)		6	0	100

Table 2.--*Germination percentages per cycle during five wet-dry cyclings of 4 to 12 hours. Percentage survival and root tip necrosis, and hypocotyl length of germinated seeds after an additional 12 hours of wetting*

Wet-dry hours	:	Cycle					:	Survival	:	Root necrosis	:	Hypocotyl length
	:	1	2	3	4	5	:		:		:	
		Percent germination						- - - - - *Percent* - - - -				*mm*
4-20		0	7	12	5	3		76		11		4.7
8-16		31	23	17	8	1		43		44		3.4
12-12		62	22	3	0	0		29		74		2.5

6

was incipient or proceeded to barely detectable root growth during the decline, with 6 and 12 h wetting, growth of hypocotyl and root ranged to 0.1. to 1.5 mm.

In late spring field plantings, when soil water levels are favorable for many species, irrigation was required for even modest survival (fig. 5). In squares irrigated as required by a drying soil surface, survival declined 24 percent in the 2 days following emergence, and 33 percent over the remaining 12 days to a final 4 percent. When irrigation was discontinued, none survived the following 2 weeks. Early survival in nonirrigated blocks, aided by rain on day 3, was comparable. However, even after an additional 2 days of scattered light showers, survival declined to zero by day 12. Under the drier conditions of early summer, plantings gave similar results for irrigated blocks, but further reductions for nonirrigated blocks--from 22 percent on day 2 to zero on day 8.
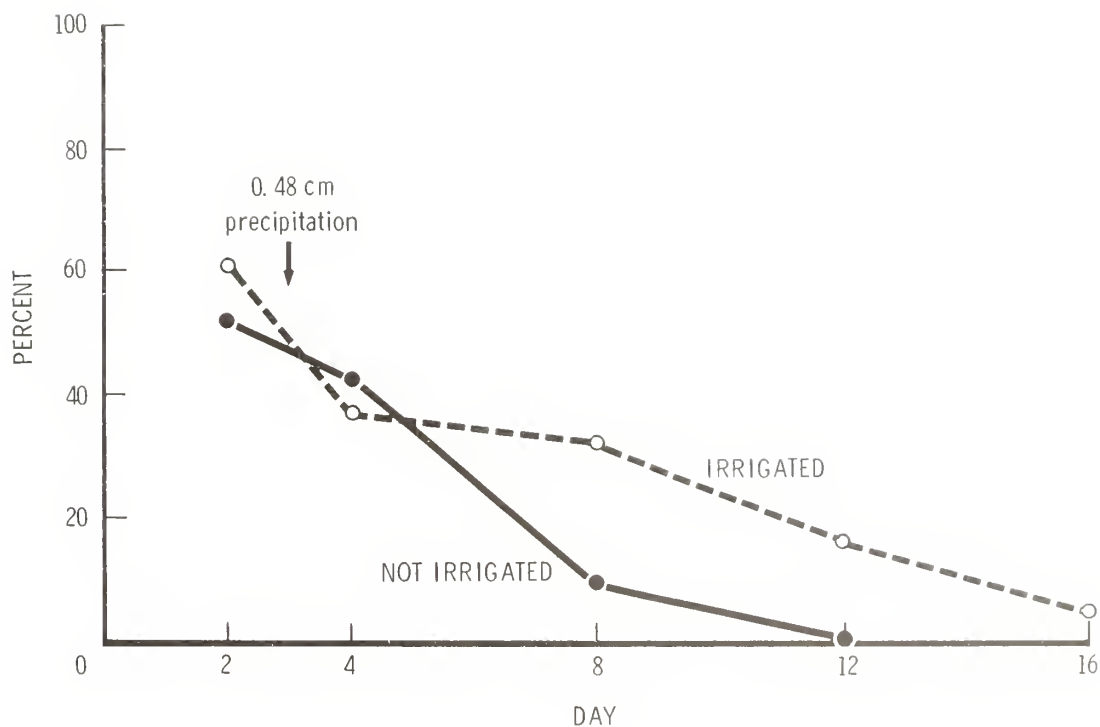
Figure 5.--Emergence and survival percentages of seedlings in irrigated and nonirrigated plots.

Soil Factors

Percentage of seedling emergence was influenced by depth of planting and temperature during emergence (fig. 6). In general, emergence declined as depths and temperatures increased. A depth of 0.08 in (2 mm) was inhibitory at 86°F (30°C). A 0.16 in (4 mm) depth significantly depressed emergence at the lower temperatures. At 0.24 in (6 mm), emergence was virtually eliminated at all temperatures.
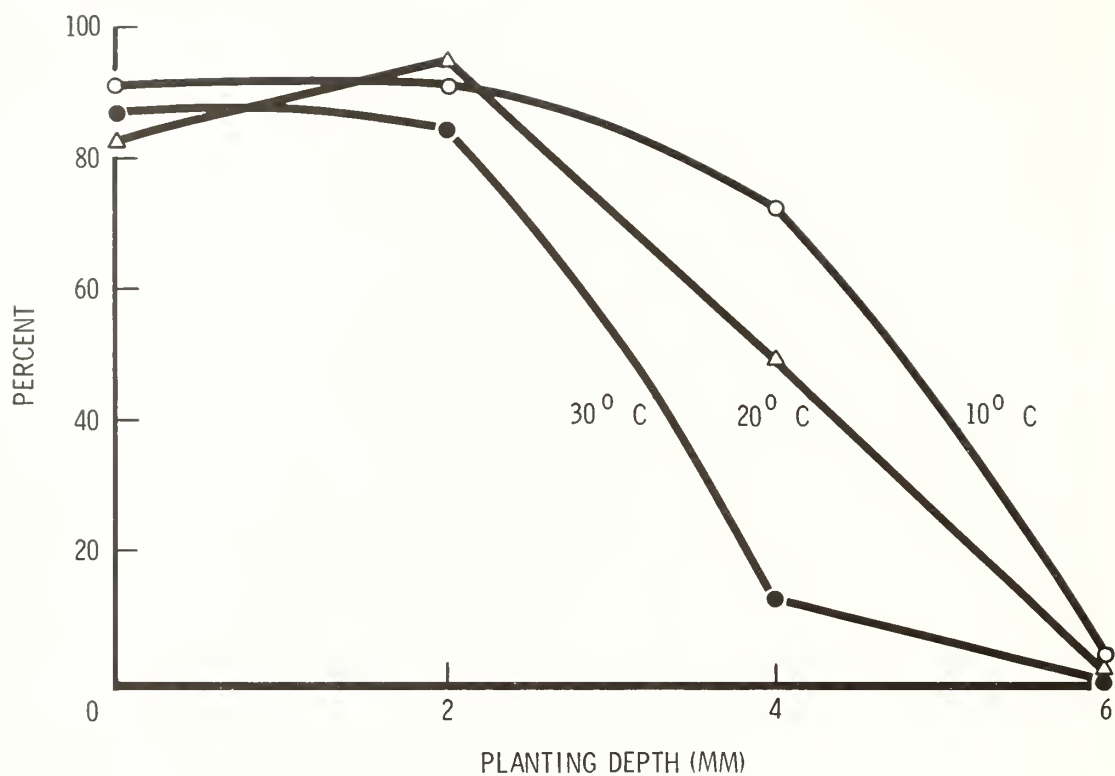
Figure 6.--Seedling emergence percentages at four planting depths and three temperatures.

When water is adequate, emergence occurs equally well on mineral substrates. Litter depressed emergence significantly, the amount depending upon the primary plant composition. Tests showed the following percentages of emergence:

Clay	96
Sieved aspen topsoil	92
Sand	89
Aspen seed hairs	85
Aspen leaves	84
Groundsel	81
Coneflower	79
Cheatgrass	63
Tarweed	59

8

Examination of the surfaces under magnification indicated that the effect was physical, at least in part; some seeds were stranded on pieces of litter (or root hairs) that wetted with difficulty or dried out more rapidly than the adjacent soil. This left the seeds not fully imbibed, or left the seedlings desiccated after growth had begun.

The four inhibitor compounds depressed root hair and root growth at concentrations of 0.6 to 2.9 grains/gal (10 to 50 p/m). Other seedling parts were less sensitive. Coumarin (fig. 7) was most effective and gallic acid least.
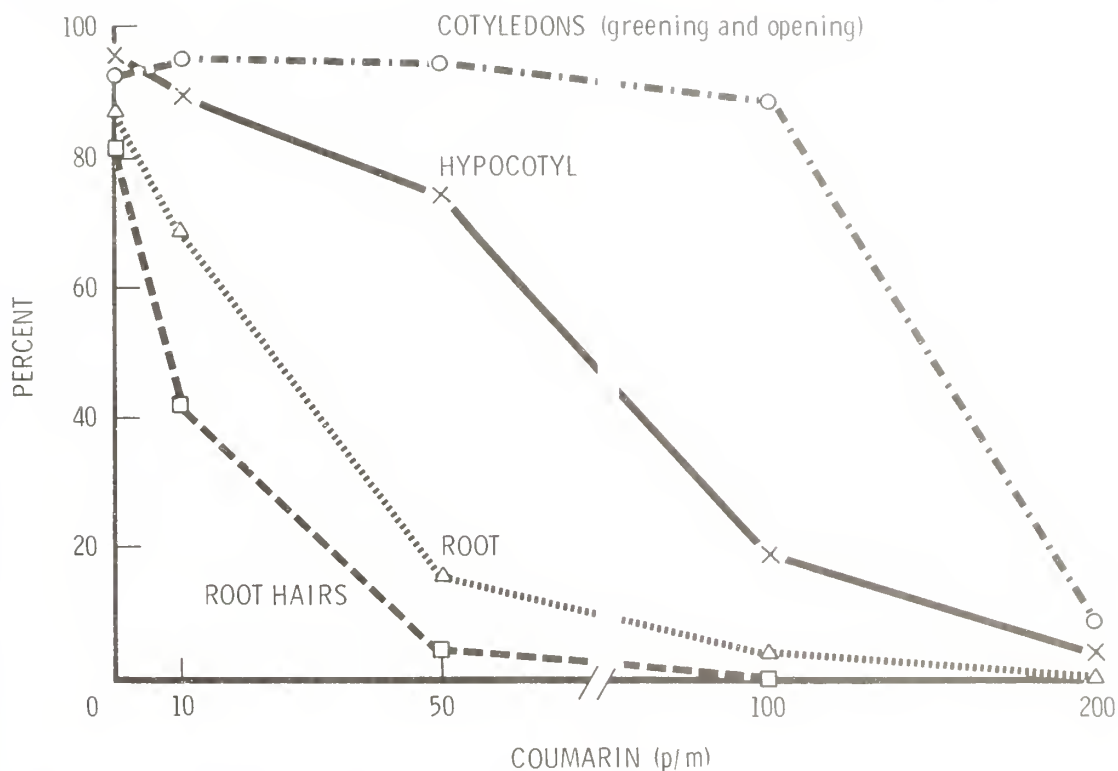
Figure 7.—Percentage of seedlings showing detectable growth of each part in the presence of coumarin.

Seed Aging

Loss of germinability depended on age, conditions of storage, and temperature during germination (fig. 8). Field storage in containers protected from precipitation but not from fluctuating temperatures and humidities was more detrimental to longevity than storage under the narrower range of atmospheric conditions of room storage. Seeds refrigerated at 23°F (-5°C) retained 90 percent or more germinability through 46 weeks, the longest interval tested.
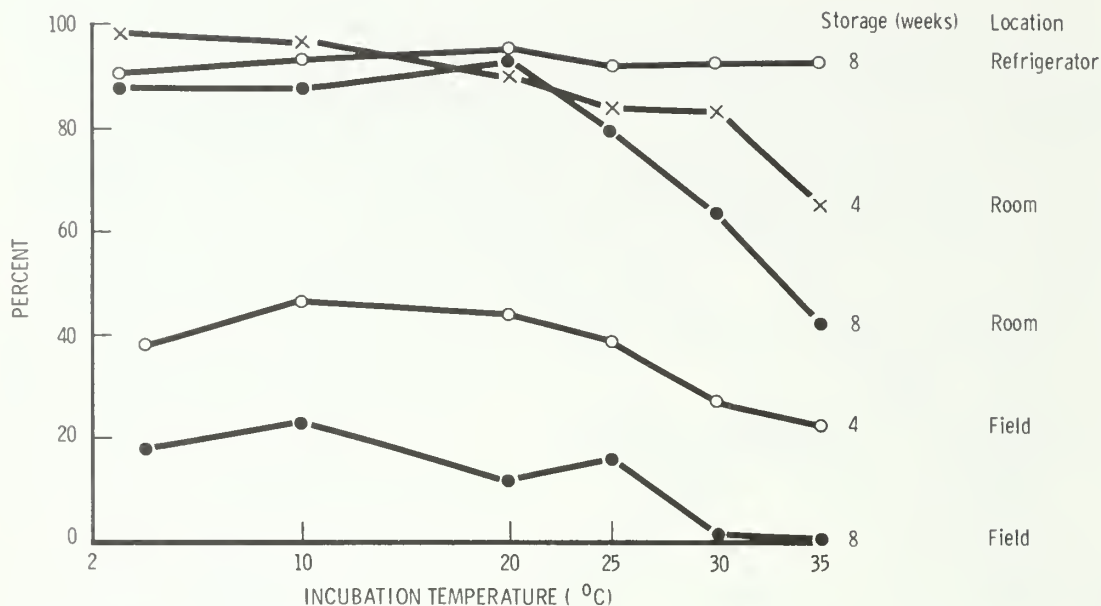
Figure 8.--Effect of storage conditions and incubation temperature on percentage seed germination.

Under unfavorable storage conditions, there was a trend toward reduced germinability at test temperatures higher than 68°F (20°C). Also, abnormal germination as a percentage of the total increased with temperature. For example, after 4 weeks of field storage, the percentages were 11, 28, and 41 at 50°, 68°, and 86°F (10°, 20°, and 30°C), respectively. No such seedlings survived when transplanted. These seeds were also more susceptible to osmotic inhibition. The germination percentages were 17 percent and 4 percent at -2.3 atm (-2.3 bars) and -4.4 atm (-4.5 bars), respectively, compared to 77 percent and 48 percent for refrigerated seeds.

DISCUSSION AND CONCLUSIONS

The wide range of temperature tolerance for germination (fig. 1) and rapid germination rates (fig. 2) potentially favor large numbers of seedling starts. However, progressively higher temperatures become increasingly detrimental (figs. 1, 4, 6, 8); lower temperatures near freezing are depressing (figs. 2, 4), but not permanently so after transfer to intermediate regimes. The initial rapid growth at 86°F (30°C) represents a short term optimum only, since growth falls off rapidly after the first week (fig 4.), and mortality increases. The damaging effects of higher temperatures also are seen in the reduced germination of aged seeds (fig. 8). The trend in longer term temperature optima lies in the intermediate range and is 68°F (20°C) for the stem and 50° to 68°F (10° to 20°C) for the root (fig. 4). Stem growth significantly exceeds root growth at all tested temperatures (fig. 4).

Air temperatures of 86°F (30°C) or higher are rarely reached on mountain sites. However, direct solar insolation on a dark soil surface and other characteristics of a microsite may result in temperatures well above atmospheric and would represent a limitation to seedling establishment. Germination and slow growth near freezing (figs. 2, 4) suggest the possibility of seedling survival under the insulating snow cover which occurs during occasional years at the time of seed dispersal.

From the limited number investigated, there is no evidence that declining clones produce seeds having lower germinability or seedlings with inferior growth. Any physiological basis for a clone's decline appears unrelated to factors that control vigor of its seeds' germination and early growth. Declining clones may produce fewer seeds per unit of photosynthetic surface (not investigated) and a smaller total number of seeds. Otherwise, these results indicate that both types of clones probably have about equal potential for contributing to seedling establishment.

High and continuous availability of water is critical for initial and firm establishment of seedlings. Normal germination is substantially reduced at approximately -2.0 atm (-2 bars), and successively fewer seeds progress beyond the incipient germination stage with lowering soil water potentials (table 1). These values are higher than the -3.9 to -7.9 atm (-4 to -8 bar) range that inhibited germination in several crop plants (Kaufman 1969), and toward the higher end of seed and substrate water potentials of -2.0 to -19.7 atm (-2 to -20 bars) in several range and pasture plants (McDonough 1972, 1975a, 1975b). This sensitivity to even mild deficits of water ranks aspen among the least tolerant species.

The turgor required by the seedling axis to start elongation and penetrate the testa is predictably more sensitive to lowering water potentials than the initial swelling due to inhibition (table 1, incipient/normal germination). The capacity to start growth in opposition to lowering substrate water potentials is further reduced by seed aging. Thus, with lengthening intervals between dispersal and onset of conditions suitable for germination, the capacity to overcome obstacles to growth by turgor development is reduced more rapidly than germinability.

In wet-drying cycling (table 2), loss of water during the pregermination to incipient germination stages is less harmful to eventual seedling growth and survival than less water loss at later stages. This is seen in the progressive extent of reduced hypocotyl length and root tip necrosis with longer wetting phases (table 2). Seeds in the pregerminative and incipient germination stages attained under shorter wetting phases apparently retain sufficient water for continued metabolic activity. Germination peaks toward the middle of the cycle and extensive growth resumes during the final wetting phase (table 2). Rapid changes in soil water conditions at the surface on exposed sites are common and may be a factor in reducing emergence and survival.

The rate and pattern of early seedling growth (fig. 3) appears to favor quick starts on suitable sites. However, even when water supply is adequate through the first week or more, a continuing supply is required for the firmer establishment that results from enlargement of the photosynthetic surface and increased capacity for water and nutrient uptake by appreciable plumule and root growth. These limitations probably cause high mortality even under favorable field conditions (fig. 5, irrigated).

A mineral surface is favorable for emergence; physical and chemical heterogeneity of the surface and burial are unfavorable (tabulated results above and fig. 6). The more pronounced inhibition of emergence by litter parent compounds (fig. 7) suggests allelopathic effects in addition to the purely physical effects that surface heterogeneity has on availability of water. Inability to emerge from even relatively shallow plantings is a liability, in that lower temperatures and higher soil water levels of the deeper layers favor germination and growth. The inability of the seedling to penetrate shallow layers of soil may be attributed to weak turgor development and scant nutrient reserves in the minute seeds.

11

Lower temperatures favor retention of germinability during aging of air-dry seeds, and germination of aged seeds during incubation (fig. 8). Storage under highly fluctuating field temperatures and humidities is more detrimental than storage at room temperature or refrigeration. Since low temperatures and high water levels prevail under a snowpack, late season snowfall should favor initial seedling starts. In contrast, early and extended onset of milder and drier weather would result in loss of turgor potential and germinability before the other hazards of establishment are faced. The timing of seed dispersal in relation to seasonal weather fluctuations may result in potentially good or bad years for establishment. Since hazards increase as spring progresses, it would be mandatory that a large, early season crop of seedlings be available for even modest survival through the first growing season.

Given the exacting seedbed requirements of this species, there seems to be hardly any practical scheme of management that would promote seedling establishment significantly over the normally large and thinly seeded dispersal areas. Seed collections and controlled dispersal over restricted areas of prepared ground subject to irrigation would have small effect, be prohibitively expensive, and have doubtful lasting value. Under favorable weather and site conditions, natural seeding and establishment may well be sufficient to insure the benefits of reproduction by seed.

PUBLICATIONS CITED

Baker, F. S.
  1918. Aspen reproduction in relation to management. J. For. 16:389-398.
Barnes, B. V.
  1966. The clonal growth habit of American aspens. Ecology 47:439-447.
Day, M. W.
  1944. The root system of the aspen. Am. Midl. Nat. 32:502-509.
Faust, M. E.
  1936. Germination of *Populus grandidentata* and *P. tremuloides* with particular
    reference to oxygen consumption. Bot. Gaz. 97:808-821.
Goldstein, A.
  1964. Biostatistics. 272 p. The MacMillan Co., New York.
Kaufmann, M. R.
  1969. Effect of water potential on germination of lettuce, sunflower, and citrus
    seeds. Can. J. Bot. 47:1761-1764.
Larson, G. C.
  1944. More on seedlings of western aspen. J. For. 42:452.
Maini, J. S.
  1967. Variation in the vegetative propagation of *Populus* in natural populations.
    Bull. Ecol. Soc. Am. 48:75-76.
Maini, J. S.
  1968. Silvics and ecology of *Populus* in Canada. *In* Growth and utilization of
    poplars in Canada, p. 20-69. J. S. Maini and J. H. Cayford, eds. Can. Dep.
    For. and Rural Develop., Publ. 1206
McDounough, W. T.
  1972. Grass seedling emergence as influenced by soil water potential. *In* Psychro-
    metry in water relations research. p. 229-230. R. W. Brown and B. P. Van Haveren,
    eds. Utah Agric. Exp. Stn., Logan, Utah.
McDonough, W. T.
  1975a. Water potentials of *Salsola kali* L. at differing levels of substrate water
    availability. Plant and Soil 42:387-393.
McDonough, W. T.
  1975b. Water potential of germinating seeds. Bot. Gaz. 136:106-108.
Moss, E. H.
  1938. Longevity of seed and establishment of seedlings in species of *Populus*. Bot.
    Gaz. 99:529-542.
Rice, E. L.
  1974. Allelopathy. 353 p. Academic Press, New York.
Schier, G. A.
  1974. Deterioration of aspen clones in the middle Rocky Mountains. USDA For. Serv.
    Res. Pap. INT-170, 14 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

McDonough, W. T.
1979. Quaking aspen--seed germination and early seedling growth. USDA For. Serv. Res. Pap. INT-234, 13 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Although freshly dispersed aspen seeds germinate quickly and nearly completely over a broad range of temperatures, early growth of seedlings is highly sensitive to availability of water, temperature, and physical and chemical conditions of the seedbed.

KEYWORDS: Quaking aspen (*Populus treumolides* Michx.), seedseedling, source, age, temperature, light, water potential, wet-dry cycling, turgor, seedbed, allelopathy, emergence, growth, primary root, root hairs, cotyledons, plumule.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field programs and research work units are maintained in:

Billings, Montana
Boise, Idaho
Bozeman, Montana (in cooperation with Montana State University)
Logan, Utah (in cooperation with Utah State University)
Missoula, Montana (in cooperation with University of Montana)
Moscow, Idaho (in cooperation with the University of Idaho)
Provo, Utah (in cooperation with Brigham Young University)
Reno, Nevada (in cooperation with the University of Nevada)

FIRE'S INFLUENCE ON WILDLIFE HABITAT ON THE BRIDGER-TETON NATIONAL FOREST, WYOMING

VOLUME I -- PHOTOGRAPHIC RECORD AND ANALYSIS
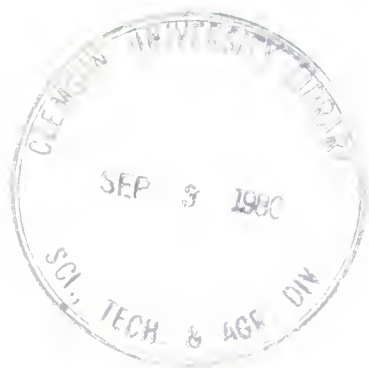
George E. Gruell

THE AUTHOR

GEORGE E. GRUELL is currently assigned as a research wildlife biologist in the Fire in Multiple-Use RD&A Program, USDA Forest Service, Intermountain Forest and Experiment Station, Ogden, Utah. This program is located at the Northern Forest Fire Laboratory, Missoula, Mont. The work reported on in this publication was accomplished between 1967 and 1977 while he was working as a wildlife biologist on the Bridger-Teton National Forest. Mr. Gruell started his career with the Forest Service in 1962 on the Humboldt National Forest in Nevada. Prior to coming to the Forest Service he was employed by the Nevada Fish and Game Department as a big game biologist from 1953 to 1958. He graduated from Humboldt State College, Arcata, Calif., in 1953 with a B.S. degree in wildlife management.

Cover Photos

Town of Jackson and slopes of Snow King Mountain   February 1918
39 years following the fire of 1879.

Town of Jackson and Snow King Mountain 60 years   February 22, 1978
later. The camera points for Plates 65a and 65b are on
distant slopes at upper extreme right.

FIRE'S INFLUENCE ON WILDLIFE HABITAT ON THE BRIDGER-TETON NATIONAL FOREST, WYOMING

VOLUME I -- PHOTOGRAPHIC RECORD AND ANALYSIS

GEORGE E. GRUELL

PREFACE

The Bridger-Teton National Forest in the Jackson Hole Region of Wyoming has long been recognized for its wildlife resource. Management efforts have emphasized the measurement of forage utilization by elk *(Cervus canadensis nelsoni)* and their effect on summer and winter ranges. Less consideration has been given to other biotic and abiotic influences. Reliable information on long-term habitat condition and trend has also been lacking. In 1968, this study was conceived to fill these information voids and to consider wildlife habitat changes from a historical perspective.

Contents provide visual evidence of vegetative succession, range condition, and trend. Many old photographs are included. Because old photographs are difficult to obtain and photo points difficult to relocate, we decided to include them in one compendium. By pulling the photographs together, others can examine them, apply their field experience, and make their own interpretations. The interpretations offered are mostly related to wildlife habitat. This presentation is an invitation to biologists, geologists, botanists, archeologists, and others to "read" these landscapes and learn from the past. It is also intended for use by nonprofessionals interested in the landscape. For those less familiar with ecological terminology, appendix I defines some important terms.

Photographs and supporting data have been gleaned from Forest Service files, universities, libraries, archives, historical societies, and other Federal agencies. This historical and ecological information helped identify the important influences that shaped the habitats of Jackson Hole.

The report also includes information pertinent to fisheries, forestry, range, geology, soils, hydrology, fire management, and management of scenic quality. Insights are provided into stream channel changes, timber growth, site potentials, plant succession, erosion rates, fire occurrence, and fuel loading.

This publication comprises two volumes--volume I acquaints the reader with important historical and ecological relationships and presents the photo record. The photos include 85 matched pairs spanning the period 1872-1975. These are separated into three geographical sections with interpretations and conclusions for each. Volume II, intended for land managers, resource specialists, and the academic community, discusses and summarizes the causes of vegetal and watershed changes. Management implications, including limitations, potentials, and future opportunities, are also explored.

ACKNOWLEDGMENTS

RESEARCH SUMMARY

This paper is volume 1 of two volumes. It documents vegetative succession and wildlife habitat condition and trend on the Bridger-Teton National Forest in the Jackson Hole region of Wyoming by means of comparison photos taken between 1872 and 1968-1972.

An introductory section describes the study area - - geology, topography, soils, climate, vegetation - - early exploration and settlement, and biotic and abiotic influences.

The body of the report comprises 85 matched photos arranged in three geographic sections: the Teton Wilderness and vicinity, the Gros Ventre drainage, the Jackson locale, and the Hoback drainage. Because of elevational differences from 5,800 feet to 12,165 feet (1 768 m to 3 709 m), plant species vary widely - - from cold desert species to alpine species.

Photo captions describe vegetational changes and their significance for each scene, with emphasis on wildlife habitat. Also discussed are the implications of vegetative change for fisheries, forestry, range, soils, hydrology, fire management, and scenic values. The role of fire - - primary influence on vegetative development - - receives special emphasis.

Vegetational changes are summed up at the end of each photographic section. Discussion is limited to identifying the changes that have taken place; why the changes occurred will be discussed in volume II.

Because of differences in physical setting, vegetational changes differ among the three geographic sections. In all three sections, however, conifers and mountain big sagebrush have increased. Other trends are as follows:

Establishment of aspen following fire; a general decline in old stands.

Decline in aspen and deciduous shrubs such as chokecherry and bitterbrush where these plants are seral to conifers.

An increase in density of herb and alpine vegetation.

General reduction in size and distribution of willow.

No appreciable change in ground cover on sparsely vegetated sites at low elevations.

No observable change in rate of geologic erosion.

Channel changes on flood plains.

Lack of stream channel change where flow has been confined by topographic features.

CONTENTS

FIGURES AND PLATES

COMPILING
THE PHOTO RECORD

Comparing photographs made many years apart provides an effective means for investigating changes in wildland ecology. This technique has been used by Phillips (1963), Hastings and Turner (1965), Progulski (1974), and Houston (1976). The author learned the merits of this method in earlier experiences on the Humboldt National Forest, Nevada (Gruell, unpublished 1966).

Photographs shown here, largely unavailable to the scientific community before this investigation, were obtained from a variety of sources. A few examples of places where early photographs were located demonstrates the opportunities that remain. Plates by Owen Wister were obtained from his daughter, Mrs. Walter Stokes, who found them in an attic trunk. Several of the W. H. Jackson photographs taken in 1878 were in a well-worn album at the Colorado Historical Society archives. These scenes, which do not appear in any of the prominent Jackson collections, are rare. U.S. Biological Survey photographs thought to have been lost during a World War II move were retrieved from the National Archives and Record Center.

The original photographs were taken for varied purposes from 1872 to 1942 by people on summer excursions, hunting trips, and government surveys. Most were taken by foresters, biologists, or geologists, some by hunters, and three by professional photographers. Many of these photographs predate significant use of the area by European man. All recent photographs were taken by the author.

A 4x5 Kodak Crown Graphic[1] camera fitted with a 135 mm lens was used to rephotograph most scenes. In a few instances, a 190 mm or 300 mm lens was used where the original exposure was made with a lens of longer focal length. Plus X Pan Professional film in 16 exposure packs proved satisfactory, except that rendition of dark tones (willow, sedge) was not always comparable to the wet plate process or the slow speed ortho film used to take the original photos.

Photographs in this report provide a representative cross-section of habitats on the Teton Division of the Bridger-Teton National Forest. Twenty additional matched sets showing comparable conditions are on file at the Forest Supervisor's office. Eighty-two originals were not rephotographed because of poor quality, duplication of scenes, unknown location, or views obstructed by human development.

The original photographers traveled through many different habitats, ranging from alpine vegetation (plate 26) to cold desert shrub (plate 38). Scenes include streams and rivers; meadows and mountain herblands; spruce-fir, whitebark pine, lodgepole pine, and Douglas-fir forests; aspen and sagebrush-grass communities; and perennial grass-low shrub vegetation.

Most photos were taken along primary drainages, which often were historic travel routes. Excepting the Teton Wilderness, many of the original trails have been replaced by roads, sometimes visible in the retake. Readily accessible photo points were located and conditions under which the original photo was exposed were noted before retaking the scene. This insured replication at the right season and time of day.

At some remote sites, prior recon-
naissance was not possible, so some
scenes were rephotographed at the im-
proper season, wrong time of day, or in
adverse weather.

Relocating photo points proved difficult
where the original photo lacked distinc-
tive land features as points of reference.
With some exceptions, precise reloca-
tion of photo points was not critical,
because the area of interest was usually
distant from the camera. In most in-
stances, the new photo point is within a
few feet of the original.

THE STUDY AREA

Location

This study was mostly confined to the
Teton Division of the Bridger-Teton
National Forest, which lies east of the
Teton Range in northwestern Wyoming
(fig. 1). This area of 1,695,000 acres
(686 235 ha) is roughly bounded by the
Snake River on the west; Yellowstone
National Park on the north; the Absaroka
Range, Continental Divide, and Green
River hydrographic divide on the east;
and the Wyoming Range on the south
and west.

The major drainage is the Snake River,
which flows southerly through Jackson
Hole from its source in the Teton
Wilderness. Principal tributaries include
Pacific Creek and the westerly flowing
Buffalo, Gros Ventre, and Hoback Rivers.
The only major northerly flowing river,
the Yellowstone, heads in the Teton
Wilderness. The Teton Wilderness oc-
cupies 557,311 acres (225 632 ha) in the
northern third of the Teton Division.

Elevation ranges from 5,800 ft (1 768 m)
at Bailey Creek on the Snake River to
12,165 ft (3 709 m) on Younts Peak in the
northeastern quarter of the Teton Wilder-
ness. Many peaks and high plateaus lie
above 10,000 ft (3 049 m).

Geology

Six major physiographic features are
recognized (Fenneman 1931): the Snake
River, Hoback and Gros Ventre Rivers,
Mount Leidy and Pinyon Peak Highlands,
and Hoback Basin. Compared with other
Rocky Mountain ranges, these features
are geologically young, having been
uplifted to nearly their present eleva-
tions less than 10 million years ago
during Pliocene time (Love 1956).

Following uplift, land features were sub-
jected to successive erosion cycles that
stripped away great quantities of
material, particularly highly erosive
sedimentary formations. A final period of
extensive alteration occurred during the
Pleistocene ice age. The region was first
strongly glaciated by local ice caps,
followed by individual valley glaciers.
Five glaciations separated by warmer in-
terglacial periods have been recognized
(Bailey 1971). Following the warm-dry
Altithermal interval, about 6,000 years
ago, minor episodes of cirque glaciation
took place during the Little Ice Age inter-
val about 70 and 400 years ago (Bray
1971; Benedict 1968). Glaciation,
especially during the initial stages,
buried some areas under glacial debris
while stripping rock and soil from others.

Topography

Topography, as described by Love (1968)
and Bailey (1971), is that of a dissected
plateau resting upon sedimentary rocks
of complex structure. Even where best
preserved, much of the original plateau
has been destroyed by the growth of
deep valleys. Recent uplifting and glacial
activity have developed many steep
slopes, except in areas of highly erosive
materials and low relief. Long, sharp
ridges and rugged peaks cut by steep
canyons 2,000 to 3,000 ft (610 to 915 m)
deep are common. Those formations,
highly resistant to erosion, have been
dissected by streams into an intricate
pattern of narrow, deeply incised
V-shaped drainages. Level ground oc-
curs only as narrow flood plains along
major streams, as small remnants of
slightly undulating surface representing
old valley levels, and on glacial outwash
plains. Because of low gradients,
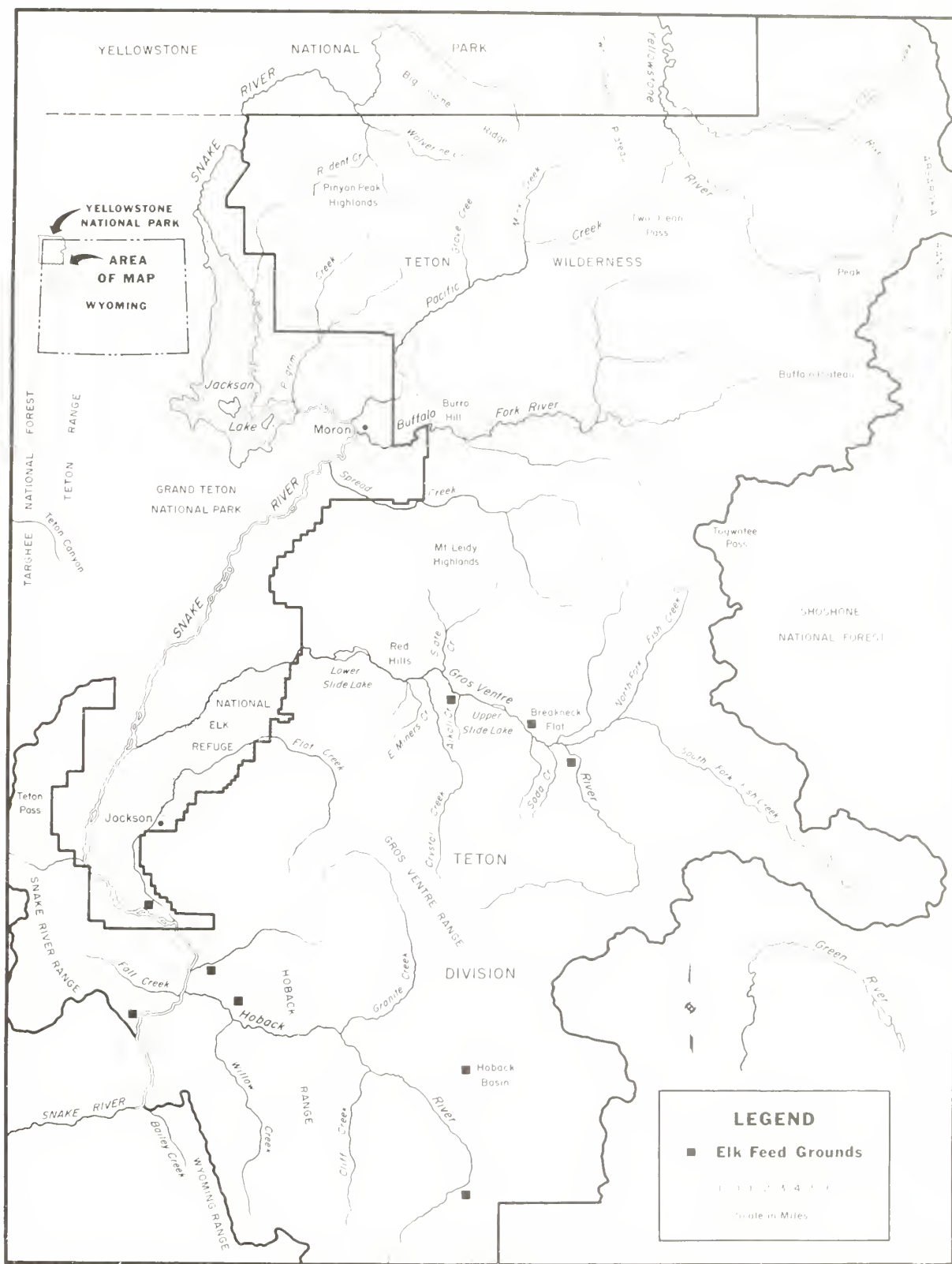meandering streams are common in the
valleys.

Figure 1. Study area, showing major physiographic features.

3

On many slopes landslides are frequent because of weak parent materials, high relief, undermining by stream cutting, and high seasonal precipitation.

This region constitutes one of the largest landslide-prone areas in the United States.

Soils

Soils differ due to considerable variation in soil-forming processes. Complex geology alone accounts for many differences in soil textures. Sandy and heavy clay soils are sometimes interbedded along the same exposure. Loam and clay loam soils are most common.

Soil productivity varies; sites with high productivity potential are commonly only a few feet from sites with low potentials. Overall, highly productive sites are more extensive than sites of low productivity. Productive sites are characterized by deep soils and ample moisture. Shallow soils on ridges and south-facing slopes have much lower productivity.

Soil erosion rates are strongly affected by steepness of slope and the amount of litter and vegetation covering the soil surface. The amount of cover required to minimize soil loss decreases as slope gradients decrease. Most of the soils in the area are inherently not very erosive; however, all soils on steep slopes without good vegetative and litter cover are moderately to highly erosive.

Climate

The region's climate is classified by Alyea (1966) as a cold-snowy-forest type with humid summers. Summers are short and cool; winters are long and cold. Snow covers the valley of Jackson Hole about 5 months each year whereas the high country above 9,000 ft (2 744 m) is snow-covered about 8 months. Local conditions vary widely because of differences in elevation and exposure. Semiarid conditions prevail in the lowermost valleys on south-facing slopes. Prevailing winds are from the southwest. Strong winds are much rarer than in most of Wyoming, but occasionally brief

storms may bring gusts exceeding 75 miles (121 km) per hour. Because of the cold air flow from Canada, cold air drainage from surrounding mountains, rapid nighttime radiation cooling, and high elevation, freezing temperatures can occur at any time of the year.

Temperatures range widely between summer and winter and between daily maximums and minimums. The mean annual temperature from 1931 to 1960 was 38° F (3.3° C) at Jackson elev. 6,244 ft (1 904 m) compared with 33° F (0.6° C) at slightly higher Bondurant elev. 6,504 ft (1 983 m) in the Hoback Basin. December and January, the coldest months, averaged 11.7° F (-11.3° C) and 7.4° F (-13.7° C), respectively, and July, the warmest month, averaged 56.3° F (13.5° C) at Jackson. Summer temperatures rarely exceed 90° F (32.2° C) at low elevations. A lapse rate of 4.4° F (-l5.3° C) per 1,000 ft (305 m) elevation developed by Potter (1969) for northwestern Wyoming suggests that the mean annual temperature at 9,000 ft (2 744 m) elevation is about 26° F (-3.3° C).

Mean annual precipitation varies from 15 inches (38 cm) in Jackson to 50 or 60 inches (127 or 152 cm) in the Absaroka Range. Most precipitation falls as rain in Jackson, while approximately three-quarters of the total above 7,000 ft (2 134 m) is snow. Snow depths at the highest elevation exceed 100 inches (243 cm). Snow cover normally remains nearly complete at high elevations until mid-June or even through mid-July. Peak runoff occurs during May, June, and early July. Recurrent summer thunderstorms cause some streams to become muddy very rapidly and produce wide fluctuations in flows, but do not contribute significantly to the annual runoff.

Vegetation

The flora of the Jackson Hole area is typical of the central Rockies. Shaw (1976) recognized 836 indigenous and 85 alien species in Teton County, ranging from alpine plants to cold desert species more characteristic of the semiarid Green River region in a few localities. Scientific names of most species found

4

on elk summer and winter ranges, along with less conspicuous species referred to in the text, and listed in appendixes II and III, are after Hitchcock and Cronquist (1973). Common names largely follow Plummer and others (1977).

As a whole, the plant cover is predominantly herbaceous species, and production potential is high. Shrubs, excepting mountain big sagebrush are localized in distribution. Common shrubs in range habitats are bitterbrush, serviceberry, and chokecherry. Willows predominate on flood plains and along tributaries.

Seven broad plant communities were recognized in this study: sagebrush-grass, aspen, lodgepole pine, Douglas-fir, spruce-fir, whitebark pine, and tall forb vegetation (herblands). Many habitat types occur within these communities.

Sagebrush-grass mainly occurs on glacial outwash plains, river terraces, and well-drained slopes. This community is a conspicuous feature of the landscape, particularly at lower elevations where it is interspersed with aspen, lodgepole pine, Douglas-fir, and spruce-fir. Many streams, ponds, and wet meadows within this complex provide habitats for plants adapted to moist environments. Mountain big sagebrush predominates in the sagebrush-grass community. Associated grasses usually include many species, and growth potential is high. Long-leaf sagebrush occurs on stony soils or those with root restricting layers but is replaced on more droughty sites by fringed sagebrush, Douglas rabbitbrush, and winterfat.

Aspen is the most common deciduous tree up to 9,000 ft (2 744 m) elevation except in the northern two-thirds of the Teton Wilderness where it only occurs in a few isolated stands. Best development of aspen is on loamy soils between 6,500 to 7,500 ft (1 982 to 2 287 m) in elevation. Stands are rarely large and vary from those with closed canopies to those with widely scattered, mature and overmature trees. The understory beneath intact stands usually contains many different herbaceous plants. Increased sunlight in deteriorated stands has allowed the invasion of mountian big sagebrush and other shrubs. Where plant communities have progressed from seral to coniferous forest; aspen have died out with advancing succession.

Lodgepole pine is the most abundant conifer at intermediate elevations. It forms a more or less continuous cover where the landscape is not dissected by drainages. More often, however, it grows in small stands or is intermixed with Engelmann spruce, subalpine fir, or whitebark pine. Most stands are between 100 and 250 years old. Because stands have had many trees with relatively large diameters and thick phloem layers, lodgepole pine has been susceptible to mountain pine beetle *(Dendroctonus ponderosae)* attacks over wide areas. This has often resulted in widespread mortality of lodgepole pine followed by a predominance of subalpine fir. Understory vegetation varies from sparse elk sedge cover under closed stands to an association of various shrubs and herbaceous species in open stands.

Douglas-fir is more restricted in distribution reaching best development at 6,500 to 7,500 ft (1 982 to 2 287 m) elevation in pure stands about 100 years old on north and west slopes along the Gros Ventre, Snake, and Hoback River drainages. Distribution at higher elevations is usually restricted to southerly exposures or ridges where scattered individuals may exceed 300 years of age. Understory vegetation is sparse beneath closed stands, but contains a wide assortment of species under more open stands.

Engelmann spruce and subalpine fir predominate on north slopes above 8,000 ft (2 439 m) and along drainages. Blue spruce is restricted to localized areas in the lower valleys. Engelmann spruce occurs in nearly pure stands or in association with subalpine fir, lodgepole pine, or both. Subalpine fir predominates at the highest elevations. Herbaceous vegetation in the spruce-fir community is characterized by a profusion of grasses, sedges, and forbs in forest openings,

mountain meadows, and parks, while shrubs often predominate beneath the tree canopy.

Whitebark pine occurs in pure stands above 8,500 ft (2 591 m) or mixed with spruce-fir, lodgepole pine, or limber pine. At timberline, whitebark pine dominates. Herbaceous vegetation in the whitebark pine community varies from sparse to abundant, depending upon the site.

Tall forb communities are usually found above 8,000 ft (2 439 m) elevation where they occupy forest openings, open slopes, and ridges. Characteristic species are mountain brome, duncecap larkspur, thickstem aster, western yarrow, silvery lupine, and sticky geranium. Production varies from low density vegetation on shallow soils to dense, luxuriant growth on deep soils. Optimum development occurs above 9,000 ft (2 744 m), where stands sometimes exceed several hundred acres.

HISTORY OF
THE STUDY AREA

Various Indian tribes, including the Blackfeet, Shoshone, and Gros Ventre, visited the Jackson Hole region during the summer for centuries before the appearance of mountain men and explorers.

John Colter, in 1807, was probably the first white man to see the region; however, he may have been preceded by French fur trappers prior to 1800. From 1809 to about 1840, numerous mountain men visited the Jackson Hole region to trap beaver. Unfortunately, only a few recorded their travels. The first to do so were Hunt and Stuart (Rollens 1935) who guided the Astorians from St. Louis to Oregon in 1811. Stuart returned east via Jackson Hole in 1812. An insight into prevailing big game populations is contained in their journals.

Others who frequented western Wyoming during the trapping era, including a few who left a written record, were the celebrated Jim Bridger, William Sublette, David Jackson, Edward Robinson, John Hoback, Jacob Rezner, W. A. Ferris, Samuel Parker, Nathaniel Wyeth, Joe Meek, and Osborne Russell. Russell left the most explicit diary, including a precise description of wildlife (Haines 1965). William Sublette named Jackson Hole for David Jackson in 1829.

After the trapping era ended about 1840, the region was seldom visited for the next 15-20 years. Then a succession of geographical, topographical, geological, and biological surveys were initiated by the Federal government. The official reports documenting these surveys provide some of the best descriptions of conditions before settlement.

The first survey was led by Captain W. F. Raynolds, with Jim Bridger as guide. The group traveled down the Gros Ventre River and over Teton Pass in the summer of 1860 (Raynolds 1868). Raynold's report is a good commentary on the remote and rugged nature of the country at that time.

During the 1860's an occasional exploratory mining party passed through Jackson Hole. DeLacy's (1876) account of his 1863 trip contributed to an understanding of early wildfire occurrence. Henderson (1867), also a miner, came through Jackson Hole in 1867.

Barlow and Heap (1872) conducted an engineering reconnaissance in 1871 that penetrated into the northern portion of the present Teton Wilderness. Their report, although lacking detail, gives some insight on watershed conditions and big game populations at the time. Bradley (1873) led a contingent of F. V. Hayden's Geological and Geographical Survey Of The Territories to the same general locality in 1872. His report provides information on watershed conditions, past fire occurrence, and elk populations. In 1873, Captain W. A. Jones led an engineering reconnaisssance along the upper Yellowstone River, down the Buffalo River, and over Togwotee Pass (Jones 1875).

Lieutenant G. C. Doane entered the region by way of the headwaters of the Snake River in the early winter of 1876 (Doane 1877). Despite many hardships, part of this group floated by boat down the Snake River and through Jackson Hole. This report is one of the most interesting and informative records of pre-settlement conditions. Elk were observed in what is now the Teton Wilderness. The diary records the earliest instance of a white man (John Pierce) wintering in Jackson Hole. It also provides the first written record of elk wintering in Jackson Hole.

Ingersoll (1883) left a fine narrative of his experience with the Hayden survey while in the Green River and Hoback River drainages during the summer of 1877.

In 1878, W. H. Jackson, the famous pioneer photographer and a member of the Hayden Survey, took the first photographs of Jackson Hole. Coming into the Hoback drainage from the East, he found the region enveloped in haze from forest fires and was unable to take good photographs. On his return from Yellowstone National Park in the fall, conditions were favorable, and he captured a number of outstanding scenes on glass plates.

Thomas Moran, the distinguished painter, had a similar experience in 1879 on the west slope of the Teton Range. His objective of painting the Tetons was most difficult, because of the pall of smoke enveloping the higher peaks (Fryxell 1932).

Baille Grohman, a wealthy English sportsman, was one of the first sportsmen to enter Jackson Hole (Grohman 1884). He spent 10 days in the valley in September 1880, and found that the region was virtually unfrequented by whites. Buxton (1893) also reports seeing only two whites during several weeks in Jackson Hole in 1884.

President Chester Arthur and his army escort traveled down the Gros Ventre River in 1883. A detailed account of the journey was not kept; however, F. J. Haynes did take photographs that have been useful in interpreting current conditions.

The first permanent settlers came to Jackson Hole in 1883. They consisted of three bachelors, John Carnes, John Holland, and Mike Detweiler, who homesteaded, built cabins, and spent the winter a few miles northeast of the present town of Jackson.

Owen Wister, author of *The Virginian*, made yearly fishing and hunting trips to the region starting 1886. His diaries and several photographs provide valuable documentation of early conditions. Another celebrity who came to Jackson Hole to hunt was Theodore Roosevelt (Roosevelt 1893). In September 1891, he hunted elk and other big game in the Two Ocean Plateau-Big Game Ridge locality with good success. His narrative provides a good insight on the availability of game and factors affecting distribution.

Between 1884 and 1904 Arnold Hague, a geologist who had been with the Hayden Survey, led an intensive geological study of Yellowstone National Park and adjacent mountain ranges. Hague had a compelling interest in wildlife and was a close personal friend of Theodore Roosevelt and other noted conservationists. Many hours of observation equipped this man with a comprehensive knowledge of wildlife in the area. His paper, *The Yellowstone Park as a Game Reservation* (Hague 1893), informed administrators about the importance of the Yellowstone region as wildlife habitat. The Yellowstone Geologic Survey also provided important early photographs by Professor Iddings in 1886 and T. R. Jagger in 1893.

In 1891 the Federal government moved to protect natural resources south of Yellowstone National Park through creation of the Yellowstone Park Forest Reserve. The reserve extended from the Wyoming state line on the west to a partially surveyed line between ranges 109 and 110 west on the east and the 44th parallel on the south. A further conservation measure was taken in 1897 by including in the Teton Forest Reserve all land south of the Yellowstone Park

Forest Reserve to the south boundary of Township 43 north. In 1905 most of the Yellowstone Park Forest Reserve and the north portion of the Teton Forest Reserve were included in the Teton Game Preserve. Elk hunting was prohibited in most of the area until termination of the Preserve in 1945. Forest conditions on the two Forest Reserves were examined for 3 months in 1897 by Dr. T. S. Brandegee (Brandegee 1899). His reports provide valuable data on forested conditions before 1900. In 1908 both Forest Reserves were combined with added acreage to the south to form the Teton National Forest, which was, in turn, combined with the Bridger National Forest in 1973 to form the Bridger-Teton National Forest.

One of the better accounts of early elk distribution was provided by Sir Rhodes Lambert Price, another English hunter (Price 1898). During a long stay in the fall of 1897, he wrote that the trout fishing was the best he had experienced and surpassed any that he had known in various other parts of the world.

The distinction of conducting the first comprehensive fisheries survey in Yellowstone National Park and the northern part of the Teton Wilderness belongs to Dr. B. W. Evermann (1893).

By 1897, Jackson Hole contained 21 ranches (Brandegee 1899). Long harsh winters and limited arable land discouraged all but the most hardy individuals from settling in the valley. Most ranches were small, had little land in cultivation, and were devoted to raising cattle with numbers limited to the amount of hay that could be cut and stacked for winter use. Early residents of Jackson were keenly aware of the importance of wildlife, particularly the winter elk herd, whose range completely encircled the town. Income was usually supplemented by or, in some instances, entirely dependent upon outfitting hunters and fishermen. The experiences of these early residents are not only interesting but also help interpret early wildlife conditions.

The settlement of Jackson Hole progressed steadily after the turn of the century, with less productive lands being taken up last. By 1908, nearly all arable land was privately owned.

INFLUENCES ON THE LANDSCAPE

Elk, Deer, and Other Ungulates

The past and present status of elk and other wild ungulate populations have been described by Anderson (1958), Houston (1968), Cole (1969), Gruell (1973), and Gruell and Loope (1974). Elk were indigenous to western Wyoming, and large numbers migrated annually from summer to winter ranges in the valley of Jackson Hole and along the Gros Ventre River drainage. Elk populations fluctuated widely due to starvation during severe winters such as in 1886-87, 1889-90, and 1896-97. Subsequent conversion of important valley winter range in Jackson Hole to ranching left the elk herd with reduced winter forage, and large numbers died during the severe winter of 1908-09. Concern over the situation led men such as S. N. Leek to initiate a winter feeding program. Heavy winter losses in 1909-10 and 1910-11 brought investigations by professional range and wildlife biologists (Preble 1911; Barnes 1912). Reports by these men and others focused national attention on Jackson Hole that resulted in the establishment in 1912 of a refuge on purchased land northeast of Jackson. This facility was first operated by the Biological Survey and was known as the "Elk Ranch." By a Presidential executive order of August 10, 1912, it became the National Elk Refuge. Initially containing only 1,760 acres (713 ha), subsequent land purchases increased the refuge to its present 23,972 acres (9 705 ha).

Another outcome of early elk investigations was restriction in 1919 of livestock

grazing on winter game range where conflicts with elk were apparent. Some cattle and horse permits were revoked, seasons of use were cut, and regulations imposed which restricted livestock grazing on specific areas, including lower elevations along the Gros Ventre River, slopes east of the National Elk Refuge, and low-lying National Forest lands east of the Snake River below Jackson and north of the Hoback River from its mouth to the Hoback Canyon.

The present elk population wintering in areas drained by the upper Snake River (above Alpine, Wyoming) and its tributaries numbers between 15,000 and 20,000. Of these, 7,000 to 9,000 are fed supplements on the National Elk Refuge near Jackson, while 6,000 to 9,000 winter at nine feedgrounds operated by the Wyoming Game and Fish Department. The balance free-range on traditional wintering areas, primarily on the Buffalo Fork, Spread Creek, and Gros Ventre drainages.

In recent decades, moose *(Alces alces shirasi)* have also become an important biotic influence on the landscape. This large ungulate was apparently rare in Jackson Hole prior to and immediately following the turn of the century. They were not mentioned during the fur trapping era, and government survey people in the 1870's as well as hunters in the 1880's rarely observed them (Ingersoll 1883; Buxton 1893). The moose population gradually increased through the late 1800's and early 1900's. By 1916, it was considered large enough to support 27 hunting permits in western Wyoming. The population has continued to increase or has leveled out depending on the locality. In 1975, 807 moose were harvested in Jackson Hole on 1,005 permits.

Other wild ungulates that have used Jackson Hole ranges over the years include mule deer *(Odocoileus hemionus)*, bighorn sheep *(Ovis canadensis)*, pronghorn antelope *(Antilocapra americana)*, and bison *(Bison bison)*.

Mule deer were apparently scarce prior to 1930 but had increased markedly by 1950 (Murie 1951). The summer population is widely distributed, with the primary range being south of the Gros Ventre Mountains. Most of the herd winters south and east of Jackson along the Snake and lower Hoback Rivers.

Fragmentary accounts from hunter diaries suggest that bighorn sheep were more numerous than today. The current population in Jackson Hole is about 200. Except for some areas in the Teton Wilderness, most of these sheep winter along the Gros Ventre River.

Early settlers recounted that several thousand pronghorn antelope grazed in the valleys of the Snake, Gros Ventre, and Hoback River drainages during the summer. Numbers were decimated by the turn of the century, but have increased in recent years to more than 600.

Bison were numerous in Jackson Hole until about 1830, but were eliminated prior to settlement (Fryxell 1928). Currently, a herd of about 20, which originated from Yellowstone National Park stock, range freely on Grand Teton National Park and adjacent lands.

Domestic Livestock

Cattle (about 100) were first brought into Jackson Hole in 1883 (Van Derver *ca.* 1939). During the following decade, cattle numbers gradually increased. Brandegee (1899) described livestock distribution in 1897 as follows: "The number of cattle and horses in Jackson Hole is very small, being limited by the amount of forage which can be cut and stored for winter use. At present they range in the valley, to all parts of which their range does not yet extend!" After 1900, homesteads were taken up in the Gros Ventre and Hoback River drainages. Cattle numbers increased quite rapidly thereafter, and by World War I approximately 15,000 were permitted on the Teton National Forest. Numbers have fluctuated somewhat over the years, currently numbering about 14,500.

Domestic sheep grazing has almost entirely been limited to range west of the Hoback River at the headwaters of the Hoback, Cliff, and Willow Creek drainages where some 45,000 sheep reportedly grazed when the Teton National Forest was established in 1908. Numbers were reduced to 20,000 by 1913. Currently some 4,000 are permitted on the Teton Division.

Over the years, range examiners have been impressed with the high production of forage and generally good condition of Teton National Forest livestock ranges. "First-class" or "surprisingly good" have been used at times to describe conditions. These descriptions were no doubt influenced by comparing local conditions with those of other regions with less potential for forage production and heavier stocking. Stocking intensity was materially limited by the amount of hay that could be put up to overwinter cattle.

Insects and Diseases

Insects, mites, and diseases have affected vegetation for milleniums. Furniss (1972) lists 228 insects and mites believed to damage five shrub families on western game ranges. Krebill (1972) accounted for 111 diseases caused by fungi, bacteria, viruses, and parasitic plants, which likewise attack seven shrub families on western game ranges. These lists are incomplete and only cover a few of the plants indigenous to Jackson Hole.

The influence of these agents on plant communities is usually subtle with little of the growth conspicuously affected. In most instances damage sets the plant back and new growth develops from the stem and base. Plant mortality can result, however, from repeated attack on trees or shrubs which do not regenerate by sprouting. A noteworthy example has been loss of lodgepole pine to infestations of the mountain pine beetle.

Small Mammals

Rodents influence plant communities depending upon the situation and rodent species involved. Both the red squirrel *(Sciurus hudsonicus ventorum)* and the white-footed mouse *(Peromyscus maniculatus maniculatus)* benefit regeneration of some deciduous shrubs and conifers by dispersing or caching seeds and cones some distance from where they were gathered. Seeds that are not eaten sometimes germinate.

Mice can damage sagebrush, bitterbrush, and other shrubs considerably by girdling stem bases during the winter months. During a 12-year study of bitterbrush in Idaho, Phillips (1970) found that 10 to 20 percent of 200 plants were killed by girdling during two of three eruption years. On eight areas in southwestern Montana which varied from 20 to 1,200 acres (8 to 986 ha), 10 to 84 percent of the big sagebrush was killed in one year by voles *(Microtis montanus)* (Mueggler 1967).

During this study, I observed mortality of mountain big sagebrush girdled by the snowshoe hare *(Lepus americanus)* during winter and early spring when food was scarce. During population highs, the white-tailed jackrabbit *(Lepus townsendi campanius)* heavily utilizes half-shrubs on the Gros Ventre elk winter range.

Porcupines *(Erethizon dorsatum)* kill conifers and some deciduous trees by eating the cambium, especially during winter. Although impact on coniferous forests is usually not great, porcupine damage around developments or where timber is being managed for future harvest may not be tolerable.

Beaver *(Castor canadensis)* have had a striking impact on stream-bottom vegetation. With successional advances and a shrinking food supply, these industrious mammals have virtually eaten themselves out of house and home. Old dams, cuttings, and felled aspen indicate that in the past the habitat was able to support much higher populations than currently.

The pocket gopher *(Thomomys talpoides)* affects vegetation and soil throughout the study area. Gophers are particularly numerous in high elevation, tall-forb

vegetation where they often move great quantities of soil and eat considerable forage. In recent years, ideal habitat for pocket gophers has been created by clearcutting timber. The resulting eruption of pocket gophers has in some cases made reforestation difficult. This rodent extensively damages seedlings by girdling stems and eating terminal buds under the snow cover.

Fire

Various investigators have demonstrated that wildfire was a key environmental factor influencing plant communities of North America in primeval times (Phillips 1962; Wellner 1970; Swain 1973). Wildfire's role in the Jackson Hole area has been described by Loope and Gruell (1973). The fire history on the Teton Division was reconstructed in some detail from early narratives and photographs, sampling of fire scars, and examination of fire records dating from 1931.

In early times, fires were frequent and widespread, but did not completely burn the landscape except under extreme weather conditions and continuous fuels. Burning was often irregular, ranging from stands untouched by fire to others that were entirely burned. Where slope, fuels, and weather allowed uniform spread, fires intensified until they crowned. Today these localities show a contrast between younger, even-aged trees in the burns and larger, older trees in adjacent stands. Fires that produced the even-aged stands often stopped on or near ridgetops, in discontinuous fuels, or because of changes in weather. During cool weather, burning was largely on the forest floor, with only scattered tree mortality.

DeLacy (1876) observed wildfires in August 1863 between Swan Valley, Idaho, and Jackson Lake. He described the landscape as being under a pall of smoke from fires burning north of Jackson Lake and noted that in summer, smoke from forest fires was common in the mountains. The area's greatest fire year on record was 1879. Van Derver (*ca.* 1939) reported that much of Jackson

Hole was swept by fire in late August. Artist Thomas Moran witnessed the 1879 fires in the Teton Range and described widespread burning during August 25 to 27. In 1880 a large, fast-moving fire was observed by an English hunter camped on Jenny Lake (Grohman 1884).

The recurrent nature of fires in the region is suggested by Government Survey personnel in the 1870's who noted that burns covered by young tree growth were a common feature of the landscape (Bradley 1873; Hayden 1878).

The appearance of the landscape in the northern half of the study area around 1900 contrasted sharply with that of today. Brandegee (1899) commented:

> *It is only occasional that tracts of timber of merchantable size are found, and areas containing notable quantities of merchantable forest are few and limited. This condition appears to be simply and soley due to fires which have swept over the country so completely and persistently that scarcely any part has been entirely exempt from them, while nearly all portions have been burned again and again within a generation.... Under present conditions the tree-bearing regions as a whole decrease, while the aspen areas increase at the expense of those now producing conifers.*

Covering the timber preserves systematically, Brandegee found a mosaic of burns. Conifer stands in varying stages of succession ranged from a few acres to 4 or 5 square miles or even larger as indicated by fire scars sampled in recent years. For example, fire scars suggest an 1879 burn extended about 8 miles (5 km) along the south side of the Gros Ventre River from the Forest boundary to Miner Creek. An 1872 burn of comparable length appears to have covered the south side of the Gros Ventre River between Alkali Creek and Soda Creek.

Only fragmentary fire history is available for 1900 to 1930. Records for Yellowstone National Park suggest that 1900

11

was an extremely dry year with many fires, three of which were considered serious (Taylor 1969). The summer of 1910 was one of the most extreme fire years in recent history in Idaho, Washington, and Montana (Wellner 1970); the largest known fire on the Teton Division in 1910 was approximately 2,500 acres (1 012 ha) on the Cliff Creek drainage. In 1919, another extreme year, several thousand acres burned on the Jack Creek drainage in the Hoback Basin

Some indication of the frequency of early fires was obtained from 72 fire-scarred trees, primarily lodgepole pine, in the Gros Ventre River drainage. Wildfire was apparently equally prevalent in the 1700's and 1800's. Fires occurred on the Gros Ventre in every decade of the 1800's. Fire frequency was apparently highest in the 1840's, 1870's, and 1880's.

Good fire records kept on the Teton Division since 1931 have been invaluable in interpreting the area's susceptibility to wildfire. Through 1976, 1,023 fires have been suppressed. Only seven have burned 1,000 acres (405 ha) or more.

Location	Year	Acres	Hectares
Gravel Creek	1931	10,980	4445
Mosquito Creek-Taylor Creek	1934	5,500	2227
Fall Creek-Munger Mountain	1934	12,000	4858
Upper Yellowstone River	1935	1,000	405
Red Creek	1937	1,020	413
Mink Creek	1940	4,000	1619
Sheffield	1940	1,000	405

From 1931 through 1940, 21 fires burned more than 100 acres (40 ha), while from 1941 to 1951 none exceeded 100 acres (40 ha). Since 1951, only eight fires have ranged from 100 to 700 acres (40 to 283 ha). Since 1931, burning conditions have varied, not only from year to year, but also during a single season. As indicated by acreage burned and number of fires larger than 100 acres (40 ha), only during July 1931, September 1934, and August 1940 were conditions extreme enough to thwart suppression. "Fire" years since 1931 (40 or more fires/year) were: 1931 (72 fires), 1934 (40),

1935 (55), 1940 (40), 1953 (43), and 1974 (45). Low fire years were: 1936 (9), 1950 (4), 1951 (10), 1955 (9), 1965 (6), and 1972 (7). Periods of high fire danger are invariably brief and are abruptly terminated by cool weather, precipitation, or both.

Since settlement, the potential for fire spread has been reduced by yearly consumption of fine fuels by livestock grazing. The consumption of fine fuels has, in turn, contributed to the success of initial attack by fire suppression crews.

Climatic Fluctuations

Houston (1976) reconstructed the climate of Yellowstone National Park by summarizing climatological studies by several researchers. From 25,000 to 8,500 years ago, glaciers covered much of the landscape and mean temperatures were about 10.6° F (4° C) colder than at present. A warming trend ended the glacial period, culminating in the warmer, drier "Altithermal" period dated variously from 9,000 to 4,500 years ago. During the warmest part of the Altithermal, temperatures at snowline were 4.7° F (2.6° C) higher than at present (Richmond 1972).

Bray (1971) analyzed temperatures over the past 2,000 years by comparing various physical measurements such as glacial advances, drift ice off the coast of Iceland, freezing of the Thames River in England, successful crop harvests, and altitudinal changes in tree growth. These data indicate that, with some exceptions, temperatures during the first 3 or 4 centuries A.D. were probably similar to the 1930's. A period of general stability followed, then slight cooling around 600-700 A.D. From 900 to 1200 A.D., temperatures between 40° to 90° N. latitude were warmer than today and the warmest since the "Thermal Maximum" around 4,000 B.C. This warm period was followed by a fluctuating decline in temperatures that bottomed out around 1650-1700 A.D. Notable lows occurred in the 1430's, 1560's, 1590's, and especially the 1690's and early 1700's. Reversions to milder temperatures occurred in the late 1300's, the mid-to-late 1400's, par-

ticularly the early to mid-1500's and brief-ly in the 1630's and mid-1600's. After 1810, temperatures followed an upward trend. Notable warm periods occurred in the 1730's, around 1780, in the 1830's and 1870's, and especially in the 1930's. Exceptions to the warming trend occurred in the 1740's, around 1790, especially in the early 1800's, around 1850, in the 1890's, and around 1910.

Worldwide alpine glacial advances during the past 2,000 years were largely confined to between 1600 and 1900. Most occurred from 1700 to 1900, with a maximum from 1800 to 1850. Peak activity occurred during the Little Ice Age from 1700 to 1850. This sequence is particularly noteworthy as there was a lag between the time of lowest temperatures and maximum glaciation.

Since 1850, glaciers in the Wind River Range 30 airline miles (48 km) from the study area have receded. This corresponds to the observed worldwide retreat of glaciers, which was gradual until about 1920 then rapid (Mears 1972). The present episode of warming temperatures in the Northern Hemisphere began about 1920 (Mitchell 1970). Twelve glaciers in the Wind River Range have shrunk 7 to 41 percent since their maximums during the Little Ice Age (Dyson 1952).

Since about 1950, there apparently has been a slight reduction in world temperatures. Although some glaciers are no longer receding and others are advancing worldwide, observations and photographs by Finis Mitchell (personal communication 1977) have shown a general retreat since 1942 in the Wind River Range. Since 1952, the Dinwoody Glacier has retreated 0.3 mile (0.5 km).

The amount of warming necessary for glacial retreat need only be a small systematic change in climate (Bryson 1974). Similarily, glacial advances take place when accumulation is greater than melt by a tiny amount. Richmond (in Houston 1976) postulated that the climate during neoglacial advances may have been characterized by later springs, earlier falls, more cloudy weather, greater flow from springs, more water in streams, and more swampy ground. Plants requiring mesic conditions would obviously be favored under these circumstances.

Bray (1971) concluded that vegetation was sensitive to climatic change on the order of centuries and millennia. He states: "This sensitivity is in marked contrast to the usual failure to establish vegetation - climate relationships based on yearly or decadal means which has led some scientists to consider climatic change of little significance in interpreting vegetation dynamics." If one accepts this hypothesis, it follows that changes in plant communities most likely occurred on the most climatically sensitive sites. This possibility is discussed in volume II.

THE PHOTOGRAPHIC RECORD

This investigation has proved the old axiom "a picture is worth ten thousand words." Repeat photographs have allowed visual interpretations of the early landscape, how it is changing, and what may be expected in the future.

The photographic record has been arranged in three geographical sections that are vegetatively dissimilar. The northern section includes the Teton Wilderness and adjacent lands. A central section takes in the Gros Ventre River drainage, while a southern section includes lower Jackson Hole, the Hoback River drainage, and Teton Canyon. All photographs are on the Teton Division of the Bridger-Teton National Forest or closely adjacent lands except those in Teton Canyon, which are on the Targhee National Forest.

The paired scenes have been numbered consecutively; the original labeled "a" is on the left page and the retake labeled "b" on the right. Dates of the originals are as precise as possible. Estimated dates are considered to be accurate

within 5 years. Elevations to the nearest 100 ft (30 m) were determined from USGS quadrangles. Captions briefly describe important relationships and the changes observed. Causes of apparent changes are discussed in volume II. Scientific equivalents of common plant names used in the captions and elsewhere are in appendix II and III. The eight or more willow species in Jackson Hole are usually referred to collectively as "willow." The collective term "spruce" is used where the species is questionable.

Northern Section--

Teton Wilderness and Vicinity

INTRODUCTION

The northern section is represented by 27 plates in the Teton Wilderness 557,311 acres (225 632 ha) and adjacent areas within 3 miles (4.8 km) of the wilderness boundary (fig. 2). Elevations range from 6,900 to 12,165 ft (2 104 to 3 709 m). The eastern part of the wilderness is a high elevation, dissected volcanic plateau cut by steep-sided canyons. To the west are a series of ridges and valleys formed by uplifting and erosion of sedimentary beds.

The landscape is characterized by expanses of forest interspersed with open parks, meadows, and herblands. Lodgepole pine is the principal conifer below 9,000 ft (2 744 m). Douglas-fir grows on warmer slopes and ridges in the southern part of the wilderness. Engelmann spruce grows in moist valley bottoms, on north slopes, and in association with subalpine fir with increasing elevation. Whitebark pine often dominates above 9,000 ft (2 744 m). On drier sites it is sometimes associated with limber pine. Nonforested areas are largely comprised of herbaceous plants. Where soils are shallow or well drained, plant cover is sparse. Willow is often conspicuous along primary drainages and in large, moist meadows.

Major drainages include the Thorofare, Yellowstone, Buffalo Fork, and Snake Rivers. Runoff from these drainages fluctuates widely with seasons. Peak flows occur in early summer when high elevation snowpacks are rapidly melting. Most streams carry heavy loads of sediment during this period and immediately following high intensity summer storms.

Wildlife is an intregal part of the ecosystem. The elk herd which frequents Big Game Ridge and other high elevation summer range is of primary importance.

Man's influence on the Teton Wilderness has been restricted to hunting, fishing, trapping, camping, fire ignition and suppression, and limited livestock grazing. Fire suppression since the early 1900's has effectively kept all but a few fires from exceeding 1,000 acres (405 ha). With the exception of pack and saddle stock, livestock grazing is confined to portions of three cattle allotments covering 36,700 acres (14 858 ha) on the southern boundary. None of the photographs inside the wilderness are on cattle allotments. Past cattle grazing in localities pictured outside the wilderness has varied from moderate (plate 27) to incidental. Domestic sheep have never grazed in the wilderness.

Plates 1 to 13 show conditions on river bottoms and meadows at elevations of 6,800 ft to 8,100 ft (2 073 to 2 470 m). Plates 14 to 27 depict conditions on tall forb and alpine habitats from 7,500 ft to 10,100 ft (2 287 to 3 079 m).
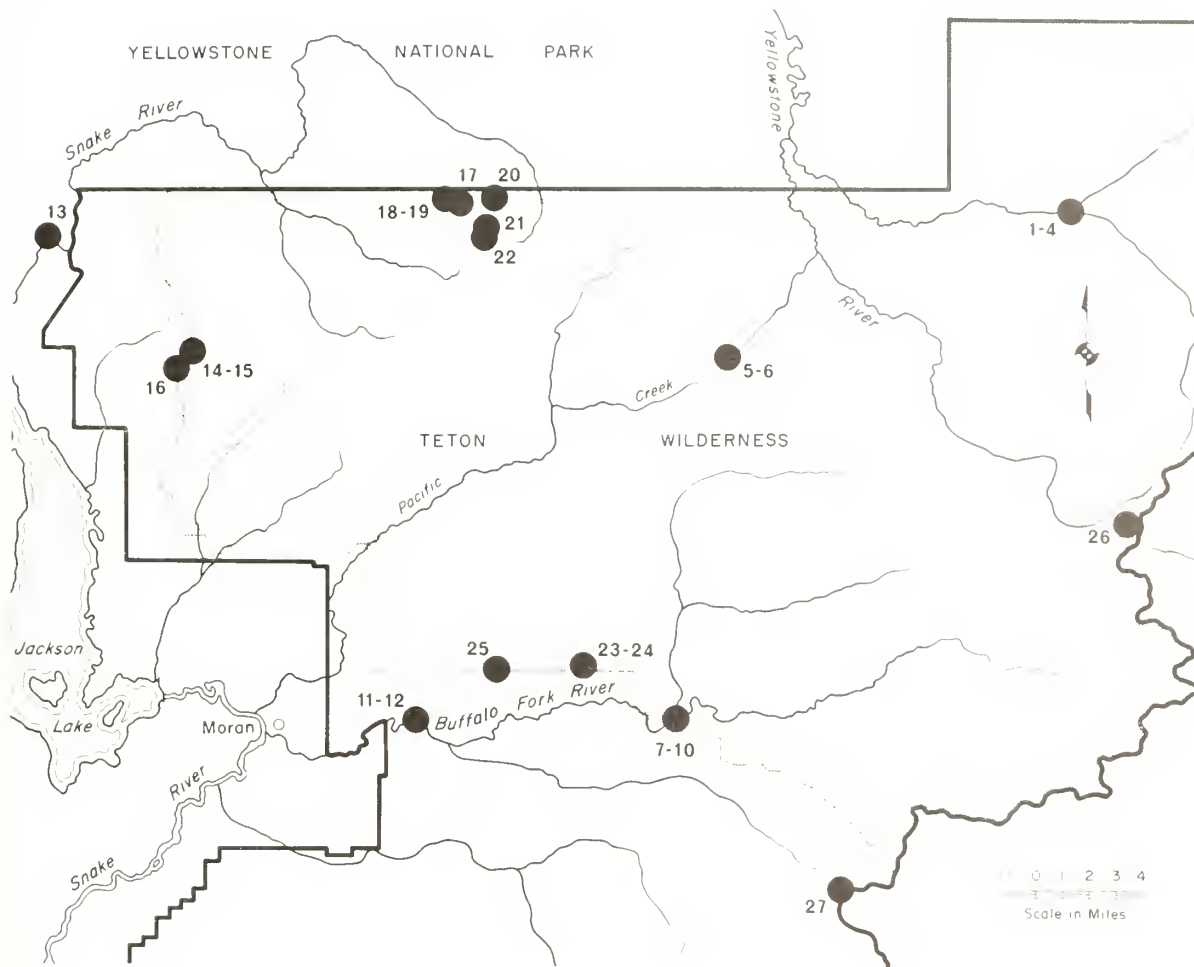
Figure 2.   Location of camera points in northern section.

Plate 1a   (September 16, 1893)

Elevation   8,000 ft (2 439 m)

Looking east up the Thorofare River from a point immediately above the outlet of Pass Creek. Dead trees are the result of a ground fire or insect epidemic. Arrow points to conifers in early succession on distant slope. The Thorofare River flows through the middle of the floodplain at right center. Shrubs in openings on far bank are willow.

U.S. Geological Survey (USGS) photograph 125 by T. Jaggar.

Plate 1b   *(September 18, 1968)*

75 years later

Lodgepole pine, Engelmann spruce, and subalpine fir have regenerated and put on added growth. Little evidence of insect damage can be seen. Note the heavy conifer growth on far slope which was in early succession in accompanying plate. Willow on opposite bank has been replaced by conifers. The river has swung south and now runs along the far bank. Arrow points to patch of conifers growing on site which was occupied by river 75 years ago.

Plate 2a   *(September 16, 1893)*

Elevation   8,000 ft (2 439 m)

A southwest view down the Thorofare River as seen from a position just east of the outlet of Pass Creek. Dead trees appear over the entire area. Shrubs on flood plain below are willow, while mountain big sagebrush predominates on slope in foreground.

USGS photograph 126 by T. Jaggar.

Plate 2b   *(September 18, 1968)*

75 years later

Camera was moved forward some 40 feet to avoid conifers which now block former scene (inset). Rock in foreground identifies original camera position. Timber stands are more dense. Willows below were removed by shift in channel of Pass Creek. Mountain big sagebrush is less dense in foreground (not shown) than in Plate 2a.

Plate 3a   *(September 16, 1893)*

Elevation   *8,000 ft (2 439 m)*

The camera faces northwest across Pass Creek just above its outlet. Shrubs on far bank and around spring are willow. Distant timber stands include a high incidence of dead trees.

USGS photograph 127 by T. Jaggar.

Plate 3b   (September 18, 1968)

75 years later

Pass Creek has swung west, removing much of the willow. An increase in conifers is evidenced by lodgepole pine growth in foreground. Openings on far slope retain their former appearance.

Plate 4a   *(September 16, 1893)*

Elevation   *8,000 ft (2 439 m)*

The camera faces northeast up Pass Creek from a position at its outlet. Camera points for plates 1 and 2 are on river terrace off photo on right. That for preceding plate is on ridge at left-center. Willows and lodgepole pine predominate on flood plain in midground. Debris and wide flood plain are indicative of heavy spring runoff. Prostrate aspen persist on near slope, which is composed of coarse gravels and boulders (arrow). Timber stands have a high incidence of dead lodgepole pine.

USGS photograph 128 by T. Jaggar.

Plate 4b   *(September 18, 1968)*

75 years later

A portion of the willow community on extreme left has disappeared as a result of a shift in the stream channel. Willows that remain on flood plain are of reduced growth form and in competition with lodgepole pine, which have increased. The aspen indicated by arrow in plate 4a are now obscured by lodgepole pine. Their growth continues to be of a prostrate form comparable to early scene. Timber stands are more thrifty, with fewer snags.

Plate 5a   *(August 20, 1921)*

Elevation   *8,100 ft (2 470 m)*

Looking south in the vicinity of Two Ocean Meadow. Vegetation in foreground is primarily sedges and willows. Willow border far edge of meadow. Tree cover includes Engelmann spruce, subalpine fir, and lodgepole pine. Dead conifers are conspicuous throughout the stand.

Yellowstone National Park photograph by Charles Adams.

Plate 5b   *(September 12, 1972)*

51 years later

Willow density has increased in foreground and decreased on the far edge of meadow. Conifer cover on far slopes has increased significantly and a majority of dead trees visible in 1921 have since fallen to ground.

Plate 6a   *(August 21, 1921)*

Elevation   *8,100 ft (2 470 m)*

The camera faces southwest across Two Ocean Meadow toward outlet of Two Ocean Creek. Meadow vegetation is primarily sedges, perennial grasses, and willow. Lodgepole pine, Englemann spruce, and subalpine fir covers far slopes. Many dead trees are evident.

Yellowstone National Park photograph by Charles Adams.

Plate 6b   *(September 12, 1972)*

51 years later

Willow appear to be more dense in foreground. Lodgepole pine have invaded the edge of meadow. Most of the dead trees on far slope have fallen to the ground and the conifer cover is more dense.

Plate 7a   (Fall, 1893)

Elevation   7,100 ft (2 165 m)

Looking east at Owen Wister camp on Buffalo Fork River about one-quarter mile from confluence of the north and south forks. The sparse ground cover in foreground and midground is comprised of herbaceous species and mountain big sagebrush. The Buffalo Fork cannot be seen, but flows in front of large willows on left. Dead lodgepole pine in distance were killed by wildfire. Scarred trees suggest two fires, the most recent occurring in the late 1800's.

Owen Wister photograph, courtesy of his daughter, Mrs. Walter Stokes.

Plate 7b   *(September 15, 1975)*

82 years later

A closed stand of mountain big sagebrush now occupies foreground. Site has been enhanced since 1893 by flooding, which deposited accumulative sediments. Conifer cover has increased markedly.

Plate 8a   *(Fall, 1893)*

Elevation   *7,100 ft (2 165 m)*

Camera point is a short distance to right of preceding plate. View is northeast towards Terrace Mountain. Young lodgepole pine and scattered mountain big sagebrush interrupt the otherwise smooth, grassy plain in foreground. The Buffalo Fork River can be seen at left of tent, while willow of large growth form occupy far bank at right.

Owen Wister photograph, courtesy of his daughter, Mrs. Walter Stokes.

Plate 8b   (September 15, 1975)

82 years later

Camera was moved forward some 40 feet to avoid lodgepole pine that obstructed original view. Jacket (arrow) approximates position of left tent corner. The increased density of mountain big sagebrush evident in plate 7b is emphasized in this scene. The Buffalo Fork River has swung south during the past 82 years, cutting away much of the bank and removing the willow. Conifers have increased markedly and many lodgepole pine have been killed by mountain pine beetle.

Plate 9a   (Fall, 1893)

Elevation   7,100 ft (2 165 m)

View is southwest down Buffalo Fork River in opposite direction of preceding plate. Fire scars on lodgepole in foreground show the stand had burned at least once in the 1800's. Stumps suggest this was a favored campsite. Distant open slopes show the effects of wildfire.

Owen Wister photograph, courtesy of his daughter, Mrs. Walter Stokes.

Plate 9b   (September 15, 1975)

82 years later

Camera is positioned approximately 30 to 40 feet behind and 3 to 5 feet below original station, which was removed by a shift in river channel. This scene typifies the dramatic increase and growth of lodgepole pine on sites burned in earlier years.

Plate 10a   (Fall, 1893)

Elevation   7,100 ft (2 165 m)

Camera point is just beyond tent in plate 7a and view of distant slopes is quite similar. In foreground, the Buffalo Fork River swings in a wide meander, while willow of large growth form grow on opposite flood plain. Near slopes show the effects of wildfire in the late 1800's.

Owen Wister photograph, courtesy of Western History Department, University of Wyoming.
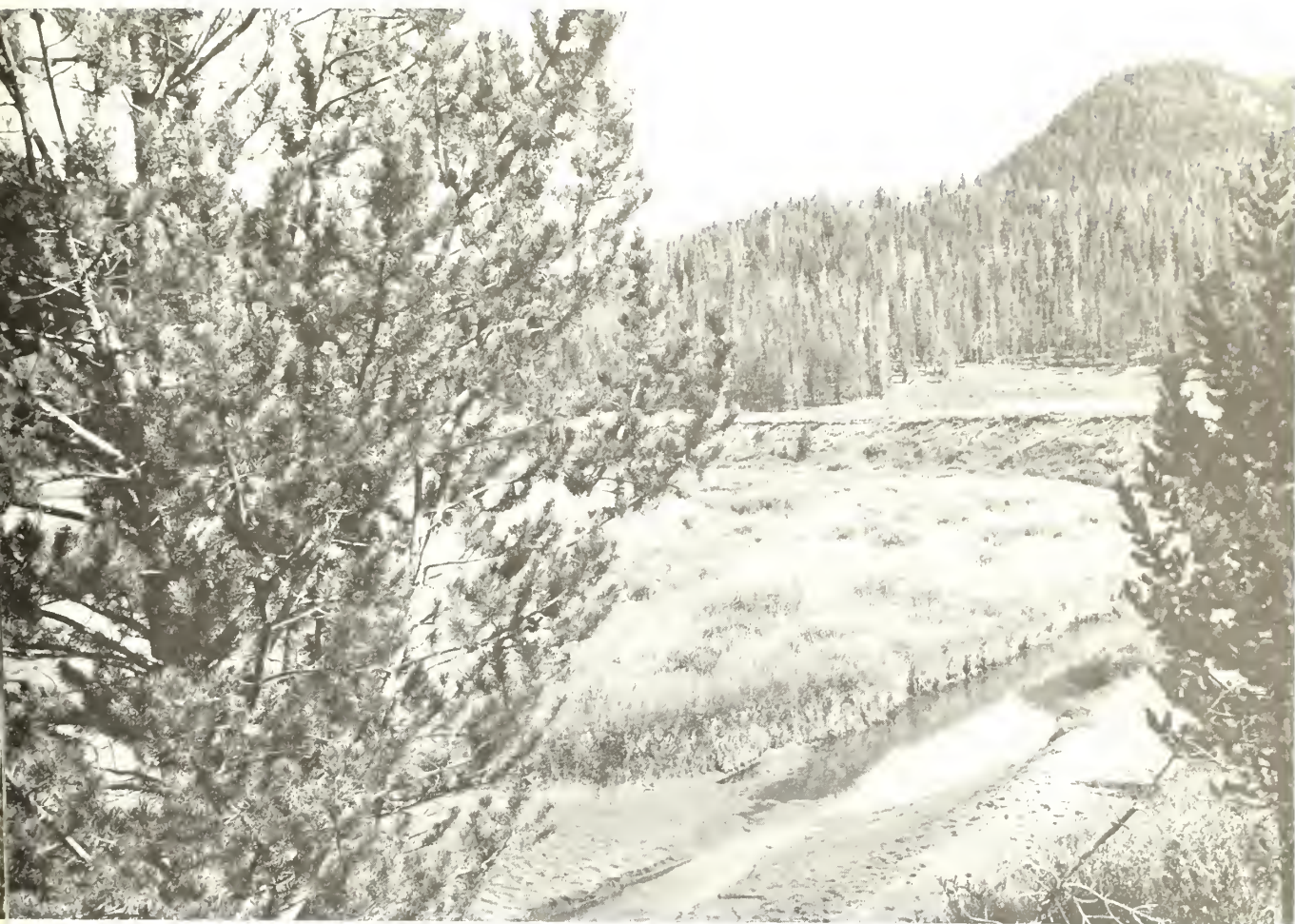
Plate 10b   *(September 15, 1975)*

82 years later

Lodgepole pine regeneration screens much of former view. The river now flows to the north, with the channel situated where willows were growing in 1893. With this shift, the former channel has been bypassed. It presently carries water only during floodstage. Accumulative sediments support a sedge-grass-willow complex. Willows are of smaller growth form than those in early scene. The lodgepole pine stand in distance contains many trees killed by mountain pine beetles.

Plate 11a   (Fall, 1893)

Elevation   6,800 ft (2 073 m)

Looking east up the Buffalo Fork River from a point about 1 mile southeast of the Heart Six Ranch. Bush cinquefoil is the predominant shrub in foreground. The large shrubs in sunlight and on flood plain are various species of willow. Scattered mountain big sagebrush shrubs can be seen on near slope on left (open arrow). Trees on flood plain are almost entirely cottonwood. Aspens occupy north slope of Burro Hill in distance on right.

Owen Wister photograph, courtesy of Western History Department, University of Wyoming.

Plate 11b   (September 8, 1969)

76 years later

In 1893 willow foliage was comprised of accumulative growth, whereas in 1969 current growth makes up a major portion of these shrubs. Note the long leaders. Sagebrush density has increased markedly on near slope. Cottonwoods on flood plain have largely been replaced by spruce. A channel change removed willow from opposite bank, while in distance depositional areas are now occupied by willow. Aspen cover on Burro Hill has deteriorated.

Plate 12a   (Fall, 1893)

Elevation   6,800 ft (2 073 m)

From the same camera position as preceding plate, the view is southeast across the Buffalo Fork River flood plain. The south slope of Burro Hill is on left and Hatchet Ranch vicinity in distance. Cottonwoods occupy far edge of flood plain, while willow dominate the scene.

Owen Wister photograph, courtesy of Western History Department, University of Wyoming.

Plate 12b   *(September 8, 1969)*

76 years later

Willow now occupy site in right-foreground formerly covered by low growing vegetation. Except for increased bank cutting, the river channel has not changed significantly. As a whole, willow distribution and height appears similar to that in early scene. In distance, cottonwoods are being invaded by spruce.

Plate 13a (September, 1896)

Elevation 7,100 ft (2 165 m)

Looking northwest across Soldier Meadow some 2 miles south of the south entrance to Yellowstone Park. The large contingent of men includes the William Seward Webb hunting party accompanied by General Coppenger and 50 soldiers. The meadow in foreground has a well-utilized appearance, having been grazed by horses and mules. Dead lodgepole pine appear to be the result of attacks by the mountain pine beetle. Cabins in distance were quarters for U.S. Army personnel assigned to patrol Yellowstone Park and adjacent country.

F. Jay Haynes photo, courtesy of Samuel B. Webb.

Plate 13b   *(October 4, 1968)*

72 years later

The camera is positioned several feet lower, since the hill from which early scene was photographed had been removed to accommodate road. Lodgepole pine have increased on margin of meadow. A loss of trees to pine beetles has altered the skyline at right. The site formerly occupied by cabins is now forested. Willow on far edge of meadow at right are of smaller growth form.
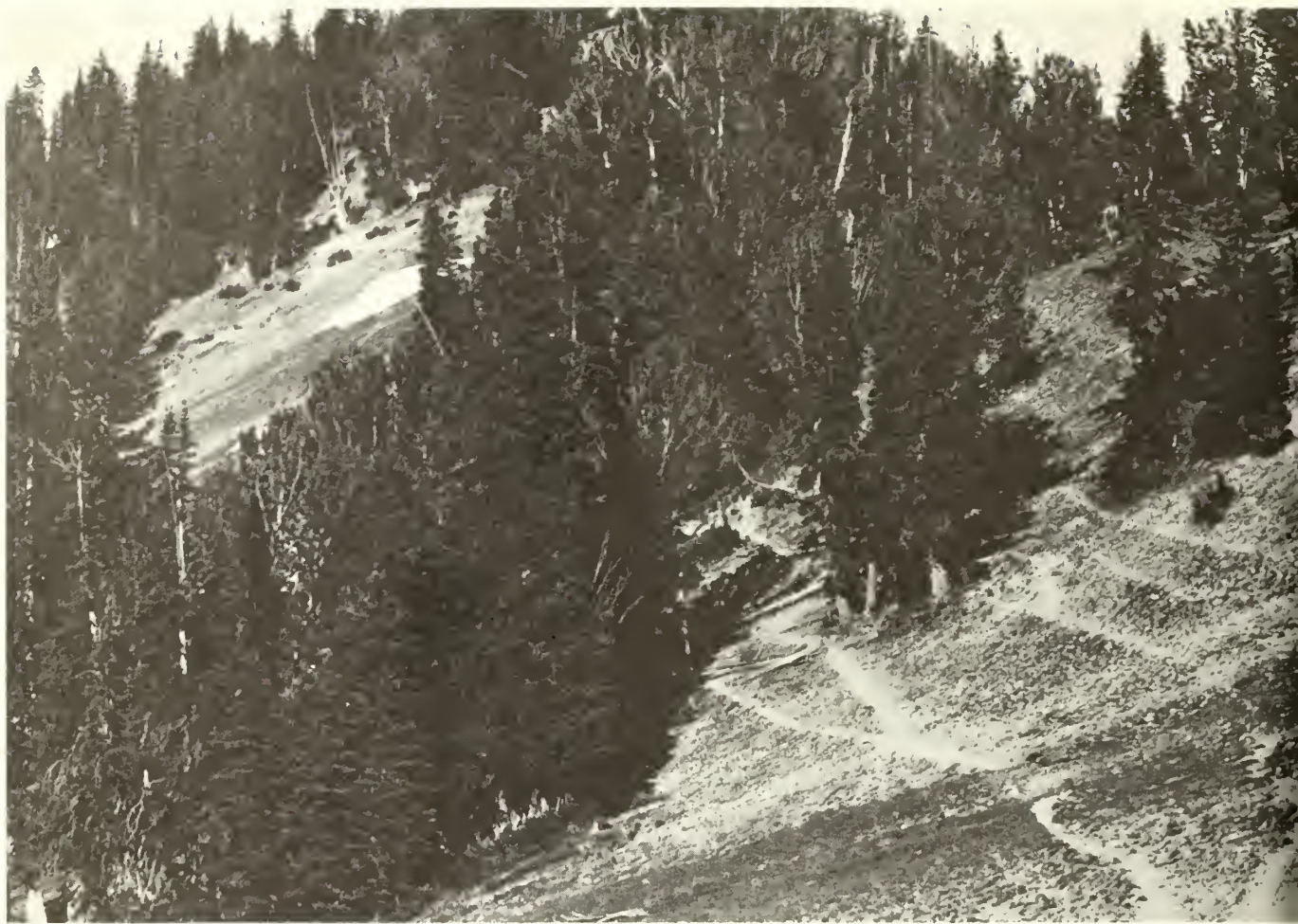
Plate 14a   *(July 24, 1928)*

Elevation   *9,500 ft (2 896 m)*

View is south from head of Rodent Creek near Wildcat Peak. Ground cover consists of herbaceous species. The Brown's Meadow-Coulter Creek Trail is on right. A network of subsidiary trails reflect the high occurrence of summering elk in 1928. Several conifers show the effect of mountain pine beetle attacks.

Fish and Wildlife Service photograph 22-WB-34027 by Olaus Murie, courtesy National Archives and Record Service.

Plate 14b   *(August 28, 1969)*

41 years later

A difference in lighting, season, and lenses limits value of photo in determining trend in herbaceous vegetation. Mountain lupine and longleaf arnica are the conspicuous forbs. Other species common to the site include western yarrow, mountain dandelion, thickleaf aster, and sedges. A pronounced increase in the regeneration of subalpine fir is evident in midground. A long-term decline in the summer elk population is suggested by fill in of plants on former trails. Historically, the Brown's Meadow-Coulter Creek Trail has received infrequent human use.

Plate 15a   (July 24, 1928)

Elevation   9,300 ft (2 835 m)

Looking southeast from slopes of Wildcat Peak across headwaters of Pilgrim Creek. Tall forbs comprise the predominant ground cover, while whitebark pine and subalpine fir are the primary conifers. This locality has been historic elk summer range and was described by Olaus Murie in 1928 as a summer elk feedground.

Fish and Wildlife Service photograph 22-WB-34028 by Olaus Murie, courtesy of Mrs. Murie.

Plate 15b   *(August 28, 1969)*

41 years later

Ground cover looks more dense than in previous photo. This contrast is partly explained by a seasonal difference in plant development. Gully system in foreground appears comparable to early scene. Conifers show increased growth in midground. Arrow points to old slump, which has become well vegetated.

Plate 16a   (August 2, 1928)

Elevation   9,100 ft (2 774 m)

Historic tall forb elk summer range on extreme west end of Wildcat Ridge at headwaters of Pilgrim Creek. Vegetation patterns vary widely on this southeast exposure, being characteristic of high elevation summer ranges in the Teton Wilderness. Olaus Murie described this locality as a favorite elk summer range in 1928.

Fish and Wildlife Service photograph 22-WB-34048 by Olaus Murie, courtesy of National Archives and Record Center.

Plate 16b   (August 27, 1969)

41 years later

*Taken at midday, this scene lacks shadows and corresponding contrast of original photo.
Nonetheless, it is evident that variable vegetal patterns persist and are quite comparable to those 41
years ago. Predominant species include thickstem aster, big mountain brome, showy stickseed and
tall larkspur. Elk still prefer this locality as summer range.*

Plate 17a   (August 19, 1915)

Elevation   9,600 ft (2 927 m)

The view is northwest at headwaters of the middle fork of Wolverine Creek on Big Game Ridge. Elk in foreground are grazing small subalpine meadow on historic elk summer range. Sparse plant cover on adjacent slopes is comprised of herbaceous species. The steep, bare slopes are snowbank sites. Snags in distance resulted from a wildfire that occurred about 1885.

Fish and Wildlife Service photograph 22-WB-16073 by Vernon Bailey, courtesy of National Archives and Record Center.

Plate 17b   *(August 13, 1969)*

54 years later

The herbaceous plant cover is more dense. This is particularly apparent on meadow edge where skyline bluegrass has thickened (closed arrow) and on snowbank sites where spreading community of longleaf arnica is more conspicuous (open arrow). Growth of whitebark pine and subalpine fir contrasts sharply with the earlier photo.

Plate 18a   (August 19, 1915)

Elevation   9,600 ft (2 927 m)

Westerly view of herbland vegetation and slope dissected by numerous deeply eroded draws at head of west fork of Wolverine Creek. Camera point is about 1 mile west of previous plate. The photographer took this scene to document elk occurrence. Though obscure, some 55-60 elk are present.

Fish and Wildlife Service photograph 22-WB-B16070 by Vernon Bailey, courtesy of National Archives and Record Center.

Plate 18b   *(August 19, 1971)*

56 years later

Camera position may be lower than original. Conifers are more conspicuous, while changes in herbland vegetation are comparable to plate 17b. Improvement in plant cover is particularly noticeable on near snowbank site (arrow).

Plate 19a   *(August 19, 1915)*

Elevation   *9,800 ft (2 988 m)*

A northwest view from Big Game Ridge into a tributary of the Snake River. Scene is just outside the Teton Wilderness in Yellowstone Park. The darker vegetation is herbaceous plants. Note the occurrence of young conifers in midground, which are comparable in growth stage to those in plates 17a and 18a.

Fish and Wildlife Service photograph 22-WB-16076 by Vernon Bailey, courtesy of National Archives and Record Center.

Plate 19b   *(August 13, 1969)*

54 years later

As in previous two plates, herbaceous growth patterns appear more extensive than in 1915. Talus slopes, sites which support late-melting snowbanks and ridges continue to support sparse ground cover. In midground, conifers have increased in density and height.

Plate 20a   *(August 27, 1935)*

Elevation   *8,900 ft (2 713 m)*

The camera faces northwest from a position along the Yellowstone Park-Teton Wilderness "boundary trail" on northeast side of Big Game Ridge. Plant cover in foreground consists of herbaceous species. Bare interspaces between plants are the result of soil brought to the surface by pocket gophers. Subalpine fir dominate midground. Distant slopes in Yellowstone Park are prime elk summer range.

Yellowstone National Park photograph 9283-4 by Christensen.

Plate 20b   *(August 21, 1973)*

38 years later

Alignment is accurate, but camera placement is farther back than before. Note position of snag, with reference to skyline in accompanying plate. Density of herbaceous vegetation in foreground was increased. This, however, is exaggerated, because pocket gophers continue to perpetuate many bare interspaces, which are occupied by low-growing annuals. This scene demonstrates the widespread increase in the growth of subalpine fir on Big Game Ridge.

Plate 21a   (September 2, 1928)

Elevation   9,400 ft (2 866 m)

The camera faces southeast towards Mink Creek from the east side of Big Game Ridge. The more productive slope in foreground supports a good herbaceous cover, while plants on near slope are sparse because of less favorable site. Tree cover is largely whitebark pine.

Fish and Wildlife Service photograph 22-WB-34073 by Olaus Murie, courtesy of National Archives and Record Center.

Plate 21b   *(September 16, 1969)*

41 years later

No appreciable changes in herbland vegetation are evident. Gully at lower-center shows no change in headcutting. At left, several whitebark pine have been killed by mountain pine beetles, while many others along with subalpine fir have regenerated since 1928. The open slopes in distance were burned in the Mink Creek fire of 1940.

Plate 22a   *(September 21, 1928)*

Elevation   *9,500 ft (2 896 m)*

Big Game Ridge approximately 1 mile north of pass between Wolverine Creek and Fox Creek. Bare soil in foreground is pocket gopher mounds and winter casts. Conifers are mostly subalpine fir and whitebark pine.

Fish and Wildlife Service photograph 22-WB-34070 by Olaus Murie, courtesy of National Archives and Record Center.

Plate 22b   *(September 16, 1969)*

41 years later

Density *of herbaceous plants in foreground has increased. Primary species include subalpine needlegrass, skyline bluegrass, cloud sedge, thickstem aster and lupine spp. Ponds such as the one pictured are frequented by elk. Some conifers have died, while a majority have survived and grown substantially. The Mink Creek burn of 1940 can be seen in distance.*

Plate 23a   *(September, 1878)*

Elevation   *7,500 ft (2 287 m)*

The camera faces southwest from a position high on the ridge overlooking Turpin Meadow. Rosie's Ridge is immediately beyond the Buffalo Fork River and Leidy Mountain is in distance. Lodgepole pine and Douglas-fir dominate the slopes below. Profuse downfall at lower-right attests to past wildfire. Arrow points to river meander which has been largely bypassed as a result of a channel change.

USGS photograph 57-HS-605 by William H. Jackson, courtesy of National Archives and Record Center.

60

Plate 23b   *(September 4, 1968)*

90 years later

Conifers on slopes below have increased in d[...] size. The Douglas-fir snag at left has largely disappeared and a new tree, which obs[...] of Turpin Meadow, now dominates foreground. The old river meander continues to car[...] volume of water (closed arrow), while another 1878 meander has been bypassed and the area is now well vegetated (open arrow). As a whole, the flood plain shows a significant increase in vegetation, particularly lodgepole pine and spruce.

Plate 24a   (September, 1878)

Elevation   7,500 ft (2 287 m)

The scene is west towards the Tetons from a point immediately below previous plate. Mt. Randolph is in distance on extreme right. In foreground, Dr. F. V. Hayden and companions view landscape. The surrounding vegetation has been dusted by an early season snowstorm. The extent of burn noted in previous plate is better appreciated in this scene.

USGS photograph 57-HS-1216 by W.H. Jackson, courtesy of National Archives and Record Center.

Plate 24b   (September 4, 1968)

90 years later

In foreground, mountain big sagebrush is more dense and composites less conspicuous. The Douglas-fir snag at right of Bill Jackson has largely disintegrated. An increment sample from large Douglas-fir in center of photo showed 296 rings, thus indicating the tree to exceed 300 years of age. This tree and others in vicinity were scarred by past fires. The old burn, conspicuous in the 1878 scene, is now covered by a maturing conifer forest. Tall forb openings on distant slopes show no apparent change. The camera point for plate 25 is in large opening at upper right.

Plate 25a   *(About 1906)*

Elevation   *8,000 ft (2 439 m)*

The camera faces sontheast from high on the slopes of Mt. Randolph. Turpin Meadow is in center of photo and the Buffalo Fork River is on right. Camera points for plates 23 and 24 are behind tree on left. The early stage of conifer development on burn suggests a later burn than that pictured in plate 24a. Aspen in early succession occupy site near patch of snow at left-midground.

Ben Sheffield photograph, courtesy of Grand Teton National Park.

Plate 25b   *(August 1, 1968)*

62 years later

The ground cover in foreground is composed of herbaceous plants. Predominant species include perennial grasses, mountain lupine, arrowleaf balsamroot, helianthella spp., thickstem aster, horse-mint, and thick-stem groundsel. The larger subalpine fir which occupied foreground in early scene has since died and the smaller tree now dominates scene. Lodgepole pine, subalpine fir, and Douglas-fir are growing profusely on old burn. Many lodgepole pine have reached maturity and have been killed by mountain pine beetles. The aspen stand has also reached maturity (arrow). Meander changes noted in plate 23b are also evident in this scene.

Plate 26a   (September 4, 1893)

Elevation   10,100 ft (3 079m)

Looking southeast from Buffalo Plateau on Continental Divide at headwaters of the Marsten Fork tributary of South Fork Shoshone River. The small lake drains into Lost Creek and South Fork of Buffalo River. Late season snowbanks attest to the harsh environment at this elevation where the growing season is about 5 weeks. The low-growing dark vegetation in midground is sedge. Arrow points to willow community on knoll in distance.

USGS photograph 117 by T.A. Jagger.

Plate 26b   *(September 10, 1968)*

75 years later

The sparse plant cover in foreground is predominately sedges in association with mountain dandelion, varileaf cinquefoil, bluegrass spp., Eschscholtz butter cup, and parsley spp. Though not readily distinguishable because of film contrast and differences, there has been a significant increase in sedge over the past 75 years. Examples of sedge plants not present in early scene are indicated by arrows. Soils are silt loam derived from breccia parent material. Close comparison of rocks in the two scenes indicates amount of soil loss. The willow community has decreased in density. A gully at upper left appears to be headcutting, while the lower portion is stable and more uniformly vegetated. Perennial snowbanks are smaller sized. The small patches of snow are from an early season storm.

Plate 27a   *(August, 1921)*

Elevation   *9,700 ft (2 957 m)*

Looking east towards Togwotee Pass from a position about one-quarter mile south of Highway 26-287. The occasion is the dedication of the Togwotee Highway completion. A herbaceous plant cover occupies foreground. The only species readily identifiable is showy elkweed. Conifers are whitebark pine, Douglas-fir, and subalpine fir.

F. J. Haynes photograph, courtesy of Wyoming State Archives and Historical Department.

Plate 27b   (August 1, 1968)

47 years later

A log worm drift fence, which marks boundary of Shoshone and Bridger-Teton National Forests (and cattle allotments), now bisects scene. The old highway has been long abandoned, being used only by hunters and cattlemen. The foreground continues to support an excellent ground cover. Representative species include western yarrow, common dandelion, lupine spp., fleabane spp., bluegrass spp., carex, mountain timothy, varileaf cinquefoil, thickstem groundsel, mountain sorrel, elephanthead pedicularis, and showy elkweed. Showy elkweed is not as conspicuous as in 1921. An increase in mountain big sagebrush is indicated on slopes in midground, while whitebark pine are more dense.

CONCLUSIONS

The 27 plates representing the Teton Wilderness and vicinity cover a maximum period of 97 years. Vegetative changes vary considerably, depending upon site potential and time since disturbance. Some photographs show pronounced changes, while others show none. The more noteworthy changes include:

1. Increased density and growth of conifers.

2. Reduction in height and decline in distribution of willow.

3. Increased in size and density of mountain big sagebrush.

4. Increase in density of herbland and alpine vegetation.

5. No observable change in the rate of geologic erosion.

6. Striking changes in stream channels.

The most extensive change is the increased density and growth of coniferous species at all elevations. More subtle, perhaps, has been the invasion of the drier margins of meadows by coniferous forest (plates 5, 6, 13). Changes on valley bottoms and along tributaries are pronounced. Spruce are replacing cottonwoods (plate 11), and lodgepole pine are increasing on flood plains and alluvial soils (plates 1, 4, 7). The degree of change is often striking (plates 9 and 23).

The current appearance of coniferous species depends largely upon the amount of time since the last fire. Plate 15 shows older stands of spruce, subalpine fire, and whitebark pine that apparently had not been burned for many years. In 1969 some new trees were evident, while those that persisted became large. A similar situation is illustrated by plates 21, 22, and 27 where the tree cover is principally whitebark pine. As in plate 15, new trees have invaded openings, but the overall change is not striking.

Pronounced changes have occurred in localities which were in an early stage of succession when originally photographed (plates 17, 18, 24, 25). Plates 17 and 18 were first taken about 30 years following fire. Accelerated growth over a 54-year period accounts for the marked contrast. The modern scenes in plates 24 and 25 contrast sharply with those 65 to 90 years ago.

The increased age of conifers has made them vulnerable to attacks by forest insects. For example, lodgepole pine in plates 8, 10, and 25 have developed to where they are susceptible to heavy attack by mountain pine beetles. Evidence of earlier insect activity is suggested in plates 1 through 4.

With few exceptions, willows have changed significantly since the late 1800's. Of particular interest is a reduction in height and change in growth form (plates 4, 10). On some valley bottoms the height of willow is similar to that of earlier years, but much of the canopy now consists of current growth (plates 11 and 12). Willow has declined where it is competing with conifers (plates 1, 4). Stream channel changes have also caused losses of both willow and other vegetation (plates 1-4, 7-8). This loss is often compensated by establishment of new plants in the old channels (plates 10,11).

The general trend of mountain big sagebrush has been toward increased growth and density (plates 3, 7-9, 11, 24). However, a decrease in density is suggested in plate 2.

Changes in tall forb vegetation have been less pronounced. Plant density lacked uniformity, thereby producing uneven patterns of growth. Snowbank sites have historically been sparsely vegetated as have sites with shallow, well-drained soils (plates 16-19). More productive sites apparently did not change (plate 21). The overall trend of tall

forb vegetation appears to be toward increased plant density. This is particularly evident on the thinner soils (plates 19, 26) and snowbank sites (plates 15, 17, 18). Plate 25 suggests that on sites capable of carrying fire the composition of herbland vegetation has varied depending upon the successional stage. At the turn of the century this site was predominantly grasses, whereas forbs predominate today.

High elevation watersheds (plates 14-25) show no observable change in gully patterns. Geologic erosion has continued, but not at an accelerated rate. Sediments are transported from slopes and down gully systems as they have been for centuries. All evidence points to a state of dynamic equilibrium.

Lateral movement of stream channels has been occurring over the centuries, but the rate of change is often underestimated. The photographs dramatically show the dynamic nature of this process. Great quantities of material are washed away from stream banks (plates 3-4, 8-9, 11), which takes the stream on a new course. With reduced flows, sediments are deposited in the old channels that in time become vegetated (plate 10).

Central Section--

Gros Ventre River Drainage

INTRODUCTION

The 35 plates in this series depict conditions on the Gros Ventre game winter range at elevations from 7,000 to 8,400 ft (2 143 to 2 561 m) (fig. 3). Semiarid conditions prevail on southerly exposures. Soils are droughty and vegetation is characteristic of a drier climate. Northfacing slopes and bottom lands are quite productive.

Lodgepole pine or Douglas-fir are the primary conifers near the camera points. Aspen stands are widespread and of advanced age. Willows are the principal shrubs along streams and on wet soils. Mountain big sagebrush dominates openings.

Elk have historically wintered on the Gros Ventre River drainage because of southerly exposures and low snow accumulation. Since the early 1960's, most wintering elk have been fed hay at Wyoming Game and Fish Department feedgrounds. Moose have increased dramatically during the past several decades. The area is also winter range for bighorn sheep.

Suppression of wildfires has allowed the vegetation to develop toward climax. Since 1930 only one fire has reached 1,000 acres (405 ha).

Cattle have grazed the Gros Ventre River drainage since 1900. This use has been restricted primarily to spring, fall, or both, in those localities photographed.

Allowing for deviations on tributaries, the order of plates is progressively west to east up the Gros Ventre River.
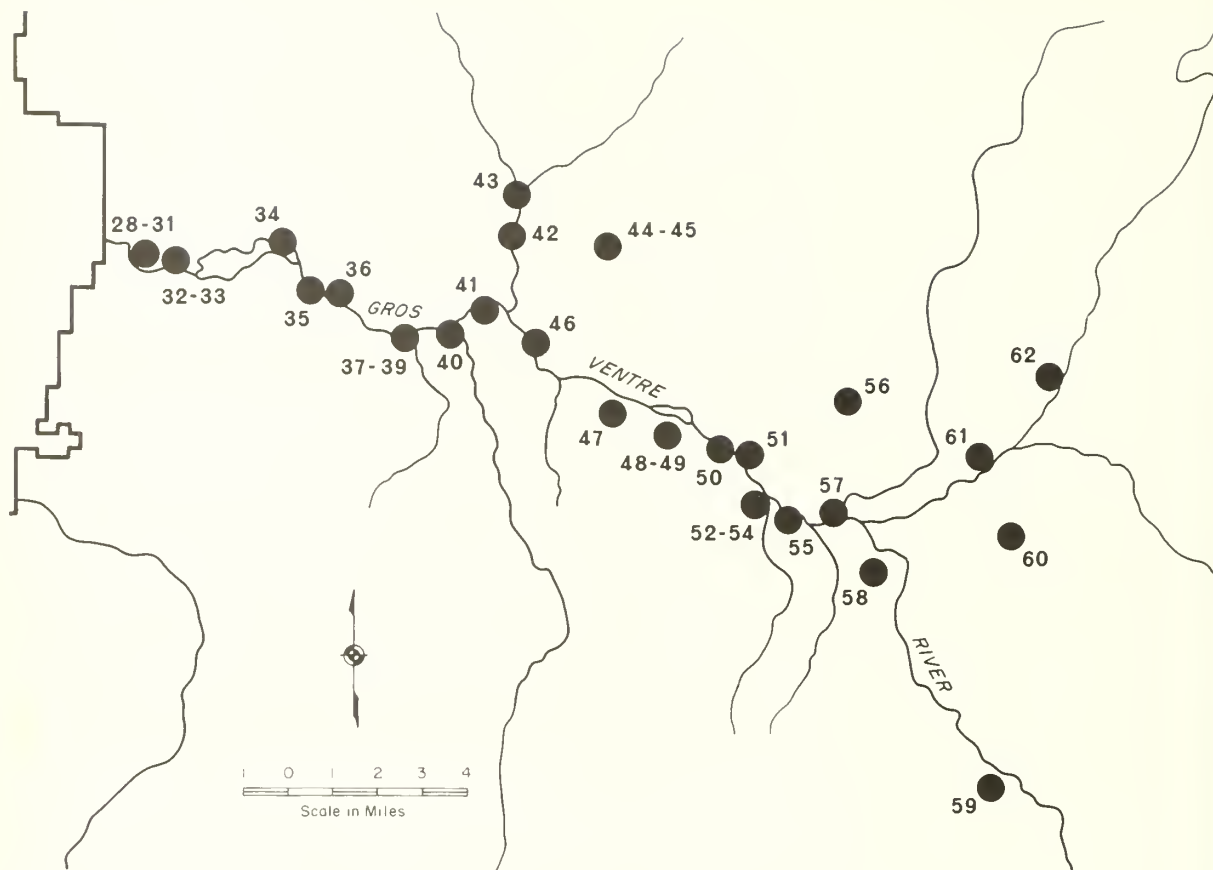
Figure 3.   Location of camera points in central section.

Plate 28a   (1899)

Elevation   7,100 ft (2 165 m)

A westerly view of the Gros Ventre River from Turpin Hill. Location is north of a point on Gros Ventre Road, 1.4 miles from the Bridger-Teton Forest - Grand Teton Park bonndary. Vegetation is largely in early succession some 20 years following the wildfire of 1879. Ground cover on near slope is an association of half-shrubs, herbaceous species, and a scattering of monntain big sagebrush on a conglomerate formation. Based on present composition, a few widely dispersed serviceberry and snowberry shrnbs of low-growth are also present. Aspens at left and right midgronnd are in early succession. Note even-aged aspen (closed arrow) on terrace across river. Bitterbrnsh and serviceberry shrubs prevail on deeper soils between sparsely vegetated areas on southeast exposnre in distance (open arrows). Haze obscures Teton Range in distance.

Stimson photograph, courtesy of Wyoming State Archives and Historical Department.

Plate 28b   *(July 28, 1971)*

72 years later

Vegetation is in advanced succession following some 92 years of fire exclusion. The open half-shrub and herbaceous plant association in foreground is now dominated by mountain big sagebrush. Douglas-fir and limber pine are also invading the locality. Aspens in near stands have matured. Seral aspen on far terrace have largely been replaced by Douglas-fir. Bitterbrush and serviceberry shrubs on southeast exposure have increased in growth form, as have nearby limber pine. The associated ground cover appears to have improved.

Plate 29a   (1899)

Elevation   7,100 ft (2 165 m)

Southeasterly view of the Gros Ventre River valley from a position slightly east of preceding plate.
Young aspens dominate vegetation in foreground. Near shrubs have a hedged appearance. Ground
cover on southwest facing slope in midground is sparse. Parent material is continuation of con-
glomerates pictured in plate 28a. Trail was historic travel route. Fire scars suggest foreground and
far slopes at right burned in 1879. Note the numerous fire-killed snags and response of aspen,
willow, and other shrubs on lower slopes that have burned.

Stimpson photograph, courtesy of Wyoming State Archives and Historic Department.

Plate 29b   *(July 28, 1971)*

72 years later

A maturing aspen stand completely screened view, making it necessary to move camera about 50 ft right to an elevated position. Ground cover on near slope remains sparse. Primary plant species are horsebrush, rabbitbrush, fringed sagebrush, grasses, and forbs. Timber-producing sites on far slopes are now dominated by Douglas-fir and lodgepole pine. Upper Slide Lake below, formed following the Gros Ventre Slide of 1925.

Plate 30a   (About 1908)

Elevation   7,100 ft (2 165 m)

Looking up Gros Ventre River from Turpin Hill immediately below plates 28 and 29. Trees in right-foreground are aspen in early succession. Hedged growth form and multistem development suggest suppression by winter elk foraging. The open herbaceous and half-shrub cover in foreground and midground is comparable to that in plate 28a. This vegetation appears to have been grazed. Summer utilization would have been by livestock.

Photo courtesy of Slim Lawrence; photographer unknown.

Plate 30b   *(September 6, 1968)*

60 years later

Today's scene contrasts sharply with that of 60 years ago. Aspen growth obstructs much of the view, while dense mountain big sagebrush occupies the once open terrain in the foreground. The growth form of bitterbrush (darker shrubs, arrow) has increased considerably.

Plate 31a   *(August, 1907)*

Elevation   *7,000 ft (2 134 m)*

Camera faces west from a position 75 yards northwest of the Turpin Hill overlook and about 150 yards below plate 30. The aspen stand on left is in early succession while an association of grasses and forbs occupies the foreground. Mountain big sagebrush is of low density.

General Land Office photograph, courtesy of Bureau of Land Management.

Plate 31b   (July 20, 1971)

67 years later

Aspens show a significant increase in growth. Plant cover in foreground appears more profuse. Note that boulders are partly obscured. Mountain big sagebrush at right shows marked increase.

Plate 32a   (August, 1907)

Elevation   7,000 ft (2 134 m)

Looking west from the Gros Ventre road, 0.4 mile east of preceding plate. The far slope is a mosaic of burned and unburned conifer stands. Lodgepole pine and Douglas-fir in early succession occupy burned areas. Young aspens predominate at left-center of photo. Burned areas are primarily attributed to the fire of 1879.

General Land Office photograph, courtesy of Bureau of Land Management.

Plate 32b   (July 20, 1971)

64 years later

A closed conifer stand now occupies far slopes, while aspens are in advanced succession. The boulder-strewn flood plain and change in the Gros Ventre River channel resulted from a 1927 breach in the lower Slide Lake dam.

Plate 33a   *(About 1900)*

Elevation   *7,000 ft (2 134 m)*

Looking southeast across the Gros Ventre River towards the outlet of Bierer Creek on left and slopes of Sheep Mountain. Photo point is above Gros Ventre Slide overlook, 0.4 mile from preceding plate. View includes a continuation of the burn pictured in plate 29.

S.N. Leek photograph, courtesy of Mr. and Mrs. Claude Crisp.

Plate 33b   (September 25, 1970)

70 years later

This scene typifies the dramatic increase in timber cover on the Bridger-Teton Forest. Trees are approaching maturity and have been attacked by the mountain pine beetle in recent years. Forest openings comparatively free of trees are edaphically controlled. The landscape in midground is covered by material from the 1925 Gros Ventre Slide, which also obliterated the original camera point and covered the rock ledge in early scene.

Plate 34a   *(April 12, 1920)*

Elevation   *7,100 ft (2 165 m)*

Looking north at slopes west of Tent Creek from a point 2.5 miles east of plate 33. Much of aspen and conifer cover is in early succession. Network of trails attest to recurrent winter elk use. Note lone elk highlighted by lower snowbank.

Fish and Wildlife Service photograph B-20648 by Goldman.

Plate 34b   (May 4, 1970)

50 years later

In foreground, density of mountain big sagebrush has increased. Elk use on near slopes has been almost entirely eliminated by winter feeding. Today, the primary big game foraging in this locality is by moose. Sections from mature aspen on distant slope showed a stand age of 100-120 years. With advancing succession, stand density has declined. Willows (arrow) show an increase in growth.

Plate 35a   *(August, 1883)*

Elevation   *6,800 ft (2 073 m)*

Camp Arthur, the third of six camps established by President Arthur and his party. Camera faces north, with Gros Ventre River in midground and Horsetail Creek in distance. Although a haze impairs view of distant slopes, it is evident that aspen and conifers are in early succession.

F. Jay Haynes photo, courtesy of Haynes Foundation; Mrs. Isabel M. Haynes, President.

Plate 35b   *(September 26, 1970)*

87 years later

The valley bottom is now covered by Lower Slide Lake, which provides ideal habitat for various waterfowl. Aspens on far slopes, which were not visible in 1883, are now quite conspicuous. The conifer cover is also heavier.

Plate 36a   (About 1900)

Elevation   7,400 ft (2 256 m)

High on the sontheast slope of Russold Hill, the camera faces east-northeast toward the Red Hills. Downfall in midground is fire-killed aspen, as evidenced by charred remains in 1970. Scattered shrubs in midground are mountain big sagebrush. White spots (arrow) are Unita ground squirrel diggings.

S.N. Leek photograph, courtesy of Mr. and Mrs. Claude Crisp.

Plate 36b   *(September 21, 1970)*

70 years later

Camera point was precisely duplicated. Original view is now screened by aspen, spruce, and limber pine. Dense plant cover prevails in foreground and in draw below. Mountain big sagebrush in particular, has increased (inset). In contrast, the Red Hills in distance support a sparse plant cover comparable to earlier years. No appreciable changes can be detected in watershed conditions. The Uinta ground squirrel diggings continue to be occupied (inset).

Plate 37a   (August, 1883)

Elevation   7,000 ft (2 134 m)

President Arthur's party crossing Gros Ventre River at outlet of Miner Creek. View is southwest with fork of Miner Creek at left. Willows line the river banks, while the darker shrubs in foreground, based on present composition, appear to be Woods rose. Ring counts of fire-scarred lodgepole pine suggest the fire of 1879 killed the spruce in foreground and swept the far slopes. At the time, aspen were in advanced succession.

F. Jay Haynes photo, courtesy of Haynes Foundation; Mrs. Isabel M. Haynes, President.
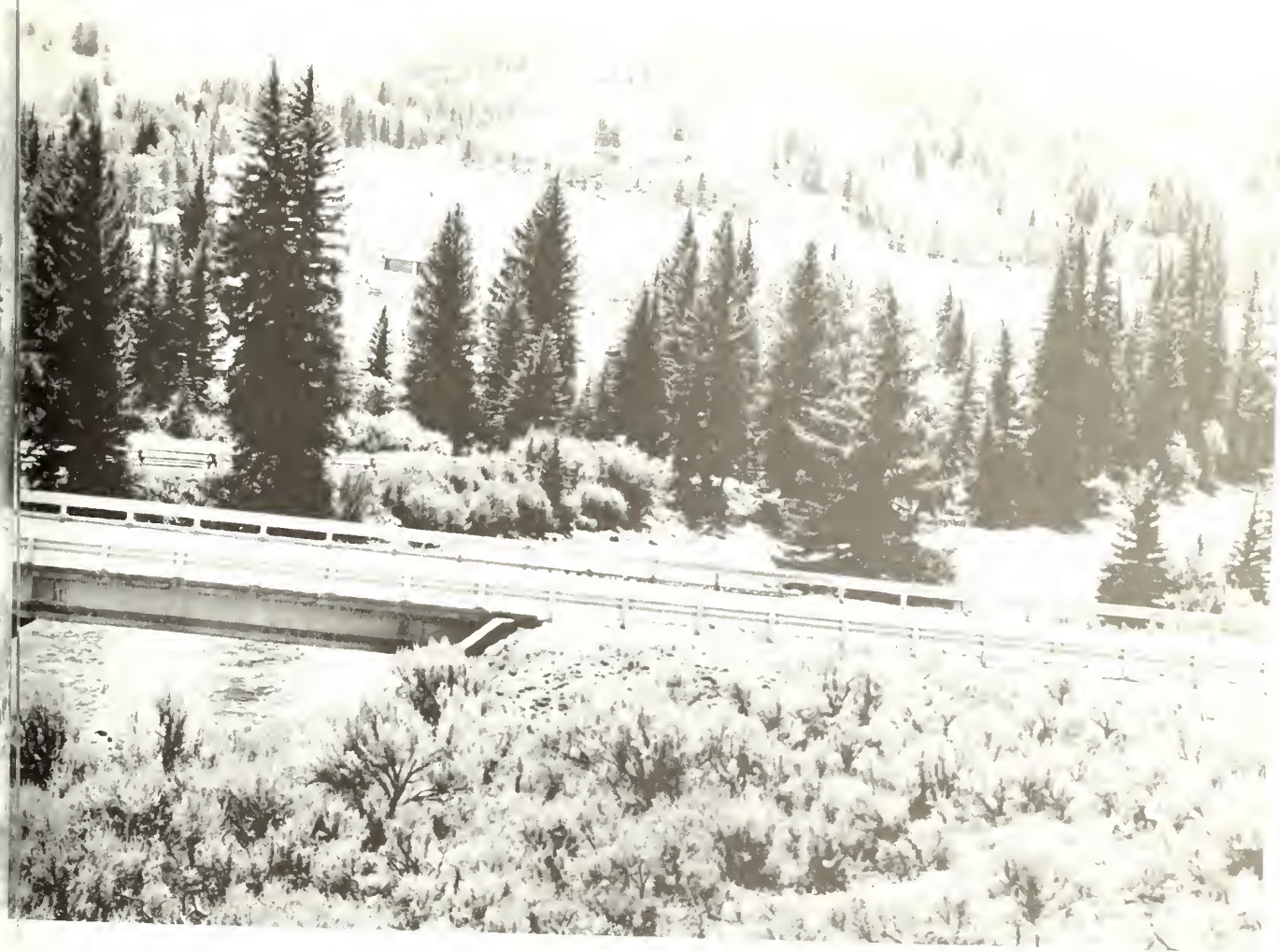
Plate 37b   (August 21, 1970)

87 years later

Mountain big sagebrush has replaced Woods rose in foreground and is now conspicuous across the river. The Gros Ventre cattle driveway runs through foreground. Disturbance from bridge construc-tion has removed much of the vegetation in the road right-of-way. Blue spruce now dominate midground. Conifer cover in distance has increased at the expense of aspen.

Plate 38a   *(Between 1900 and 1906)*

Elevation   *7,000 ft (2 134 m)*

Looking north toward Red Hills from below Gros Ventre Bridge. Camera point in previous scene is at left edge of photo. Mountain big sagebrush, the most conspicuous shrub, occupies deeper soils. Based on present composition, the primary plant species on sparsely vegetated sites include perennial grasses, Hoods phlox, rabbitbrush spp., fringed sagebrush, winterfat, and horsebrush. Gully and rill patterns attest to recurrent runoff from snow and rain. This slope has been historic winter range for bighorn sheep and elk. Note series of game trails.

S.N. Leek photograph, courtesy of Mr. and Mrs. Claude Crisp.

Plate 38b   (May 6, 1973)

67-73 years later

The view is now partly obscured by a new bridge.

Mountain big sagebrush has increased on localized sites. Erosion patterns and extent of cutting is comparable to former condition. Vegetative changes have been subtle, being comparable to those in plate 36 on the west end of the Red Hills.
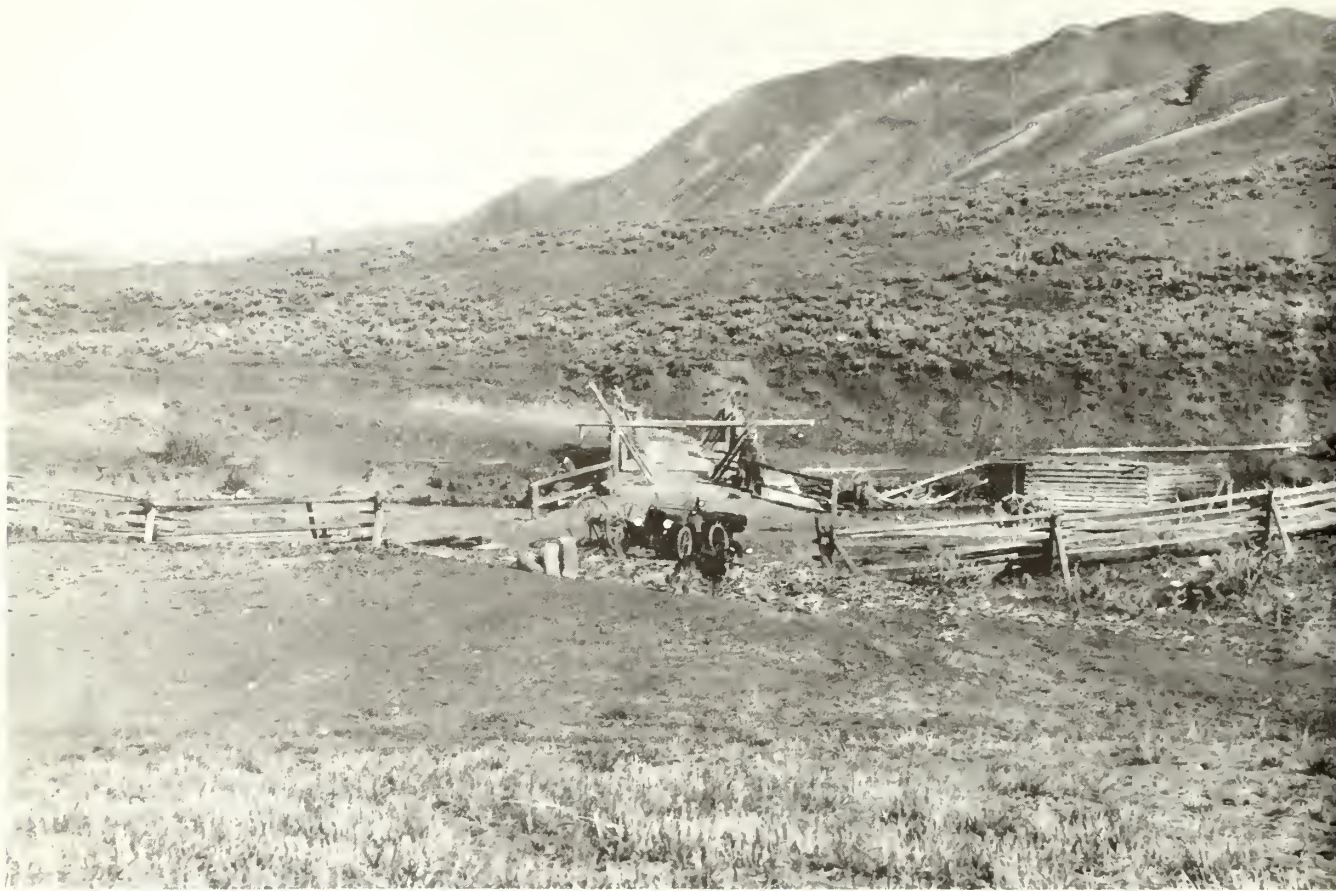
Plate 39a   (1918)

Elevation   7,000 ft (2 134 m)

Taken just below preceding plate, the view is northwest toward the Red Hills. Foreground is on edge of hay meadow, while cattle driveway and road occupy near slope. Mountain big sagebrush constitutes principal shrub cover. Men are working on new bridge, the previous two having been washed out during high water in 1907 and 1918.

Forest Service photograph, photographer unknown.

Plate 39b   (July 18, 1968)

50 years later

Mountain big sagebrush has increased in density. Willow now grow on sites formerly occupied by bridge abutments. Vegetal patterns on Red Hills in distance are comparable to 1918.

Plate 40a *(1899)*

Elevation *7,000 ft (2 134 m)*

A fall scene on the Gros Ventre River about one mile east of plate 38, which lies immediately below rock outcrops on skyline. The predominant tree cover along river is spruce. Dark shrubs on opposite bank appear to be mostly willows. Dead branches suggest a reduction in size. Shallow soils on far slope are sparsely vegetated, while mountain big sagebrush is confined to deeper soils. Aspen are in early succession on ridge (arrow). Associated conifers are Douglas-fir, lodgepole pine, and limber pine.

Stimson photograph, courtesy of Wyoming State Archives and Historical Department.

Plate 40b   *(August 25, 1975)*

76 years later

Spruce have increased in both size and numbers, while the adjacent shrub cover on opposite bank is more dense, being comprised of cottonwood, willow, and silver buffaloberry. The ground cover on far slope is comparable to 1899, excepting that mountain big sagebrush has increased in density on localized sites. With advancing succession, aspen on ridge are being out-competed by conifers.

Plate 41a   (About 1905)

Elevation   7,000 ft (2 134 m)

The S.N. Leek hunting party crossing the Gros Ventre River below the outlet of Slate Creek. The view is northwest toward the Lavender Hills. Primary shrubs on opposite river bank are silver buffaloberry, while mountain big sagebrush predominates on the slopes beyond. The dark shrub communities in midground are bush cinquefoil, found on moist sites.

S.N. Leek photograph, courtesy of Mr. and Mrs. Claude Crisp.

Plate 41b   (September 25, 1970)

65 years later

*Spruce have regenerated in foreground, while buffaloberry and willow have increased on far bank.
Density of big sagebrush has increased. Density of bush cinquefoil has increased slightly. Far slopes
continue to support a sparse ground cover.*

Plate 42a   (About 1905)

Elevation   7,300 ft (2 226 m)

S.N. Leek hunting party crossing a slump on Slate Creek about 1 mile below the junction of the Car-michael and Dallas Forks. East Leidy Peak is in distance on right. The vegetal cover in foreground and midground appears to be an association of scattered mountain big sagebrush, bush cinquefoil, and herbaceous plants. Arrows point to willow communities. Sampling of fire-scarred trees suggested this area burned about 1842 and 1879.

S.N. Leek photograph, courtesy of Mr. and Mrs. Claude Crisp.

Plate 42b   (September 10, 1970)

65 years later

Vegetation has changed dramatically. Mountain big sagebrush and bush cinquefoil dominate the foreground. Note establishment of vegetation in old trail, while the adjacent willow communities are less prominent. Far slopes now support an uneven-aged lodgepole pine stand.

Plate 43a   (About 1905)

Elevation   7,400 ft (2 256 m)

A northerly view of Mt. Leidy (left) and East Leidy (right) from the valley floor near confluence of the Carmichael and Dallas Forks of Slate Creek. Location is about 1 mile upstream from previous scene. The foreground vegetation is an association of herbaceous species and mountain big sagebrush; the bottom land below is primarily silver sagebrush, willows, and herbaceous plants. Large shrubs in front of boulders are willow. A willow community dominates the valley bottom beyond boulders, while on the adjacent slope, willow is restricted to the more moist sites (arrows).

S.N. Leek photograph, courtesy of Mr. and Mrs. Claude Crisp.

Plate 43b   *(September 10, 1970)*

65 years later

The foreground shows an increase in mountain big sagebrush, as does the far slope. Little change is apparent in the herbaceous plant-silver sagebrush association in midground. The willow shrubs near boulders are also much the same. No appreciable differences in the large willow community can be detected from photos; however, field examinations indicate a loss of plants and reduction in size. Willows on adjacent slopes have deteriorated significantly.

Plate 44a   *(June, 1918)*

Elevation   *8,400 ft (2 561 m)*

From the ridge above the Haystack Fork of Slate Creek, the view is northwest into the Carmichael Fork of Slate Creek. The dark vegetation on valley floor is the same willow community in preceding plate. Sparse ground cover persists on the Pinyon conglomerate formation in foreground. Snags on ridge at right attest to past fire.

Forest Service photograph 39581A by Smith Riley.

Plate 44b   *(June 17, 1969)*

51 years later

The Pinyon conglomerate formation in foreground continues to support a sparse ground cover comprised largely of bearded bluebunch wheatgrass, spikefescue, Hoods phlox, milkvetch spp., eriogonum spp., and fringed sagebrush. The willow community on valley floor has deteriorated, a condition exaggerated by a difference in tonal quality of the prints. Tree cover has increased considerably.

Plate 45a   (June, 1918)

Elevation   8,400 ft (2 561 m)

Inspection party on ridge between Haystack Fork and Bear Paw Fork of Slate Creek, some 100 yards east of preceding plate. View is east-southeast across Haystack Fork. Southeast exposure in foreground was described as sparsely vegetated and covered by droppings from wintering elk. Note elk trail on slope and highlined conifers. Down timber in Haystack Fork beyond near ridge at right was killed by fire.

Forest Service photograph 39588A by Smith Riley.

Plate 45b   *(June 17, 1969)*

51 years later

Plant growth on near slopes is severly limited by poorly developed sandy soils. Ground cover is comparable to early scene despite less precipitation than 1918. Elk foraging has been reduced by the winter feeding program in Gros Ventre valley. Conifers now dominate old burn in Haystack Fork, while little change in the timber cover is evident on slopes above.

Plate 46a   *(1911)*

Elevation   *7,400 ft (2 256 m)*

Southwest exposure on slopes of Gray Hills between Lightning Creek and Haystack Fork. Parent material is sandstone and claystone. This locality received heavy utilization by elk at the time of this photo.

Fish and Wildlife Service photograph B-13479 by Edward Preble.

Plate 46b   (July 2, 1969)

58 years later

Lack of snow on far ridge indicates this photo was taken later in the season than the original. Note increased tree cover in locality occupied by snowbank in 1911 scene. Little can be said about plant cover in foreground, except that the two scenes appear comparable. The most conspicuous species include bearded bluebunch wheatgrass, Douglas rabbitbrush, and mountain big sagebrush. Other species represented are rubber rabbitbrush, fringed sagebrush, Hoods phlox, eriogonum spp., pussytoes spp., bluegrass spp., and fescue spp.

Plate 47a   (February, 1919)

Elevation   7,400 ft (2 256 m)

Looking south across Goose Lake adjacent to Gros Ventre road. An inspection party took this photograph to show foraging by free-ranging elk. Trees on near slope are aspen. Willow occupy edge of lake at left.

Forest Service photograph 40166A by Smith Riley.

Plate 47b   *(February 4, 1970)*

51 years later

The aspen at left have deteriorated, while at right an aspen clone has developed on a site formerly occupied by shrubs. Willow have increased on the opposite shore. Conifers in distance are more conspicuous. Elk foraging in this locality has been reduced by winter feeding at nearby Alkali Creek.

Plate 48a   *(1909)*

Elevation   *7,500 ft (2 287 m)*

One mile northeast of Goose Lake. Camera points west across Burnt Creek at upper Gros Ventre Slide. Evidence of recent surface movement is suggested by fractures above Burnt Creek. This massive, slow-moving earth flow pinched off the Gros Ventre River in about 1904, forming Upper Slide Lake pictured in plate 49.

USGS photograph 224 by E. Blackwelder.

Plate 48b   *(June 20, 1968)*

59 years later

A smoother appearance suggests that the upper Gros Ventre Slide is more stable than formerly. Advancing plant succession is evidenced by an increase in mountain big sagebrush and growth of aspen (arrow) which were hardly visible in 1909.

Plate 49a   *(1919)*

Elevation   *7,500 ft (2 287 m)*

The camera points northeast across Upper Slide Lake. Shrubs in the foreground and midground are principally mountain big sagebrush and silver sagebrush, while trees are aspen in early succession. Samples from fire-scarred conifers between Alkali Creek and this vicinity suggest widespread burning in 1872. The far slopes include the heart of the historic elk winter range and were being intensively grazed by elk in 1919.

U.S. Forest Service photograph 49881A by M. Anderson.

Plate 49b   *(September 6, 1968)*

49 years later

Shrub cover in foreground has thickened, while in midground growth of aspen stands screen part of lake. Alluvial deposits in lake originate from unstable lands in the upper watershed. This geologic change favored moose by the establishment of willows on alluvial deposits. Gully patterns on southwest-facing slopes in distance are virtually the same as 1919. The slope was fenced to exclude elk and contour-trenched in 1963.

Plate 50a   *(1904)*

Elevation   *7,400 ft (2 256 m)*

Game Warden Si Ferrin (right) and assistant Charlie Harvey on south bank of Gros Ventre River. The view is north, with Coal Mine Draw at extreme right. Vegetation in foreground is predominantly herbaceous species, while a low density of mountain big sagebrush and bush cinquefoil shrubs also occupy the site. A willow shrub can be seen under horses muzzle at left.

Photo courtesy of Wyoming State Archives and Historical Department. Photographer unknown.

Plate 50b   (September 23, 1969)

65 years later

Vegetation in foreground changed markedly from principally herbaceous cover to predominately mountain big sagebrush and bush cinquefoil. Note how the boulder at right behind horse's feet in early photo is obscured by shrub growth. Arrow points to same willow as in 1904 scene. The Gros Ventre River has moved futher north. In distance, vegetative and gully patterns are remarkably similar after 65 years.

Plate 51a *(About 1905)*

Elevation *7,300 ft (2 226 m)*

Camera faces northeast toward spring at present site of Wyoming Game and Fish patrol cabin. Coal Mine draw lies immediately north. Hunter is Henry Moser or one of his party. As in preceding plate, the foreground is principally occupied by herbaceous species. Mountain big sagebrush is of low density, being more prevalent on slopes. The large, dark shrubs around spring are willow.

Photo courtesy of Mr. Almer Nelson.

Plate 51b   *(September 15, 1972)*

67 years later

Mountain big sagebrush now predominates in foreground and midground. Dead stems mark location of large willow in 1905 photo. The willow in foreground and others in front of fence became established after 1905. Accelerated erosion above spring is attributal to road which bisects gullies. A sparse plant cover continues to occupy upper slopes.

Plate 52a   *(February, 1918)*

Elevation   *7,400 ft (2 256 m)*

Westerly view across a willow community near the outlet of Tepee Creek. Note the open growth form of willow. Tree cover on distant slopes is principally aspen and lodgepole pine.

U.S. Forest Service photograph 49868A by M. Anderson.

Plate 52b   *(February 5, 1970)*

52 years later

The growth form of willow has been reduced as a result of natural die-back of branches and moose heavily browsing new growth. Aspens on near slope and in distance are less conspicuous, while conifers have increased in size.

Plate 53a   *(1925)*

Elevation   *7,400 (2 256 m)*

Forest Service patrol cabin near confluence of Tepee Creek and Gros Ventre River. View is northwest, with outlet of Coal Mine Draw at right distance. The aspen stand at left-midground and willow in lower right are also pictured in previous plate. Dark shrubs on valley floor are almost entirely willow.

Forest Service photograph by Dick Winger.

Plate 53b   *(February 7, 1968)*

43 years later

After 43 years, the aspen stand contains fewer stems, but these are of increased size. Associated mountain big sagebrush is more dense. The reduced growth form of willow as noted in preceding plate can be clearly seen by comparing shrub (arrow) with the way it looked in 1925. The Wyoming Game and Fish Department patrol cabin referred to in plate 51a can be seen in distance at right. Wintering elk have been fed in this locality since the early 1960's.

Plate 54a   *(Between 1887 and 1896)*

Elevation   *7,400 ft (2 256 m)*

The Owen Wister hunting party near the outlet of Goosewing Creek. The camera is facing south-southeast. Tree cover on the near slope is predominately aspen in early succession. Fire scars in the vicinity suggest an 1872 burn. The white trees are largely fire-killed spruce, which show that the stand was in advanced succession when burned. Note the network of well-worn elk trails high on ridge above tent.

Owen Wister photograph, courtesy of Western History Department, University of Wyoming.

Plate 54b   *(September 12, 1969)*

73-82 years later

Growth ring counts from aspens on near slope showed them to be 89-98 years old thus substantiating even-age regeneration following the 1872 fire. Spruce are re-invading beneath the canopy. The elk trails have virtually disappeared, since winter feeding has drawn elk away from this locality.

An increase in shrub cover is apparent on the deeper, more moist soils near the base of the southwesterly slope at right. Plant cover on the upper slopes continues to be sparse. The site is comparable to plate 45, with available moisture limited by sandy, shallow soils. Heavy use by campers and bedding livestock has altered the plant cover in foreground.

Plate 55a   *(August, 1918)*

Elevation   *7,400 ft (2 256 m)*

Looking north across Gros Ventre River toward the outlet of Dry Cottonwood Creek. The camera is on the road shoulder 0.3 miles east of preceding plate. Dark shrubs of large growth-form in mid-ground are willow, while the lighter vegetation is primarily mountain big sagebrush and silver sagebrush. Bush cinquefoil, which appears dark, is also present. The trees on flood plain are cotton-wood and spruce.

U.S. Forest Service photograph 49901A by M. Anderson.

Plate 55b   *(September 23, 1969)*

51 years later

A marked change has taken place in the growth form of willow (arrow). Dead stems attest to former large size. Mountain big sagebrush and bush cinquefoil are of increased size, while losses of cotton-woods are apparent in distance. Both vegetal and gully patterns on far slopes show no appreciable change.

Plate 56a   *(July, 1917)*

Elevation   *8,200 ft (2 500 m)*

Along the Oil Well Ridge road looking southwest across Dry Cottonwood Creek toward the head of Coal Mine Draw. Tree cover on far slopes is predominatly aspen. Fire scars in the vicinity suggest establishment following burning around 1885.

Fish and Wildlife Service photograph B-18300 by Dr. Field. Photograph courtesy of National Archives and Record Service.

Plate 56b   (July 2, 1969)

52 years later

Growth of aspen in foreground necessitated photographing the scene from top of pickup cab. Despite impaired view, aspen stands on the far slope have obviously deteriorated and are now largely occupied by big sagebrush. Where aspen was seral at right of photo, it has been replaced by conifers.

Plate 57a   (July, 1917)

Elevation   7,500 ft (2 287 m)

A westerly view of the Gros Ventre River bottoms from a position on the east bank of Cottonwood Creek near its outlet. Dark shrubs are willow. The light shrubs in midground and on near slopes are mountain big sagebrush. Cabin at right is reputed to have been the winter quarters of a notorious hunter who killed elk for their tusks (canines) in earlier days.

Fish and Wildlife Service photograph B-18284 by Dr. Field. Photograph courtesy of National Archives and Record Service.

Plate 57b   (July 13, 1970)

53 years later

A difference in films tends to exaggerate losses in the willow community. Losses have occurred on marginal sites where a reduction in the water table has resulted from a shift in the adjacent stream channel. The primary change in willow has been that of reduced size, while the density of mountain big sagebrush has increased.

Plate 58a   *(August, 1918)*

Elevation   *7,600 ft (2 317 m)*

The camera looks northeast across the Gros Ventre River above its confluence with Fish Creek. The junction of the north and south forks of Fish Creek is in left-distance. Willows predominate adjacent to stream meanders. The foreground vegetation is an association of herbaceous species and half-shrubs.

Forest Service photograph 49913A by M. Anderson.

Plate 58b   (September 23, 1969)

51 years later

The Fish Creek elk feedground now occupies the river terrace and flood plain below. Feeding of elk has allowed perennial grasses to replace the former mountain big sagebrush cover which was trampled out. Obvious changes in the Gros Ventre River include an isolated meander that was flowing in 1918 (arrow).

Plate 59a   (August, 1918)

Elevation   7,500 ft (2 287 m)

Looking northeast across upper Gros Ventre River from Brook Post Office. The southwest facing slopes were an integral part of the historic elk winter range. Aspen and conifers comprise the tree cover. Willow dominate the flood plain below. The three large shrubs in center of photo are also willow.

Forest Service photograph 49891A by M. Anderson.

Plate 59b   (August 25, 1971)

53 years later

Camera point was moved some 50 ft right to avoid lodgepole pine that obstructed view. No appreciable change on the southwest exposure can be detected, except for a deterioration of aspen and increased growth of conifers. Willow on flood plain show evidence of reduced density. Note that the three shrubs in 1918 scene are no longer distinguishable.

Plate 60a   *(1909)*

Elevation   *8,400 ft (2 561 m)*

From the ridge between Trail Creek at right and Bacon Creek on left, the view is north across Fish Creek. Standing snags and early stage of succession attest to a late 1800 burn. Aspen clones in early succession are in evidence on the Trail Creek Drainage (arrows).

USGS photograph 209 by E. Blackwelder.

Plate 60b   *(August 6, 1969)*

60 years later

Conifers and mountain big sagebrush now predominate on ridge in midground, while aspen stands in Trail Creek below have deteriorated. Those aspen stands that were seral have largely been replaced by conifer (arrow).

Plate 61a   (1909)

Elevation   7,500 ft (2 287 m)

Looking southeast across Fish Creek from edge of road immediately above Elk Track Ranch. Most of the dark shrubs on flood plain are willow. Tree cover on distant slope is primarily aspen and lodgepole pine, much of which is in early succession. Fire-scarred lodgepole pine in this locality suggest vegetation regenerated following an 1885 wildfire.

USGS photograph 223 by E. Blackwelder.

140

Plate 61b   (September 13, 1969)

60 years later

The willow near the arrow seem similar to those in 1909. Periodic flooding from an irrigation ditch has favored willow in foreground, while "drowning out" mountain big sagebrush. Narrowleaf cottonwoods have become established on flood plain. Shifting of the stream channel to the southeast resulted in cutting and loss of bank vegetation at left of photo, while willow became established on old stream bed. This locality receives one of the highest levels of winter moose utilization on the Gros Ventre River. Aspen and lodgepole pine stands on far slope are in advanced succession.

Plate 62a   (1909)

Elevation   7,800 ft (2 378 m)

A northeasterly view on the north fork of Fish Creek from the terrace above present drift fence. The outlet of Harness Gulch is in distance. Shrub cover on flood plain is largely willow and bush cinquefoil, while low density mountian big sagebrush occupies the drier, well-drained sites.

USGS photograph 221 by E. Blackwelder.

Plate 62b   *(September 13, 1968)*

59 years later

Mountain big sagebrush density has increased while the density of willow has declined on some sites. Shifting of the stream to the far bank has isolated the meander in foreground. Here, willow are becoming established in the silt deposits. This locality receives a moderate level of moose browsing during the winter.

CONCLUSIONS

A maximum period of 92 years is covered by the 35 plates in the Gros Ventre River drainage. Like the Teton Wilderness, changes vary with site and past disturbance. As a whole, changes parallel those in the wilderness despite considerable differences in microclimates and man's influence. Some of the more significant trends are:

1. Increased density and growth of conifers.

2. Establishment of aspen following fire and a general decline in old stands.

3. General reduction in size and distribution of willow.

4. Increase in the size and density of mountain big sagebrush.

5. No appreciable change in ground cover on sparsely vegetated sites.

6. No observable change in the rate of geologic erosion.

7. Channel changes in the Gros Ventre River flood plain.

All plates show varying degrees of conifer establishment and growth. The most pronounced change has occurred on sites that were in early stages of succession when originally photographed (plates 28-29, 32-33). In these scenes, Douglas-fir and lodgepole pine growth today contrasts sharply with that of earlier years. Pronounced changes have also taken place on spruce sites (plates 37, 54); lodgepole pine sites (plates 42, 44, 61); and spruce-fir sites (plates 45, 60) where fires burned in the late 1800's. Changes are less dramatic on sites which were in the later stages of succession when originally photographed (plates 45 (distance) and 53).

Aspen stands are currently old and mostly deteriorated. Successful regeneration in modern times has been negligible. Stands that were in early succession following wildfires when the original photographs were taken are mostly intact but declining (plates 29-32, 35-36, 40, 48-49, 54, 61). Conifer invasion is common (plates 54, 61). Older stands have typically deteriorated (plates 56, 60).

Trends in willow growth are not clearly definable. In most instances, crown size has been reduced (plates 37, 42, 51-55, 57, 59), but in localized areas its form has not changed (plates 34, 40, 61). As a whole, willow distribution has declined, particularly where it is 100 ft (30.4 m) or more from stream channels and in competition with other vegetation (plates 42-44, 52-53, 57, 59, 62). In other localities, willow distribution has increased (plates 34, 47, 50-51, 61), but only on moist sites around springs, pot holes, and river flood plains.

The trend in mountain big sagebrush has been toward increased growth and density. Only in plate 58 at the Fish Creek feedground and part of plate 61 on the Fish Creek flood plain is a decrease indicated. Mountain big sagebrush has increased on all sites where soils are deep enough to provide adequate rooting depth; including benches and ridges (plates 28, 30-31, 48-49, 60), draws (plates 34, 36), toe slopes (plates 37-39, 50-51, 53) and valley bottoms (plates 41-43, 55, 57, 62).

The rate of sagebrush establishment can be reasonably well determined where the approximate dates of disturbances that preceded the early photographs are known. Establishment was quite slow on sites originally photographed 20 years following an 1879 wildfire (plates 28, 30, 31). Slow establishment is also suggested in localities that burned about 1872 (plates 50, 51).

Vegetative trend on harsh south- and west-facing slopes and ridges was shown by 22 plates. Sixteen distant scenes show no change in growth patterns. The lighter colored, sparsely vegetated areas of recent years appear comparable with former conditions (plates 28-29, 34-36, 39-41, 43, 49-50, 55). Six close-up photos (plates 38, 44-46, 51, 54) also show that conditions in recent years on harsh sites are comparable to

earlier years. Without exception, thinner soils continue to support sparse plant cover dominated by native perennial species.

Erosion rates have been unchanged on sparsely vegetated southerly exposures. Gully cutting is geologic, having developed over long time periods (plates 40, 49-50). Both gully patterns and size are remarkably similar after 50 to 60 years. Plates 36, 38, 45-46, 54, and 59 show no evidence of accelerated cutting. High surface erosion continues to occur on steeper slopes during intensive summer storms. Only where roads or trails have interrupted natural drainages have erosion rates been accelerated (plate 51).

The Gros Ventre River flood plain has changed profoundly at various locations. A major landslide and slow moving earth flow formed Lower Slide Lake (plates 29, 33, 35) and Upper Slide Lake (plate 49). The upper portions of these lakes are filling with sediment and willow flats are developing, thus further changing the character of the river. Channel changes have been insignificant where the river is confined (plates 37, 40-41) but are often pronounced where it is unconfined (plates 50, 58, 61-62). Here, the river has moved back and forth across the wide flood plain leaving old channels and creating new ones.

Southern Section--

Jackson Vicinity, Hoback Drainage, and Teton Canyon

INTRODUCTION

The southern section is represented by 23 plates; the first 15 of which are on big game winter range at elevations between 6,000 and 7,000 ft (1 829 and 2 143 m) (fig. 4). Localitites pictured have been influenced by highway construction, homes, motels, dude ranches, elk feedgrounds, and suppression of wildfire.

As a whole, deciduous shrubs are more common than on the Gros Ventre winter range. Overuse of these shrubs has been of concern to various investigators. Winter utilization is largely by mule deer, except areas shown in plates 63, 72, and 73 immediately adjacent to elk feedgrounds. Domestic livestock grazing has been confined to horses and occurs only in areas shown in plates 64 and 65. Cattle grazing has been prohibited since 1918. Plates 78 to 85 depict conditions in the Douglas-fir and spruce-fir communities on summer range between 6,800 and 9,200 ft (2 073 and 2 805 m). Currently, only one locality (plate 78) is grazed by cattle. Domestic sheep have grazed in the Miles Canyon area of the south fork of Teton Canyon from about 1890 to the present (plates 83-85). Use in recent decades has been lighter with no grazing during the past several years.
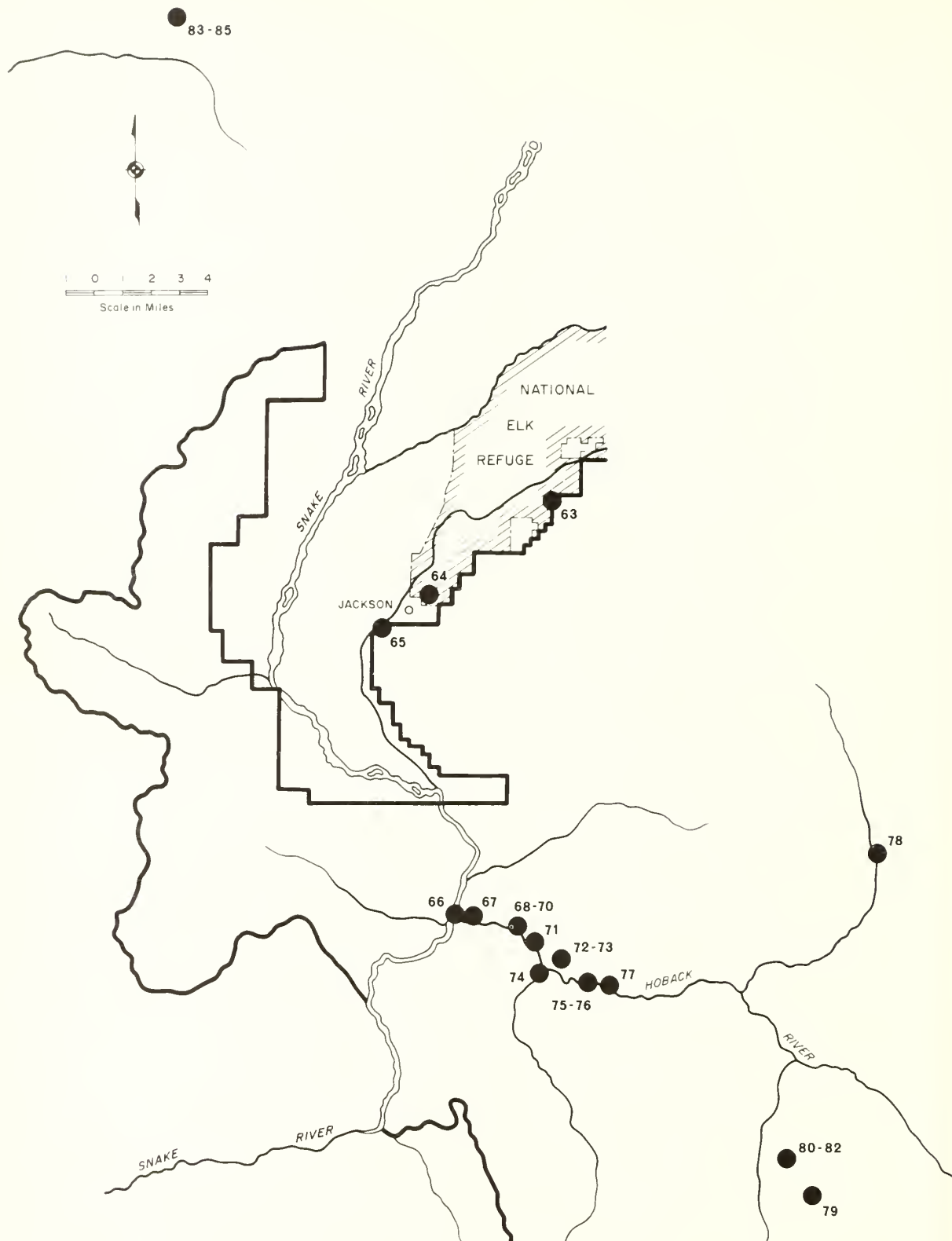
Figure 4.   Location of camera points in southern section.

146

Plate 63a   *(May 13, 1936)*

Elevation   *6,400 ft (1 951 m)*

A north-facing slope near site of Chambers homestead on east side of National Elk Refuge. A heavily utilized aspen stand dominates skyline. The closely cropped shrubs on near slope include serviceberry, currant, rubber rabbitbrush, and sagebrush spp.

Fish and Wildlife Service photo by Olaus J. Murie.

Plate 63b   *(May 14, 1970)*

34 years later

The parent aspen stand has nearly disappeared, while intensive utilization of suckers by elk has not allowed successful regeneration. Chokecherry and serviceberry shrubs now occupy interior and margin of former stand. Snowberry has appreciably increased in occurrence--notably at upper left of photo. Ground cover is excellent, being comprised of various mat-forming plants and other herbaceous vegetation.

Plate 64a   *(1899)*

Elevation   *6,200 ft (1 890 m)*

Looking west at East Gros Ventre Butte from point near south boundary of what is now the National Elk Refuge. The homestead in foreground was taken up prior to establishment of the Refuge. When this photo was taken, the East Gros Ventre Butte was part of the historic Jackson Hole elk winter range. Antlers are from bull elk that died of malnutrition during previous winters.

The conspicuous tree cover on northeast-facing slope at left-distance are even-aged aspen stands. Associated shrubs include mountain big sagebrush, bitterbrush, serviceberry, and chokecherry. Douglas-fir, Rocky Mountain juniper, curleaf mountain mahogany, bitterbrush, and mountain big sagebrush occupy the drier southeast slope.

Stimson photograph, courtesy of Wyoming State Archives and Historical Department.

Plate 64b   (September 7, 1972)

73 years later

Aspen are now largely in advanced succession, while shrub cover is more dense. The contrast in shrub cover is attributed to an increase in the density of mountain big sagebrush and growth of other shrubs. These changes were strongly influenced by exclusion of elk foraging and wildfire. Elk were fenced off the butte in 1938. The primary foragers today are horses, mule deer, a few moose, and an occasional elk. Trails were largely made by cattle in earlier years and by horses. The vegetative cover continues to be sparse on dry sites.

Plate 65a   (1902)

Elevation   7,000 ft (2 134 m)

Looking north from the south end of Snow King Mountain. Elk in foreground are on historic winter range. Adjacent aspen stands are even-aged, having regenerated after the wildfire of 1879. Willow occupy the Flat Creek bottom lands below. The Karns homestead is at right-center, while other homesteads are in distance at right.

Trester photograph courtesy of Fred Muzzula, Denver, Colorado.

Plate 65b (*March 10, 1974*)

72 years later

The original view was blocked by dense Douglas-fir growth. Camera is above and to right of 1902 position, in the largest opening. With advancing succession, a majority of the parent aspens in the original stands below have died out. A low level of ungulate browsing has allowed spotty regeneration. Elk are now almost entirely confined to the National Elk Refuge north of Jackson in distance.

Plate 66a   (About 1905)

Elevation   6,000 ft (1 829 m)

A southwesterly view of the Snake River (right) at its confluence with the Hoback River. The closely cropped shrubs and junipers in foreground attest to persistent browsing by wintering elk. The northwest facing slopes at left-center are in early succession, having burned in 1879.

S.N. Leek photograph, courtesy of Mr. and Mrs. Claude Crisp.

Plate 66b   (July 14, 1970)

65 years later

State Highway 26-89 now follows the right bank of the Snake River, while a motel complex occupies foreground. Few elk now winter in this locality, because they are accustomed to feeding on hay at nearby feedgrounds. Trees and shrubs on river banks have increased. Closed stands of Douglas-fir now occupy northwest-facing slopes in distance.

Plate 67a   *(About 1910)*

Elevation   *6,000 ft (1 829 m)*

Camera faces southeast across the Hoback River along State Highway 187-189 0.7 mile east of preceding plate. The close proximity to previous scene and comparable stage of succession suggests this north-facing slope also burned in 1879. Note the vegetation diversity produced by uneven burning.

Photographer unknown.

Plate 67b   (August 8, 1969)

59 years later

The vegetative cover on far slope is less diversified. Douglas-fir predominates, while aspen stands are deteriorating. Openings not occupied by trees are edaphically regulated. Any change in the mountain big sagebrush community at left is not readily apparent.
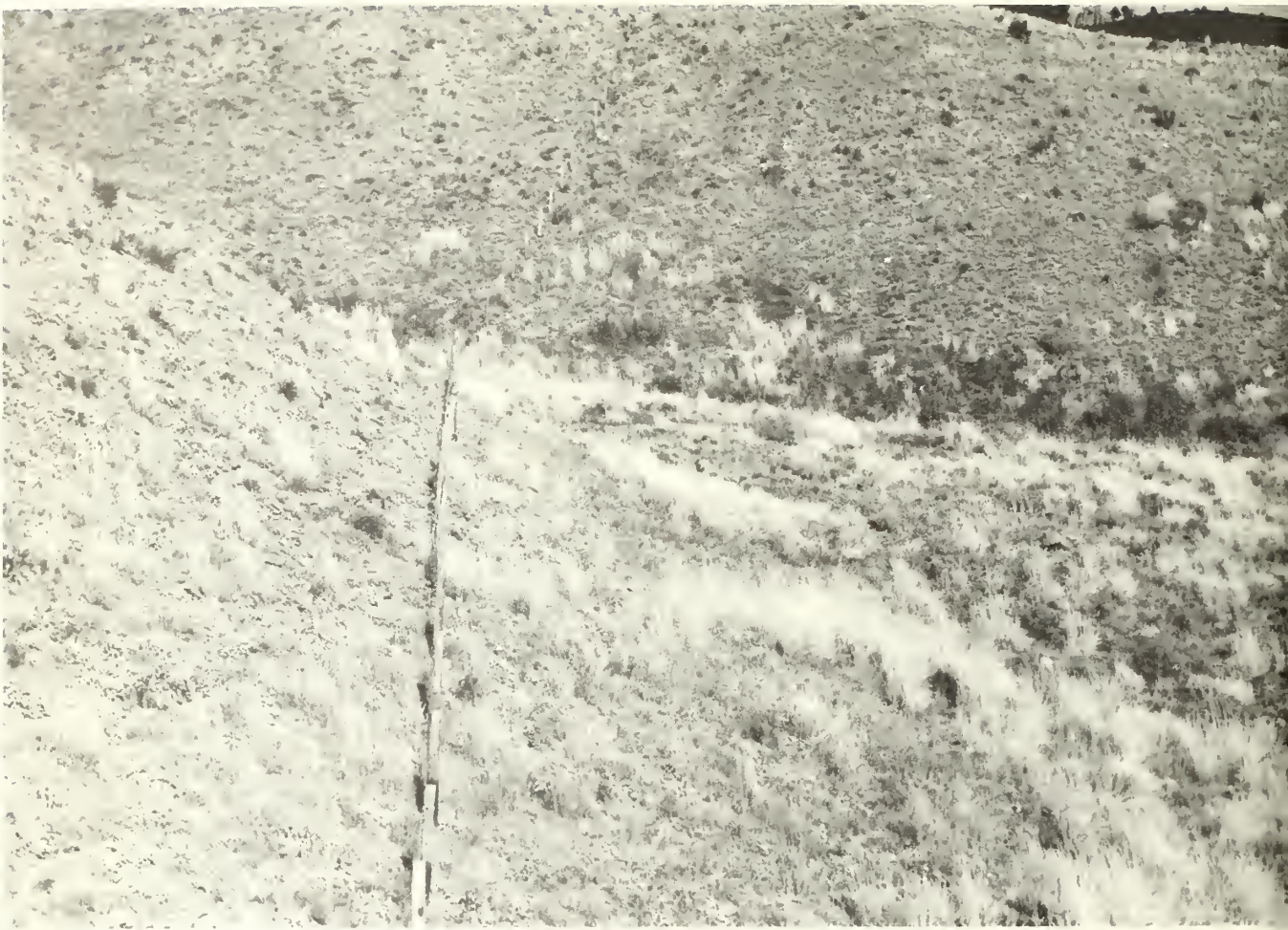
Plate 68a   (September 23, 1942)

Elevation   6,200 ft (1 890 m)

Looking east along the upper fence at the Gilcrease exclosure constructed in 1940 on the Hoback game winter range. Location is about one mile east of plate 67. The darker shrubs on far slope are serviceberry and bitterbrush. A chokecherry community persists at foot of slope, while in the foreground and midground the conspicuous grass is Great Basin wildrye. Elk were making heavy use of the Hoback winter range in 1942. Browsing by mule deer was light at this time. Soils in this locality, derived from shale, are rocky and shallow.

Forest Service photo by R. J. Costley.

Plate 68b   *(September 24, 1970)*

28 years later

The Gilcrease exclosure was removed in the early 1960's after years of costly maintenance and unsuccessful attempts to exclude elk. Significant changes in the vegetation are evident, though only 28 years have passed. Of particular note is the increased growth of serviceberry and bitterbrush. Mountain big sagebrush has also increased in density. Chokecherry at foot of slope has grown appreciably, while that at lower edge of photo is not evident in the 1942 photo. Wildrye appears to have decreased in density. This may be attributed to competition and increased shrub cover which obstructs view. Elk foraging in this locality was greatly reduced after 1960 through winter feeding on the adjacent Camp Creek feedground. Deer use has increased significantly over that of the early 1940's.

Plate 69a   (September 23, 1942)

Elevation   6,200 ft (1 890 m)

Looking down the lower fence at the Gilcrease exclosure. Trees at foot of near slope below exclosure are aspen. The prevalence of wildrye is more apparent than in previous plate.

Forest Service photograph by R. J. Costley.

Plate 69b   (September 24, 1970)

28 years later

The increased density of mountain big sagebrush and decline of wildrye is more noticeable in this scene. The aspen stand has deteriorated, while a low level of regeneration is becoming established. A large portion of the former aspen stand is now occupied by chokecherry and to a lesser extent, serviceberry. The increased growth form of serviceberry and bitterbrush is further evidenced in this scene.

Plate 70a   *(About 1900)*

Elevation   *6,000 ft (1 829 m)*

Looking east at historic elk winter range from the north bank of the Hoback River some 2 miles from the Hoback Junction. Lower slopes of mountain at right-distance are in early succession. The primary vegetation on the river banks is spruce, Rocky Mountain juniper, narrowleaf cottonwood and willow. Dark shrubs on bench at left are principally serviceberry. Associated vegetation is mountain big sagebrush, deciduous shrubs, and herbaceous plants.

S. N. Leek photograph, courtesy of Mr. and Mrs. Claude Crisp.

Plate 70b   *(August 10, 1970)*

70 years later

Tree and shrub cover along Hoback River has increased. Of note is the stable character of the stream bed, which appears comparable to early scene. Serviceberry shrubs on bench are less conspicuous despite increased growth. Associated shrubs include rose, snowberry, bitterbrush, rubber rabbitbrush, and chokecherry. Shrubs are obstructed by an increase in the density of mountain big sagebrush. The Camp Creek elk feedground lies beyond the ridge on left. Winter feeding has largely eliminated elk foraging on the bench. Mule deer utilize the locality in early winter and spring. Closed Douglas-fir stands dominate distant slopes.

Plate 71a   (About 1900)

Elevation   6,100 ft (1 860 m)

The camera faces southeast from hill behind spruce stand at right-center of preceding plate. Camp Creek is behind rock outcrop at left, while Bryan Flat is in distance. Shrubs on southwest-facing slope (arrow) were suppressed by wintering elk. The early stage of vegetative succession on far slope is more noticeable than in plate 70a. Aspen stands are young and even-aged. Fire scars suggest an 1871 burn. The influence of fire is also indicated along Hoback River where the vegetation is largely in early succession.

S.N. Leek photograph, courtesy of Mr. and Mrs. Claude Crisp.

Plate 71b   *(August 8, 1970)*

70 years later

A striking contrast prevails. Shrubs on southwest facing slope along river are robust. The winter feeding operation on Camp Creek, highway traffic, and development preclude heavy browsing. Spruce, narrowleaf cottonwood, and willow are reaching advanced succession along Hoback River. Conifer sites on distant slopes are now covered by dense Douglas-fir stands. Douglas-fir has also taken over sites formerly occupied by aspen, while mature aspen stands persist along lower slopes.

Plate 72a   *(September, 1939)*

Elevation   *6,300 ft (1 921 m)*

Camera is positioned at the southwest corner of Camp Creek exclosure No. 2, 1 year following construction. This exclosure was constructed to study vegetative potential and growth following exclusion of elk. The more prominent shrubs are serviceberry, while those of low growth form are principally bitterbrush. Elk foraging was intense prior to and during the early 1930's as indicated by the hedged shrubs. At the time of this photograph, winter feeding of elk was sporadic, being practiced only during severe winters and for short duration. Elk free-ranged over the adjacent slopes as they had historically.

Forest Service photograph by A. Buckingham.

Plate 72b   *(September 26, 1968)*

29 years later

Serviceberry and bitterbrush shrubs have robust growth forms after 29 years protection from elk foraging. The serviceberry shrub on far right has grown approximately 7 feet. Bitterbrush at lower left has spread considerably. Other shrubs that have increased in growth and density include snowberry, rose, and sagebrush spp.

Plate 73a   *(September 24, 1942)*

Elevation   *6,300 ft (1 921 m)*

Looking north from southwest corner of Camp Creek exclosure No. 2, 4 years following construction. Grazed range is on left and protected range on right. Both serviceberry and bitterbrush plants outside exclosure are closely hedged, but are growing slowly inside fence.

Forest Service photograph by R. J. Costley.

Plate 73b   (September 26, 1968)

26 years later

Changes in the growth form of bitterbrush and serviceberry outside the exclosure do not appear significant. This exclosure lies less than 1 mile from the Camp Creek feedground. Foraging is accentuated by the fence, which tends to inhibit free movement. The protected plants in exclosure demonstrate growth potential of shrubs when not subjected to intense ungulate foraging.

Plate 74a   (About 1900)

Elevation   6,600 ft (2 012 m)

Looking due east toward Stinking Springs (below rock ledges) from a point near the confluence of Willow Creek and the Hoback River. Most of the spruce-cottonwood-willow cover on flood plain is in early succession. The vegetation on southwest facing slopes in midground-left is herbaceous species interspersed by bitterbrush, serviceberry, and mountain big sagebrush. These slopes were also a key part of the historic elk winter range. Arrows denote sites burned about 1871.

S.N. Leek photograph, courtesy of Mr. and Mrs. Claude Crisp.

Plate 74b   (July 14, 1970)

70 years later

Cottonwood, willow, and other deciduous species have given way to spruce, which now predominates on flood plain. Vegetal trend on the open, southwest exposure across river is not readily apparent, but appears comparable to that in plate 70. Dense Douglas-fir stands now occupy sites denoted by arrows in previous plate. Aspen have reached advanced succession on the ecotone between conifer and mountain big sagebrush.

Plate 75a   (1878)

Elevation   6,200 ft (1 890 m)

A southeasterly view up the Hoback River at Stinking Springs. The slope at right is delineated by left arrow in plate 74a. A burn date of 1871 appears reasonable considering the initial stage of herbaceous and shrub growth. Snags and comparable growth stage of vegetation on left bank indicates this fire burned both sides of river.

W. H. Jackson photograph 7510, courtesy of State Historical Society of Colorado.

Plate 75b   (June 25, 1968)

90 years later

The vegetative cover on sites of high growth potential has increased markedly. Shrub community indicated by arrow is largely comprised of serviceberry, mountain big sagebrush, chokecherry, currant, snowberry, and russet buffaloberry. The harsh southeast exposure below cliff at left-center shows no appreciable change except increased growth of conifers.

Plate 76a   (1920)

Elevation   6,200 ft (1 890 m)

Covering much of the previous scene, the camera is situated some 150 yards southeast. Plant cover on flat in foreground appears to be predominately herbaceous species interspersed by a low density of mountain big sagebrush. Since 1878 (49 years), re-establishment of Douglas-fir has been slow on upper slope at right. Seral aspens occupy the toe of slope.

Forest Service photograph 150329 by E. S. Shipp.

Plate 76b   (June 24, 1968)

48 years later

A marked increase in mountain big sagebrush has taken place on flat, while chokecherry has largely replaced the aspen component in foreground, shown also by arrow in plate 75b. Since 1920, the far slope at right has progressed into a closed Douglas-fir stand. Seral aspen formerly occupying the toe slope have been almost entirely replaced.

Plate 77a   (1878)

Elevation   6,400 ft (1 951 m)

From old Indian trail about one mile above Stinking Springs, the view is west across the Hoback River Canyon. Limber pine and Douglas-fir are the primary coniferous species on southerly slope at right, while on the far slope, Douglas-fir predominate.

W.H. Jackson photograph 8763, courtesy of State Historical Society of Colorado.

Plate 77b   (June 25, 1968)

90 years later

Construction of Highway 187-189 has altered the canyon bottom and portion of slope at right. Some conifers on near slope have been lost to insects, while others have become established in the intervening years. Thinleaf alder is more conspicuous than formerly. Except for tree growth, plant cover on sparsely vegetated site in foreground-right shows little change after 90 years. Note the similarity in appearance of snag at left-foreground.

Plate 78a   *(1906)*

Elevation   *6,800 ft (2 073 m)*

The camera faces up Swift Creek from trail adjacent to Girl Scout Camp. Foreground vegetation includes grasses and mountain big sagebrush. The prevalence of snags and size of even-aged aspen on distant slopes attest to a fire some 20-30 years earlier. Scattered large conifers indicate that this fire burned irregularly.

USGS photograph 58 by A.R. Schultz.

Plate 78b   *(June 27, 1968)*

62 years later

Mountain big sagebrush in foreground has increased. Conifers are re-established on sites occupied prior to the burn while aspen stands have matured. Deciduous shrubs including snowbrush ceanothus, russet buffaloberry, chokecherry, and serviceberry came in profusely following burn, but are now deteriorating.

Plate 79a   (1878)

Elevation   8,400 ft (2 561 m)

The camera faces west toward Clause Creek in distance from a position on ridge separating Cliff and Little Cliff Creeks. Sandy Marshall oil drill site lies directly below. Vegetal cover on near slope is an association of tall forbs and mountain big sagebrush. Douglas-fir comprises the primary tree cover. Evidence of past fire can be seen on near peak and on distant slopes.

W.H. Jackson photograph 7515, courtesy of State Historical Society of Colorado.

Plate 79b   (July 16, 1968)

90 years later

Douglas-fir on near slope have grown appreciably. Mountain big sagebrush appears to have decreased. Stunted serviceberry and bitterbrush shrubs in vicinity of arrow were of similar growth form in 1878.

Plate 80a   (1878)

Elevation   8,400 ft (2 561 m)

Facing nearly due south up Cliff Creek, the camera is on the ridge 1.25 miles northwest of preceding plate. The near slopes show the effect of fire in recent past, with shrubs predominating. Note the irregular pattern of burning. Composites and grasses predominate in foreground.

W.H. Jackson photograph 7518, courtesy of State Historical Society of Colorado.

Plate 80b   *(July 16, 1968)*

90 years later

Scouler willow is a conspicuous component of the vegetal cover on old burn. Various shrubs and subalpine fir growing in association with the willow make this locality ideal habitat for moose. The composite cover in foreground is less dense than formerly.

Plate 81a (1878)

Elevation 8,300 ft (2 530 m)

Looking northwest down the ridge separating Cliff and Little Cliff Creeks from a point about 25 yards west of preceding plate. Note the well-worn trail in foreground. Its relative location and condition suggests it may have been an access route into the Hoback Basin.

W.H. Jackson photograph 7576, courtesy of State Historical Society of Colorado.

Plate 81b   *(July 16, 1968)*

90 years later

Taken from a slightly different camera position, the slope in midground is not comparable to early scene. An increase in the density and growth of Douglas-fir is apparent, while mountain big sagebrush also appears to have increased in density.

Plate 82a   *(1878)*

Elevation   *8,200 ft (2 500 m)*

A view northeast across Little Cliff Creek from about 30 yards below preceding plate. Vegetal cover on open slope is principally mountain big sagebrush and tall forbs. Aspens occupy skyline at left midground. A past burn can be seen to right of lone subalpine fir. Haziness was result of wildfire somewhere in the Green River country or Jackson Hole. Horses (lower right) belong to Hayden Survey party.

W.H. Jackson photograph 7517, courtesy of State Historical Society of Colorado.

Plate 82b   *(July 16, 1968)*

90 years later

The tall forb-mountain big sagebrush association shows little change after 90 years. Subalpine fir show both losses and regeneration in midground. A new stand of timber occupies old burn, while the upper portion of this timber stand is in advanced succession. Aspen stands have matured.

Plate 83a   (1872)

Elevation   9,200 ft (2 805 m)

A southeast view down Miles Canyon and up the South Fork of Teton Canyon. Snags and the early growth stage of vegetation on benches and valley bottoms attest to a relatively recent fire. A low density tall forb community occurs in foreground.

USGS photograph 57-HS-1219 by W. H. Jackson.

Plate 83b   *(August 5, 1969)*

97 years later

Taken later in the season, the foreground plant cover appears more dense. Potential for vegetal growth on near slope is limited by shallow soil and a high occurrence of surface rock. After 97 years the site continues to produce a low density plant cover. Principal herbaceous species include arrowleaf balsamroot, spikefescue, eriogonum spp., tall larkspur, Indian paintbrush, fleabane spp., thickstem groundsel, and phlox spp. Aspen and conifers have matured on benches and valley bottom.

Plate 84a   *(1872)*

Elevation   *9,200 ft (2 805 m)*

From the same camera point used in the previous scene, the camera has been swung slightly to the left. Evidence of fire is more apparent than in plate 83a. Note how the fire burned some localities and bypassed others. Young aspen stands can be seen occupying various sites.

USGS photograph 57-HS-161 by W. H. Jackson, courtesy of National Archives.

Plate 84b   *(August 5, 1969)*

97 years later

A striking contrast prevails. Conifer sites are heavily forested, while some of the openings of 1872 are dominated by trees (open arrow). Mature aspen stands occupy sites that were formerly quite open (closed arrow).

Plate 85a   *(1872)*

Elevation   *9,200 ft (2 805 m)*

The view is east toward the Grand Teton from a point adjacent to the previous camera position.
Sparse ground cover prevails on near slope, while timber-producing sites in distance show a con-
tinuation of the burn pictured in previous two plates.

USGS photograph H. S. 1217 by W. H. Jackson, courtesy National Archives and Record Center.

Plate 85b   *(August 5, 1969)*

97 years later

The plant cover on near slope continues to be sparse due to poor growing conditions. Conifers have come in profusely on burned areas.

CONCLUSIONS

The 23 plates covering the southern section span a maximum of 96 years and reveal seven general trends:

1. Increased establishment and growth of conifers.

2. Decline in willows and cottonwoods on sites where competition from conifers is intense and increased growth where conifer competition is less intense.

3. Decline in aspen and deciduous shrubs such as chokecherry, serviceberry, and bitterbrush on sites where they were seral to conifers.

4. Increase in the canopy size of serviceberry, bitterbrush, and chokecherry on open slopes.

5. Overall increase in the size and density of mountain big sagebrush.

6. No appreciable change in plant cover on sparsely vegetated sites.

7. Lack of change in the Hoback River channel where the flow has been confined by topographical features.

The southern section also demonstrates widespread increases in establishment and growth of all conifer species on both winter and summer range. The most pronounced changes have occurred in localities that were in early seral stages following wildfires when originally photographed. Changes have not been confined to any particular habitat. Spruce along the Hoback River are replacing willow and cottonwood, the primary deciduous species (plate 74). However, where conifer competition is lacking or negligible, willow, cottonwood, and other shrubs have grown substantially (plate 71). On adjacent slopes and at higher elevations aspen and various deciduous shrubs have been largely replaced by Douglas-fir, lodgepole pine, subalpine fir, and Englemann spruce (plates 66-67, 71, 75-76, 78-80, 83-84).

Plates 66 and 67 show slow conifer establishment 20 to 30 years after fire. Comparable situations occur on summer range (plates 78, 80). Such slow rates of conifer establishment assure the prevalence of deciduous shrubs and aspen for many years. Note the shrub cover in plate 75 some 7 years following burning and then about 40 years later (plate 76).

Plates 66, 70, and 71 convincingly show that historic elk winter range was heavily used around 1900 and during the 1930's and early 1940's (plate 68, 69, 72, 73) prior to significant supplemental winter feeding of elk. Shrubs were in a hedged condition around 1900 (plate 71) and as late as 1943 (plate 69). Mule deer numbers were extremely low. Canopy size of bitterbrush, chokecherry, and serviceberry has increased with the shift of elk use from traditional areas to feedgrounds. This change appears to be consistent in localities where these shrubs are more numerous. The growth potential of bitterbrush and serviceberry are vividly shown in plates 72 and 73; and that of chokecherry in plates 68 and 69.

The increased growth and density of mountain big ·sagebrush (plates 64, 68-70, 76, 78) is consistent with trends in the northern and central sections. This increase may have largely occurred during the past 20 to 30 years in some localities (plates 69, 70). Changes in sagebrush density are not apparent in plates 67 and 82, and density has apparently decreased in plate 79.

Plates 64, 75-76 (left of photos), and 77 show no appreciable change in plant cover on sparsely vegetated sites. Change has only occurred on microsites where soils are deeper.

Five scenes show that stream channels have been stable where the flow is restricted by topography (plates 67, 70, 71). Road construction caused changes in plates 75 (1970) and 77. Much of the Hoback Canyon has been affected by road construction. Marked channel changes have occurred on wide valley bottoms where flows are not restricted (plate 74).

PUBLICATIONS CITED

Alyea, J. D.
1966. Climate of Jackson Hole. Climatological summary for Jackson, Wyoming Station. Rep. No. 20-48. U. S. Dep. Comm. Weather Bureau in cooperation with Univ. Wyo. 2 p. (mimeo.)

Anderson, Chester C.
1958. The elk of Jackson Hole. Wyo. Game and Fish Comm., Bull. 10, 184 p.

Bailey, R. G.
1971. Landslide hazards related to land use planning in Teton National Forest, northwestern Wyoming. USDA For. Serv., Intermt. For. and Range Exp. Stn., 131 p. Ogden, Utah.

Barlow, J. W., and D. P. Heap.
1872. Report of reconnaissance of the basin of the upper Yellowstone in 1871. U. S. Govt. Print. Off. 43 p.

Barnes, W. C.
1912. Report on the elk using the ranges of the National Forests surrounding the Yellowstone National Park. USDA For. Serv., Bridger-Teton Forest files. 71 p. (typewritten).

Benedict, J. B.
1968. Recent glacial history of an alpine area in the Colorado Front Range. U.S.A. II. Dating the glacial deposits. J. Glaciol. 7:77-87.

Bradley, F. H.
1873. Report of Frank H. Bradley, geologist. United States Geological Survey of the Territories, p. 250-254. U. S. Govt. Print. Off., Washington, D. C.

Brandegee, T. S.
1899. Survey of Teton Forest Reserve and Yellowstone Park Forest Reserve (southern part) made in summer of 1897. Nineteenth annual report of the USGS. U. S. Govt. Print. Off., Washington, D.C.

Bray, J. R.
1971. Vegetational distribution, tree growth and crop success in relation to recent climatic change. *In* Advances in Ecological Research, vol. 7, p. 177-233. J. B. Craff (ed.). Academic Press, New York.

Bryson, R. A.
1974. A perspective on climatic change. Science 184:753-760.

Buxton, E. N.
1893. The Rocky Mountains. *In* Short stalks or hunting camps north, south, east and west. 2nd ed., p. 86-121. Edward Stanford, London.

Cole, G. W.
1969. The elk of Grand Teton and southern Yellowstone National Parks. Res. Rep. GRTE-1, Yellowstone Natl. Park, 192 p. (mimeo.).

DeLacy, W. W.
1876. A trip up the south Snake River in 1863. Contributions to Historical Society of Montana, p. 113-118.

Doane, G. C.
1877. Expedition of Lieutenant G. C. Doane - Fort Ellis, Montana, to Fort Hall, Idaho. October 11, 1876 to January 4, 1877. USDI National Park Service. 41 p. (typewritten).

Dyson, J. L.
1952. Glaciers of the American Rocky Mountains. Triennial report subcommittee on the American Rocky Mountains. Comm. on Glaciers, Sec. of Hydrol., Am. Geophys. Union. Am. Geogr. Soc., New York.

Everman, V. W.
1893. A reconnaissance of the streams and lakes of western Montana and northwestern Wyoming. Bull. U.S. Fish Comm., 11:3-60.

Fenneman, N. M.
  1931. Physiography of western United States. 534 p. McGraw-Hill, New York.

Furniss, M. M.
  1972. A preliminary list of insects and mites that infest some important browse plants of western big game. USDA For. Serv. Res. Note INT-155, 16 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Fryxell, F. M.
  1928. The former range of bison in the Rocky Mountains. J. Mammal. 9(2):129-139.

Fryxell, F. M.
  1932. Thomas Moran's journey to the Tetons in 1879. Augustana Hist. Soc. Publ. No. 2, p. 3-12.

Grohman-Baillie, W. A.
  1884. Camps in the Rockies. 438 p. Charles Scribners Sons, New York.

Gruell, G. E.
  1973. An ecological evaluation of Big Game Ridge. USDA For. Serv., Intermt. Reg. Publ., 62 p. Ogden, Utah.

Gruell, G. E., and L. L. Loope.
  1974. Relationships among aspen, fire and ungulate browsing in Jackson Hole, Wyoming. USDA For. Serv., Intermt. Reg. Publ., 33 p. Ogden, Utah. [In cooperation with USDI Natl. Park Serv., Rocky Mt. Reg.]

Hague, A.
  1893. The Yellowstone Park as a game reservation. *In* American big game hunting. The book of the Boone and Crockette Club. p. 240-270. Forest and Stream Publ. Co., New York.

Haines, A. (ed.)
  1965. Osborne Russell's journal of a trapper. 191 p. Univ. Nebr. Press, Lincoln.

Hastings, J. D., and R. M. Turner.
  1965. The changing mile. Univ. of Arizona Press, Tucson, 317 p.

Hayden, V. F.
  1878. United States geological and geographical survey of the territories - Wyoming and Idaho, 1878. Hayden Part I, p. 212-214.

Henderson, A. B.
  1867. A narrative of a prospecting trip in the summer of 1867. Yellowstone Natl. Park Libr. (typewritten).

Hitchcock, C. L., and A. Cronquist.
  1973. Flora of the Pacific Northwest. Univ. Wash. Press, Seattle.

Houston, D. B.
  1968. The shiras moose in Jackson Hole, Wyo. Grand Teton Nat. Hist. Assoc., Tech. Bull. 1, 110 p.

Houston, D. B.
  1976. The northern Yellowstone elk, parts III and IV, vegetation and habitat relations. Yellowstone Natl. Park. 444 p. (mimeo.).

Ingersoll, E.
  1883. Knocking around the Rockies. 220 p. Harper and Bros., New York.

Jones, W. A.
  1875. Report upon the reconnaissance of northwest Wyoming including Yellowstone National Park made in the summer of 1873. U.S. Govt. Print. Off. 331 p.

Krebill, G. R.
  1972. Preliminary annotated list of diseases of shrubs on western game ranges. USDA For. Serv. Res. Note INT-156, 8 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Loope, L. L., and G. E. Gruell.
  1973. The ecological role of fire in Jackson Hole, northwest Wyoming. Quart. Res. 3(3):425-443.

Love, J. D.
  1956. Summary of geological history of Teton County, Wyoming, during late Cretaceous, Tertiary, and Quaternary times. *In* Wyoming Geol. Assoc. Guidebook, 11th Annu. Field Conf., p. 140-150.

Love, J. D.
1968. Stratigraphy and structure - a summary. *In* A geophysical study in Grand Teton National Park and vicinity, Teton County, Wyoming. p. E3-E12. U.S. Geol. Surv. Pap. 516-E.

Mears, B. M.
1972. Wyoming's glaciers past and present. Wyo. Wildl. 36(4):26-34.

Mitchell, J. M.
1970. A preliminary evaluation of atmospheric pollution as a cause of the global temperature fluctuation of the past century. *In* Global effects of environmental pollution. p. 139-155. AAAS Symposium. S. F. Singer (ed.). Springer-Verlag, New York.

Mueggler, W. F.
1967. Voles damage big sagebrush in southwestern Montana. J. Range Manage. 20:88-91.

Murie, O. J.
1951. The elk of North America. 376 p. Stackpole Co. and Wildlife Management Inst., Harrisburg, Pa., and Washington, D.C.

Phillips, T. A.
1970. The status of antelope bitterbrush in the Cassia mountain area of southern Idaho. Bridger-Teton Forest files, 16 p. (typewritten).

Phillips, W. S.
1962. Fire and vegetation of arid lands. First Annu. Tall Timbers Fire Ecol. Conf. (Tallahassee, Fla., 1962), p. 81-93.

Phillips, W. S.
1963. Vegetational changes in northern great plains. Univ. Ariz. Agric. Exp. Stn. Rep. 214, 185 p.

Plummer, A. P., S. B. Monsen, and R. S. Stevens.
1977. Intermountain range plant names and symbols. USDA For. Serv. Gen. Tech. Rep. INT-38, 82 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Potter, N., Jr.
1969. Tree ring dating of snow avalanche tracks and the geomorphic activity of avalanches, northern Absaroka Mountains, Wyoming. Geol. Soc. Am. Spec. Pap. 123 (INQUA Volume), p. 141-165.

Preble, E. A.
1911. Report on the condition of elk in Jackson Hole, Wyoming, in 1911. U.S. Biol. Surv. Bull. 40. U.S. Govt. Print. Off., Washington, D.C.

Price, L.
1898. A summer in the Rockies. p. 91 93. Sampson, Lowe, Marston, and Co., Ltd., London.

Progulske, D. R.
1974. Yellow ore, yellow hair, yellow pine. South Dakota State Univ. Agric. Exp. Stn. Bull. 616, 169 p.

Raynolds, F. W.
1868. Report on the exploration of the Yellowstone River in 1859-60. Senate Exec. Doc. 77. 174 p. U.S. Govt. Print. Off., Washington, D.C.

Richmond, G. M.
1972. Appraisal of the future climate of the Holocene in the Rocky Mountains. Quart. Res. 2:315-322.

Rollens, P. A. (ed.)
1935. The discovery of the Oregon Trails. 391 p. Charles Scribner's Sons, New York, London.

Roosevelt, T.
1893. An elk hunt at Two Ocean Pass. 472 p. The Wilderness Hunter, New York and London.

Shaw, R. J.
1976. Field guide to the vascular plants of Grand Teton National Park and Teton County, Wyoming. 301 p. Utah State Univ. Press, Logan.

Swain, A. M.
1973. A history of fire and vegetation in northeastern Minnesota as recorded in lake sediments. Quart. Res. 3:383 396.

Taylor, D. L.
1969. Biotic succession of lodgepole pine forests of fire origin in Yellowstone National Park. Ph.D. thesis, Univ. Wyo., Laramie. 320 p.

VanDerver, N.
ca. 1939. Notes on history of Jackson Hole from interviews of early residents. A CCC project. Bridger-Teton Forest files, 8 p. (mimeo.).

Wellner, C. A.
1970. Fire history in the northern Rocky Mountains. *In* The role of fires in the Intermountain West: symposium proceedings. p. 42-64. Intermountain Fire Research Council, Missoula.

APPENDIX I

Definitions

abiotic - Nonliving, basic elements, and compounds of the environment.

accelerated erosion - Erosion caused by the influence of man.

advanced or late succession - A plant community that has replaced earlier communities and within the writer's judgment, 100 years or more since a major disturbance.

alluvial - Pertaining to material that is transported and deposited by running water.

bedload - Materials larger than sand carried downstream by peak flows.

clearcutting - Harvest of conifers by cutting all trees on a given site.

climax - The highest ecological development of a plant community capable of perpetuation under the prevailing climatic and edaphic conditions.

clones - Individual stands derived by asexual reproduction from a single parent.

deciduous vegetation - Trees and shrubs that shed leaves during dormancy. Most species can regenerate from root crowns or root stalks.

early succession - Refers to a plant community recently established (50 years or less) following a major disturbance - usually a fire, also flood or wind.

edaphic - A condition or characteristic of the soil that influences vegetal growth.

forbs - Herbaceous plants other than grasses, sedges, and rushes.

geologic erosion - Normal or natural erosion caused by geological processes acting over long geologic periods.

half-shrubs - Perennial plants with a woody base whose annually produced stems die back each year.

herbaceous plants - Seed-producing annuals, biennials, or perennials.

hedged condition - Shrubs whose growth form has been suppressed by persistent ungulate browsing.

indigenous - Born, growing, or produced naturally in a region or country; native.

microsite - Climatic condition of a small area resulting from the modification of the general climatic conditions by local differences in elevation, exposure, or vegetal change.

plant community - An aggregation of plants within a specified area.

plant succession - The replacement of one plant community by another over time.

rill erosion - Erosion that forms numerous small channels only several inches deep.

seral - Plant communities that are replaced through successional changes.

sheet erosion - Removal of a uniform layer of soil from the land surface by runoff water.

site potential - The inherent ability of a site to produce vegetation.

wild ungulates - Hoofed big game animals including elk, moose, mule deer, bighorn sheep, and antelope.

APPENDIX II

Plants Collected on Big Game Ridge

Scientific Name	Common Name

GRASSES

Agropyron caninun (L.) Beauv. ssp. *majus* (Vasey)
   C.L. Hitchc. var. *latigluine* (Scribn. & Smith)
   C.L. Hitchc. = A. *trachycaulun*   slender wheatgrass
   var. *andinum* (Scribn. & Smith)
   C.L. Hitchc. = *A. subsecundum*   bearded wheatgrass
Bromus carinatus Hook. and Arn. var. *carinatus*   mountain brome
Deschampsia caespitosa (L.) Beauv.   tufted hair-grass
Melica bulbosa Geyer   oniongrass
Melica spectabilis Scribn.   showy oniongrass
Phleum alpinum L.   alpine timothy
Poa epilis Scribn. = *P. cusickii* Vasey
   var. *epilis* (Scribn.) C.L. Hitchc.   skyline bluegrass
Poa reflexa Vasey & Scribn.   nodding bluegrass
Sitanion hystrix (Nutt.) J.G. Smith   bottlebrush squirreltail
Stipa columbiana Macoun. = *S. occidentalis*
   Thurb. var. *minor* (Vasey) C.L. Hitchc.   subalpine needlegrass
Trisetum spicatum (L.) Richter   spike trisetum

GRASSLIKE PLANTS

Carex haydeniana Olney   cloud sedge
Carex raynoldsii Dewey   Raynolds sedge
Carex rossii Boott.   Ross sedge
Juncus drummondii E. Meyer   Drummond rush

FORBS

Achillea millefolium L. lanulosa (Nutt.) Piper   western yarrow
Aconitum columbianum Nutt.   Columbia monkshood
Agoseris glauca (Pursh) Raf.   mountain dandelion
Antennaria rosea Greene = *A. microphylla* Rydb.   rose pussytoes
Antennaria umbrinella Rydb.
Arabis lyallii Wats.   Lyall rockcress
Arnica cordifolia Hook.   heartleaf arnica
Arnica longifolia D.C. Eaton   longleaf arnica
Aster foliaceus Lindl. *parryi* (Eaton) Gray
Aster foliaceus Lindl. var. *canbyi* Gray   alpine leafybract aster
Aster integrifolius Nutt.   thickstem aster
Caltha leptosepala DC.   elkslip marshmarigold
Castilleja miniata Dougl.   scarlet painted-cup
Claytonia lanceolata Pursh var. *lanceolata*   lanceleaf spring beauty

Scientific Name	Common Name
Delphinium nuttallianum Pritz.	Nuttal larkspur
Delphinium occidentale Wats.	duncecap larkspur
Descurainia richardsonii (Sweet) O.E. Schultz	Richardson tansymustard
Draba stenoloba Ledeb. var. *nana* (O.E. Schultz) C.L. Hitchc.	draba
Epilobium glandulosum Lehm.	glandular willow-weed
Erigeron callianthemus Greene = *E. peregrinus* (Pursh) Greene ssp. *callianthemus* (Greene) Cronq.	
Erigeron eatoni Gray var. *eatoni*	Eaton fleabane
Erigeron ursinus D.C. Eat.	Bear River fleabane
Eriogonum umbellatum Torr. var. *intectum* Nels. *(neglectum)* Greene	sulfur eriogonum
Erythronium grandiflorum Pursh var. *grandiflorum*	lambstongue fawnlily
Geranium viscosissimum F. & M.	sticky geranium
Hackelia floribunda (Lehm.) Johnst.	showy stickseed
Helianthella quinquenervis (Hook) A. Gray	fivenerve helianthella
Hydrophyllum capitatum Dougl. var *capitatum*	ballhead waterleaf
Ligusticum filicinum S. Wats.	fernleaf ligusticum
Lomatium montanum = *L. cous* (Wats.) Coulti & Rose	biscuitroot
Lupinus argenteus Pursh var. *parviflorus* (Nutt.) S.L. Hitchc.	silvery lupine
Lupinus wyethii S. Wats.	Wyethia lupine
Mertensia ciliata (Torr.) G. Don	mountain bluebells
Mertensia paniculata (Ait.) G. Don	
Microseris nigrescens Henderson	microseris
Mimulus lewisii Pursh	Lewis monkeyflower
Myosotis sylvatica Hoffm. var. *alpestris* (F.S. Schmidt.) Koch	forgetmenot
Pedicularis groenlandica Retzi.	elephanthead
Penstemon whippleanus A. Gray	Whipple penstemon
Plantago tweedyi A. Gray	tweedy plantain
Polemonium pulcherrimum Hook. var. *pulcherrimum*	polemonium
Polygonum bistortoides Pursh	American bistort
Potentilla diversifolia Lahm. var. *diversifolia*	varileaf cinquefoil
Ranunculus escholtzii Schlacht var. *alpina* (Wats.) C.L. Hitchc.	Eschscholtz buttercup
Rumex pauciflorus Nutt.	mountain sorrel
Saxifraga argusta D. Don	
Senecio crassulus Gray	thickleaf groundsel
Senecio triangularis Hook.	arrowleaf groundsel
Sibbaldia procumbens L.	
Taraxacum officinale Weber	common dandelion
Viola nuttallii Pursh	Nuttal violet

SHRUBS

Ribes montigenum McClatchie	gooseberry currant

202

APPENDIX III

Representative Plants on Gros Ventre and Hoback Winter Ranges

Scientific Name	Common Name

GRASSES

Agropyron spp.	wheatgrass
Agropyron dasystachyum (Hook.) Scribn.	thickspike wheatgrass
Agropyron smithii Rydb.	bluestem wheatgrass
Agropyron spicatum (Pursh) Scribn. & Smith	bearded bluebunch wheatgrass
Agropyron canium (L.) Beauv. spp. *majus* (Vasey) C.L. Hitchc. var. *latiglume* (Scribn. & Smith) C.L. Hitchc. = *A. trachycaulum*	slender wheatgrass
Bromus anomalus Rupr.	nodding brome
Bromus carinatus Hook. & Arn. var. *carinatus*	mountain brome
Bromus inermis Leysser	smooth brome
Bromus tectorum L.	cheatgrass brome
Calamagrostis rubescens Buckl.	pinegrass
Danthonia unispicata (Thurb.) Munro ex Macoun	onespike danthonia
Deschampsia caespitosa (L.) Beauv.	tuffed hair-grass
Elymus cinereus Scribn. & Merr.	Great Basin wildrye
Elymus glaucus Buckl.	blue wildrye
Festuca spp. L.	fescue
Festuca idahoensis Elmer	Idaho fescue
Hesperochloa kingii (Wats.) Rydb.	spikefescue
Hordeum brachyantherum Nevski	meadow barley
Koeleria cristata Pers.	prairie junegrass
Melica spectabilis Scribn.	showy oniongrass
Muhlenbergia richardsonis (Trin.) Rydb.	mat muhly
Oryzopsis hymenoides (R. & S.) Ricker	Indian ricegrass
Phleum pratense L.	timothy
Poa ampla Merr. = *P. juncifolia* Scribn.	big bluegrass
Poa canbyi (Scribn.) Piper = *P. scabrella* (Thurb.) Benth.	Canby bluegrass
Poa fendleriana (Steud.) Vasey	mutton bluegrass
Poa pratensis L.	Kentucky bluegrass
Poa sandbergii Vasey	Sandberg bluegrass
Sitanion hystrix (Nutt.) J.G. Smith	bottlebrush squirreltail
Stipa columbiana Macoun. = *S. occidentalis* Thurb. var. *minor* (Vasey) C.L. Hitchc.	subalpine needlegrass
Stipa comata Trin. & Rupr.	needle and thread
Stipa lettermanii Vasey	Letterman needlegrass

GRASSLIKE PLANTS

Carex douglasii Boott.	Douglas sedge
Carex festivella Mack. = *C. micranthara* Mack.	ovalhead sedge
Carex geyeri Boott.	elk sedge
Carex hoodii Boott.	hood sedge
Carex petasata Dewey	liddon sedge
Carex rossii Boott.	Ross sedge
Carex rostrata Stokes	beaked sedge
Juncus balticus Willd.	Baltic sedge

Scientific Name	Common Name

FORBS

Scientific Name	Common Name
Achillea millefolium L. spp. *lanulosa* (Nutt.) Piper	western yarrow
Agoseris spp. Raf.	agoseris
Anemone spp. L.	anemone
Antennaria dimorpha (Nutt.) T. & G.	low pussytoes
Antennaria microphylla Rydb.	rose pussytoes
Apocynum androsaemifolium L.	spreading dogbane
Aquilegia spp. L.	columbine
Arabis glabra (L.) Bernh.	rockcress
Arabis holboelli Hornem.	Holboell rockcress
Arnica spp. L.	arnica
Arnica fulgens Pursh	orange arnica
Artemisia dracunculus L.	tarragan
Artemisia ludoviciana Nutt.	Louisiana sagebrush
Aster canescens (See *Machaeranthera*) (Pursh) Gray	aster
Aster chilensis Nees.	Pacific aster
Aster perelegans Nels. & Macbr.	Nuttal aster
Astragalus alpinus L.	alpine milkvetch
Astragalus bisulcatus (Hook.) Gray	twogrooved locoweed
Astragalus kentrophyta Gray	
Astragalus purshii Dougl.	pursh locoweed
Astragalus vexilliflexus Sheld.	
Balsomorhiza sagittata (Pursh) Nutt.	arrowleaf balsam
Calochortus spp. Pursh	mariposa
Calochortus bruneaunis Nels. & Macbr.	
Calochortus eurycarpus Wats.	
Campanula rotundifolia L.	bluebell
Castilleja gracillima Rydb.	
Castilleja linariaefolia Benth.	Wyoming painted-cup
Castilleja rustica Piper	
Chaenactis douglasii (Hook.) H. & A.	Douglas chaenactis
Chenopodium album L.	lambsquarters goosefoot
Cirsium spp. Mill.	thistle
Cirsium foliosum = C. scariosum Nutt.	elk thistle
Cirsium vulgare (Savi) Tenore	bull thistle
Collomia linearis Nutt.	slenderleaf collomia
Camandra pallida A. DC. = *C. umbellata* (L.) Nutt. var. *pallida* (DC.) Jones	bastard toadflax
Cordylanthus ramosus Nutt.	bush birdbeak
Corydalis aurea Willd.	golden corydalis
Crepis acuminata Nutt.	tapertip hawksbeard
Cryptantha spp. Lehm.	cryptantha
Cymopterus spp. Raf.	
Descurainia spp. Webb and Berth.	tansymustard
Epilobium spp. L.	willowweed
Epilobium angustifolium L.	fireweed
Equisetum spp. L.	horsetail
Erigeron compositus Pursh	fernleaf fleabane
Erigeron pumilus Nutt.	low fleabane
Eriogonum chrysocephalum Gray	goldball eriogonum
Eriogonum umbellatum Torr.	sulfur eriogonum

Scientific Name	Common Name
Eriophyllum lanatum (Pursh) Forbes	woolly eriophyllum
Fragaria virginiana Duchense	Virginia strawberry
Frasera speciosa Dougl.	showy frasera
Gayophytum spp. Juss	groundsmoke
Galium boreale L.	northern bedstraw
Geranium viscosissimum F. & M.	sticky geranium
Geum triflorum Pursh	
Gilia aggregata (Pursh) Spreng.	skyrocket gilia
Haplopappus acaulis (Nutt.) Gray	stemless goldenweed
Hedysarum sulphurescens Rydb.	sulfur sweetvetch
Helenium hoopesii Gray	orange sneezeweed
Helianthella uniflora (Nutt.) T. & G.	oneflower helianthella
Heracleum lanatum Michx.	common cowparsnip
Hieracium spp. L.	hawkweed
Hydrophyllum capitatum Dougl.	ballhead waterleaf
Lactuca serriola L.	prickly lettuce
Lappula spp. Gilib.	stickseed
Linum perenne L.	Lewis flax
Lithospermum ruderale Dougl.	wayside gromwell
Lomatium dissectum (Nutt.) Math. & Const.	carrotleaf leptotaenia
Lupinus spp. L.	lupine
Lupinus sericeus Pursh	silky lupine
Melilotus officinalis (L.) Lam.	yellow sweetclover
Mertensia oblongifolia (Nutt.) G. Don	oblongleaf bluebells
Mimulus spp.	monkeyflower
Monolepis nuttalliana (Schultes) Greene	Nuttall monolepis
Orthocarpus luteus Nutt.	yellow owlclover
Osmorhiza occidentalis (Nutt.) Torr.	sweetanise
Penstemon attenuatus Dougl.	sulphur penstemon
Penstemon procerus Dougl.	littleflower penstemon
Penstemon radiocsus A. Nels.	matroot penstemon
Perideridia gairdneri (H. & A.) Math.	yampa
Phacelia spp. Juss	phacelia
Phlox hoodii Rich.	Hoods phlox
Physaria australis (Pays.) Roll.	common twinpod
Polygonum douglasii Greene	Douglas knotweed
Potentilla spp. L.	cinquefoil
Potentilla glandulosa Lindl.	
Potentilla gracilis Dougl.	
Ranunculus spp. L.	butterfoot; crowfoot
Rumex crispus	curly dock
Saxifraga spp. L.	saxifrage
Sidalcea spp. Gray	checkermallow
Sedum stenopetalum Pursh	wormleaf stonecrop
Senecio spp. L.	groundsel; ragwort; butterweed
Senecio canus Hook.	woolly groundsel
Sencio serra Hook.	butterweed groundsel
Smilacina stellata (L.) Desf.	starry solomon-plume
Solidago multiradiata Ait.	low goldenrod
Taraxacum officinale Weber	common dandelion
Tragopogon dubius Scop.	
Trifolium spp. L.	clover
Trillium spp. L.	trilium
Valeriana edulis Nutt.	edible valerian
Valeriana occidentalis Heller	western valerian

Scientific Name	Common Name
Viguiera multiflora (Nutt.) Blake.	showy goldeneye
Viola spp. L.	violet
Viola nuttallii Pursh	Nuttall violet
Zigadenus paniculatus (Nutt.) Wats.	foothill deathcamas

TREES AND SHRUBS

Scientific Name	Common Name
Abies lasiocarpa (Hook.) Nutt.	subalpine fir
Acer glabrum Torr.	rocky mountain maple
Alnus tenuifolia Nutt.	thinleaf alder
Amelanchier alnifolia Nutt.	Saskatoon serviceberry
Arctostaphylos uva-ursi (L.) Spreng.	bearberry
Artemisia cana Nutt.	silver sagebrush
Artemisia frigida Willd.	fringed sagebrush
Artemisia longiloba (Osterhout) Beetle	longleaf sagebrush
Artemisia tridentata Nutt. subsp. *tridentata*	big sagebrush
Artemisia tridentata Nutt. *vaseyana* (Rydb.) Beetle	mountain big sagebrush
Artemisia tripartita Rydb.	threetip sagebrush
Atriplex spp. L.	saltbush
Berberis repens Lindl.	creeping barberry
Betula glandulosa Michx.	bog birch
Ceanothus velutinus Dougl.	snowbrush ceanothus
Chrysothamnus nauseousus (Pall.) Britt. var. *nauseousus*	rubber rabbitbrush
Chrysothamnus viscidiflorus (Hook.) Nutt.	Douglas rabbitbrush
Clematis columbiana (Nutt.) T. & G.	Columbian clematis
Cornus stolonifera Michx. *stolonifera*	redosier dogwood
Crataegus spp.	hawthorne
Eurotia lanata (Pursh) Moq.	common winterfat
Gutierrezia sarothrae (Pursh) Britt. & Rusby.	broom snakeweed
Juniperus communis L. var. montana Ait.	mountain common juniper
Juniperus scopulorum Sarg.	Rocky Mountain juniper
Lonicera involucrata (Rich) Banks	bearberry honeysuckle
Lonicera utahensis Wats.	Utah honeysuckle
Menziesia ferruginea Smith	false huckleberry
Pachistima myrsinites (Pursh) Raf.	mountain lover
Picea engelmanni Parry	Engelmann spruce
Picea pungens Engelm.	Colorado blue spruce
Pinus albicaulis Engelm.	whitebark pine
Pinus contorta Dougl.	lodgepole pine
Pinus flexilis James	limber pine
Populus angustifolia James	narrowleaf cottonwood
Populus tremuloides Michx.	quaking aspen
Populus trichocarpa T. & G.	black cottonwood
Pontentilla fruticosa L.	bush cinquefoil
Prunus virginiana L. var. *demissa* (Nutt.)	western common chokecherry
Pseudotsuga menziesii (Mirbel) Franco *menziesii* Torr. var. *glauca* (Beissn) Franco	Douglas-fir
Purshia tridentata (Pursh) DC.	antelope bitterbrush
Ribes spp. L.	currant; gooseberry
Ribes cereum Dougl. var. *cereum*	wax currant
Rosa woodsii	woods rose
Salix spp. L.	willow

Scientific Name	Common Name
Salix bebbiana Sargent	Bebb willow
Salix brachycarpa Nuttall	barrenground willow
Salix drummondiana Barratt	Drummond willow
Salix exigua Nutt. spp. *interior*	sandbar; interior willow
Salix geyeriana Anderss. (Rowlee) Cronq.	geyer willow
Salix pseudocordata (Anderson) Rydberg	blueberry willow
Salix phylicifolia L. var. *planifolia* Pursh	planeleaf willow
Salix lutea Nuttall	yellow willow
Salix scouleriana Barratt	Scouler's willow
Salix wolfii Bebb	wolf's willow
Sambucus cerulea (glauca) Raf.	blueberry elderberry
Sarcobatus vermiculatus (Hook.) Torr.	black greasewood
Shepherdia argentea (Pursh) Nutt.	silver buffaloberry
Shepherdia canadensis (L.) Nutt.	russet buffaloberry
Sorbus spp. L.	mountain ash
Spiraea densiflora Nutt.	meadowsweet
Spiraea betulifolia Pall.	shinyleaf spirea
Symphoricarpos oreophilus Gray	mountain common snowberry
Tetradymia canescens DC.	gray horsebrush
Vaccinium membranaceum Dougl.	big whortleberry
Vaccinium scoparium Leiberg	grouse whortleberry

    Volume 1 (of two volumes) provides 85 pairs of photos documenting changes in
vegetation and wildlife habitat on the Bridger-Teton National Forest, 1872-1975.
Conifers and mountain big sagebrush have increased. Willow, aspen, and deciduous
shrubs have been replaced where seral to or in competition with conifers. Fire has
been the most important influence on plant succession.   Volume II explains why
vegetational changes took place.

KEYWORDS: wildfire, wildlife habitat, plant succession, range condition, historic
photographs, photographic record.

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field programs and research work units are maintained in:

Billings, Montana
Boise, Idaho
Bozeman, Montana (in cooperation with Montana State University)
Logan, Utah (in cooperation with Utah State University)
Missoula, Montana (in cooperation with University of Montana)
Moscow, Idaho (in cooperation with the University of Idaho)
Provo, Utah (in cooperation with Brigham Young University)
Reno, Nevada (in cooperation with the University of Nevada)

DATE DUE

Ref'd DEC 17 '93	