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David A. Hamilton, Jr.

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RESEARCH SUMMARY

Mortality rates specify the proportion of trees with a given set of characteristics that are expected to die in a fixed time interval. Knowledge of these rates is the weakest of the key components of yield predictions. This lack of knowledge of mortality rates is primarily due to a lack of suitable data and inappropriate or inefficient data collection procedures. The objectives of this study, stated as questions, are:

1. Can 1- and 2-year-old mortality be accurately identified on large-scale aerial photography?

2. Can species identification of mortality trees and of green trees be accurately done on large-scale erial photography?

Test results indicate that 1-year mortality can be dated and that, with acceptable accuracy, species an be assigned to green trees and to 1-year mortality trees on 1:1600 and 1:2400 scale color aerial hotography. These results have led to the design of a mortality sampling procedure that uses a quarter nile strip (8 frames) of 70 mm true color aerial photography at a scale of 1:2400 as the primary sample nit. At a scale of 1:2400, each frame covers 2.25 times the area covered by a frame at 1:1600. Use of his larger sample unit increases the likelihood of including some mortality on each sample unit. The rocedure was designed for the Northern Region, USDA Forest Service.

CONTENTS

INTRODUCTION

Mortality rates, diameter increment rates, and eight increment rates are the key components of ll yield predictions. Mortality rates are the veakest of the three components. Information on iameter and height increment rates is readily vailable from silvicultural research plots where cientists have studied growth under a wide array f environmental conditions and management trategies. In addition, in most forest survey or nanagement planning inventories, information on urrent diameter and height increment rates is ollected. Where such data are not readily availble, diameter and height increment can be oberved in a single visit to the plot. Annual rings and odal scars provide the time scale that makes nese measurements possible on many species rowing in temperate forests. There is no comarable time scale for easily and accurately postating mortality. Thus, data describing the occurence of mortality is more difficult to obtain.

Silvicultural research plots on which individual ees have been measured for many years provide potential source of data for estimating relationhips between stand and tree characteristics and nortality rates. However, use of such data is everely weakened by the common practice of eleting plots containing heavier than average nortality from the experiment. Further, such data re not available for all species and localities and o not provide measures of current levels of nortality.

Many mortality surveys estimate the amount of ead timber in a population by counting dead ees, measuring the volume of dead trees, or neasuring the number of acres that contain a ubstantial number of dead trees. Such informaon is of little value in predicting future mortality.

Sampling for mortality rates requires two types f information not collected in the usual mortality urvey: counts of green trees and the year of death or mortality trees. Mortality rates specify the roportion of trees with a given set of characterstics that are expected to die in a fixed time nterval; to know that proportion both green and ead trees must be sampled. It is also necessary to etermine a time scale for mortality occurrence; this requires that the time of death be estimated for each dead tree sampled.

Once mortality rates are established, they may be used for many purposes. Current mortality rate models are designed to describe the occurrence of mortality in a stand as the stand grows. However, if an estimate of number of dead trees or an estimate of volume in dead trees is desired, mortality rate models may be used in the context of a stand inventory compilation system to produce these estimates (much as volume equations are used to estimate stand volume).

Management planning inventory information in the Northern Region of the USDA Forest Service is collected on variable radius plots (basal area factor = 40) arranged in a 10-chain by 5-chain grid on subcompartments of about 500 acres (200 ha) selected with probability proportional to National Forest acreage (Stage and Alley 1972). Mortality data are collected by estimating which trees have died in the past 5 years on each sample point. The sampling design results in efficient estimates of variables such as volume, diameter, diameter growth rate, and height, but the design is inefficient for collecting information about mortality.

This is true for several reasons. Under normal conditions, mortality is a rare event. A rule of thumb is that the expected normal mortality rate is about 0.5 percent per year (that is, one tree out of every 200 will die in a year's time). Also, mortality is not uniformly distributed over the forest in either time or space. An assumption of some form of clustered distribution for mortality trees is probably more accurate than an assumption of either a uniform or random distribution. Thus, most standard ground inventory systems (either variable radius plot sampling designs or designs using small fixed area plots) are not very efficient for collecting mortality information. Finally, there is some question as to the ability of field crews to accurately estimate which trees have died within the past 5 years. Postdating mortality on trees dead for more than 2 years is difficult even for a trained pathologist or entomologist because of the great variability in deterioration of individual trees (Miller and Keen 1960; Keen 1955).

Because the distribution of mortality is often clustered and because of the large size of some areas to be inventoried, a sampling design making use of large-scale aerial photography would appear to offer advantages. Heller and others (1964) and Sayn-Wittgenstein (1960) determined that tree species can be identified to acceptable accuracy standards on large-scale color aerial photography. This paper investigates the use of aerial photography in mortality sampling. The study objectives, stated as questions, are:

1. Can 1- and 2-year-old mortality be accurately identified on large-scale aerial photography?

2. Can species identification of mortality trees and of green trees be accurately done on large-scale aerial photography?

METHODS

Photography Obtained

For this study, 70 mm aerial photography was taken with 60 percent endlap on two flight lines on one subcompartment and a single flight line on a second subcompartment of the Coeur d'Alene National Forest (administered as part of the Idaho Panhandle National Forests). The flight lines varied in length from 1.5 miles (2.4 km) to slightly over 2 miles (3.2 km). The photographs were taken and processed in June 1971 by John Wear and Richard Myhre, who at the time were with the Remote Sensing Research Work Unit of the Pacific Southwest Forest and Range Experiment Station. The combinations of scale and film type used in this study were 1:1600 and 1:2400 true color transparencies. However, because the photographs were taken over rough terrain, there is considerable variability in scale in different segments of the photo strips. Because 70 mm photography at scales of 1:1600 and 1:2400 frequently does not include a broad enough area to be used to locate specific photo plots on the ground, 1:4800 black and white photographs were taken simultaneously. The 1:4800 black and white photographs were not used in the identification of green or mortality trees. Instead, they were enlarged, printed, and used to locate photo plots for ground examination.

Photo Interpretation

The subcompartments photographed fell primarily in the grand fir-cedar-hemlock ecosystem. Species growing on the photographed portions of the subcompartments were Douglas-fir, grand fir, white pine, western larch, western hemlock, ponderosa pine, lodgepole pine, and western redcedar. Stand density conditions on the two subcompartments ranged from low density, poorly stocked stands to high density, well stocked stands.

All photo interpretation was done in stereo. On each photo frame all 1- and 2-year mortality trees were identified by species: the 1-year mortality by brightly discolored foliage and retention of most of this foliage; and the 2-year mortality by dully discolored foliage with very little of it retained (Miller and Keen 1960). These characteristics vary both among species and from year to year because of climatic variation. However, these characteristics are an acceptable average descriptor for general use in dating mortality on large-scale aerial photography.

On every 12th frame of 1:1600 scale photography, a 0.6 inch by 0.6 inch (1.52 cm by 1.52 cm) subplot was established near the center of the frame. Although this resulted in unequal sized plots on the ground (because of variation on scale on each flight line) it did assure that a constant proportion of the photographs were sampled. A total count of green trees by species was made on each subplot. In addition, five trees were selected on each subplot to test species identification on an individual tree basis.

Ground Examination

Every sixth frame of 1:1600 scale photography was used for ground examination. All 1- and 2-year mortality trees identified on the photographs were checked on the ground. Discrepancies were examined again both on the ground and on the photos in an effort to explain the error and thus improve future photo interpretation.

Each photo subplot used to sample green trees was located on the ground. All green trees on these plots were counted by species. The five ees selected on each photo subplot for testing dividual tree species identification were located the ground and the species recorded. Similar ethods were applied to the 1:2400 scale photog-phy. However, ground examination was limited a subset of those areas used to ground check e 1:1600 scale photography.

As a further test of accuracy of identifying 1-year ortality trees, in summer 1972, the flight lines on e two subcompartments were reflown by Robert eller, then with the Pacific Southwest Forest and ange Experiment Station. The photographs were mm, 1:3200 scale true color transparencies. is scale was selected to provide some assur-nce that a majority of the 1971 photographs ould be included in the 1972 coverage.

RESULTS OF PHOTO INTERPRETATION

The first study objective deals with the accuracy identifying 1- and 2-year mortality trees. Tables 4 summarize the accuracy with which date of ortality was assigned to mortality trees.

The results indicate that 1-year mortality trees an be accurately identified on 1:1600 scale color erial photography. There were errors in identify-g and dating white pine mortality on one of the ght lines on the 1:1600 scale photography. This as due to inadequate training of interpreters. areful examination has led me to conclude that, ith proper training, this problem can be avoided.

If white pine are omitted from the analysis, the umber of mortality trees correctly dated, ex-ressed as a percent of ground truth, increases om 74 percent to 85 percent (tables 3 and 4). hus, I anticipate that 1-year mortality can be orrectly dated at least 85 percent of the time on 1600 scale photography. Interpretation accu-cy is reduced to 70 percent when photography ale is reduced to 1:2400.

The number of 2-year mortality trees correctly dated, expressed as a percent of ground truth, is only 50 percent on 1:1600 scale photography. When the photo scale is reduced to 1:2400, interpretation accuracy decreases to 22 percent.

This reduction in interpretation accuracy is primarily due to an increase in the number of missed trees on the 1:2400 scale photography. If white pine are deleted from the analysis virtually no difference exists in the interpreter's ability to identify 1-year mortality on the two photo scales, given the dead tree is detected on the photograph (tables 3 and 4). On 1:1600 scale photography, 88 percent of the trees rated as 1-year mortality trees were correctly rated. On 1:2400 scale photography, 90 percent of the trees rated as 1-year mortality trees were correctly rated.

Tables 1 and 2 may also be used to compare the distribution of mortality trees identified on the aerial photographs with the actual distribution on the ground. On 1:1600 scale photography, the number of 1-year mortality trees is within 2 percent of the number found on the ground. On 1:2400 scale photography, the number of 1-year mortality trees is within 7 percent of the number found on the ground. Thus, the number of errors of omission (1-year mortality trees either missed or misclassified on the photos) must be almost equal to the number of errors of commission (trees identified on the photos as 1-year mortality that actually had either been dead more than 1 year or were not dead).

Interpretation accuracy of 2-year mortality is much poorer. On 1:1600 scale photography the number of 2-year mortality trees identified is only within 25 percent of the number found on the ground. The number of 2-year mortality trees identified on 1:2400 scale photography is only within 50 percent of the number found on the ground. The reduction in interpretation accuracy is due primarily to the many 2-year mortality trees missed on the photographs. Most of the missed 2-year mortality trees were identified as being dead for more than 2 years and thus were not recorded.

Table 1.—Results of photo interpretation of 1:1600 scale photography for date of mortality

	Photo classification			
Ground classification	Dead 1 year	Dead 2 years	Missed	Total
Dead 1 year	31	1	10	42
Dead 2 years	4	14	10	28
Dead more than 2 years	1	5		6
Not dead or no tree	7	1		8
Total	43	21	20	84

Table 2.—Results of photo interpretation of 1:2400 scale photography for date of mortality

	Photo classification			
Ground classification	Dead 1 year	Dead 2 years	Missed	Total
Dead 1 year	20	2	7	29
Dead 2 years	2	4	12	18
Dead more than 2 years		3		3
Not dead or no tree	5			5
Total	27	9	19	55

able 3.—Results of photo intrepretation of 1:1600 scale photography for date of mortality (excluding white pine)

	Photo classification			
round classification	Dead 1 year	Dead 2 years	Missed	Total
ead 1 year	28	1	4	33
ead 2 years	3	14	7	24
ead more than 2 years		3		3
ot dead or no tree	1			1
Total	32	18	11	61

able 4.—Results of photo interpretation of 1:2400 scale photography for date of mortality (excluding white pine)

	Photo classification			
round classification	Dead 1 year	Dead 2 years	Missed	Total
ead 1 year	19	2	6	27
ead 2 years	1	4	11	16
ead more than 2 years		2		2
ot dead or no tree	1			1
Total	21	8	17	46

The second study objective deals with the interpreter's ability to identify the species of green and mortality trees. Species identification of 1-year and 2-year mortality trees is summarized in tables 5 and 6. The results indicate that we can identify 1-year mortality by species with reasonable accuracy on either 1:1600 or 1:2400 scale color aerial photography. However, species identification of 2-year mortality is very poor.

On 1:1600 scale photography, 88 percent of the 1-year mortality trees identified on the photos were assigned the proper species identification. Species was assigned properly to only 44 percent of the 2-year mortality trees. On 1:2400 scale photography, 91 percent of the 1-year mortality trees were properly identified. Species was properly assigned to 83 percent of the 2-year mortality trees. However, so few 2-year mortality trees were included in the sample that this is probably not a true indication of the interpreter's ability to identify species of 2-year mortality on 1:2400 scale photography.

Green tree species identification has only been tested on 1:1600 scale photography. However, the results of testing the accuracy of species identification of mortality trees indicates that one should expect very little difference in interpreter's ability to identify species on 1:2400 scale photography. Of the 80 green trees selected on the 1:1600 scale photos, 95 percent were correctly identified. Thus, it is anticipated that on 1:2400 scale photos properly trained interpreters will also be able to accurately identify the species of close to 95 percent of the green trees.

Table 5.—Species identification of mortality trees on 1:1600 scale photography

Identification	Dead 1 year	Dead 2 years
Species correctly identified	28	8
Species incorrectly identified	4	10
Missed	10	10
Total	42	28

Table 6.—Species identification of mortality trees on 1:2400 scale photography

Identification	Dead 1 year	Dead 2 years
Species correctly identified	20	5
Species incorrectly identified	2	1
Missed	7	12
Total	29	18

Table 7 describes the relationship between the umber of green trees counted on the photo ubplots and the number counted when these ots were measured on the ground. The photo ount of green trees was 16 percent below the ound count. Grand fir and Douglas-fir were the ost common species on the photographs. The hoto count of grand fir was 88 percent of the ound count. The photo count of Douglas-fir was 2 percent of the ground count. The other species ere too poorly represented in the sample to ake inferences about the accuracy of the photo unts.

The second-year photo interpretation made use of both the 1971 and 1972 photography. All 1-year and 2-year mortality trees were identified by species on the 1:3200 scale, 1972 photography. Each tree that also appeared on the 1971 photography was located and examined on the 1:1600 true color photography obtained in 1971.

Of the 1-year mortality trees, 89.4 percent were properly identified on the 1:3200 scale photography. All trees identified as 1-year mortality trees on the 1:3200 scale, 1972 photography were alive in 1971. A small number of trees identified as 2-year mortality on the 1972 photography were alive in 1971.

Table 7.—Species identification of green trees on 1:1600 scale photography

Flight line	Source of data	Species								
		Grand fir	Douglas-fir	White pine	Western hemlock	Western larch	Western redcedar	Ponderosa pine	Lodgepole pine	Total
1	Photo count	48	43	23	6	5	6	4	—	135
	Ground count	57	46	30	8	5	8	5	—	159
2	Photo count	34	95	1	1	1	—	—	2	134
	Ground count	44	113	1	1	1	—	1	2	163
3	Photo count	52	69	—	1	11	—	—	3	136
	Ground count	52	92	—	1	15	—	—	3	163
TOTAL	Photo count	134	207	24	8	17	6	4	5	405
	Ground count	153	251	31	10	21	8	6	5	485

DISCUSSION

These procedures may not be applied to estimate mortality rates for larch. Larch is deciduous and thus year of mortality cannot be estimated by the foliage retention characteristics described here. Larch killed prior to the time photos are taken but showing no signs of needle discoloration, or trees killed after photos are taken, will drop their needles prior to the next growing season. Such trees will not fit the characteristics of 1-year mortality trees on either current-year photographs or on those taken the following year, and thus will never be counted as mortality trees. Similar problems exist if this approach is applied to other deciduous species. Larch mortality dating is further complicated by the defoliation of larch by larch casebearer. Such trees may be difficult to distinguish from larch that have died during the current growing season.

The description of a dead tree may also impose limitations on the use of these procedures. A tree that has died in the past year is identified by its brightly discolored foliage and by the retention of the majority of this foliage. Trees that die slowly (a few branches each year) will never fall into this category and thus will never be classified as current mortality. This is not a problem unique to photo identification of current mortality. It is difficult to determine when such a tree is to be considered dead, even when the tree is observed on the ground.

In spite of these limitations, I decided that 1-year mortality could be dated and that species could be assigned to green trees and to 1-year mortality trees on 1:1600 and 1:2400 scale photography with acceptable accuracy. A procedure was designed for sampling mortality for the Northern Region that uses a quarter mile strip (eight frames) of 70 mm true color aerial photography at a 1:2400 scale as the basic sampling unit. This scale was selected for practical reasons. With the plane, camera, and lens available to the Region, 1:2400 was the maximum scale that could be obtained.

Although a reduction in interpretation accuracy occurred when the scale was reduced from 1:1600 to 1:2400, I felt that with proper training of interpreters, the 1:2400 scale would provide acceptable results. The sampling design, estimation procedures, and photo interpretation guidelines are described in detail in two companion publications (Hamilton,[1] and Croft, Heller, and Hamilton[2]).

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Mortality rates specify the proportion of trees with a given set of characteristics that are expected to die in a fixed time interval. Results indicate that 1-year mortality trees can be dated and species can be assigned to green trees and to 1-year mortality trees with acceptable accuracy on 70 mm color photography at scales of 1:1600 and 1:2400. Attempts to date 2-year mortality trees on either scale photography were unsuccessful.

KEYWORDS: Mortality inventory, 70 mm aerial photography, mortality rate

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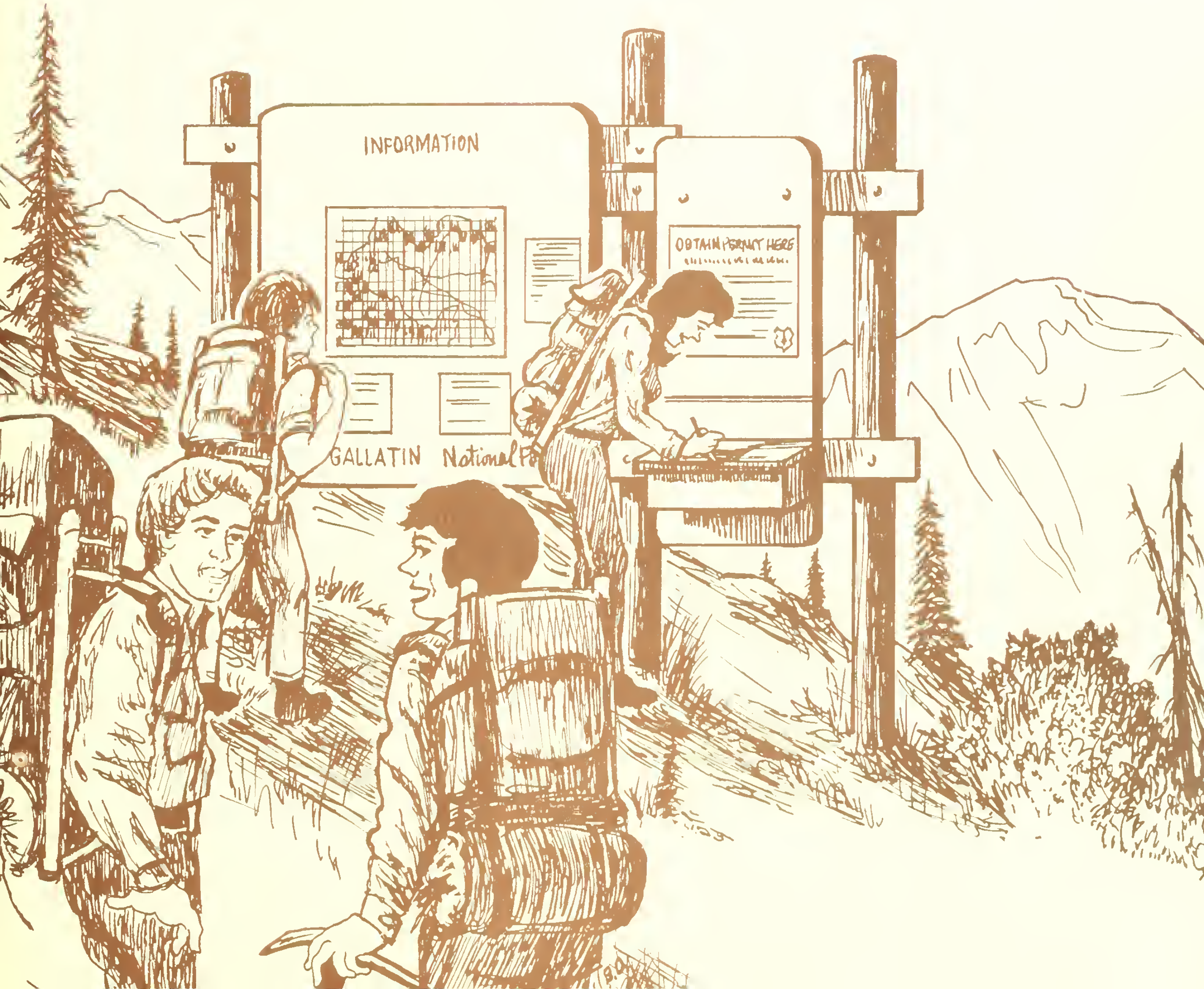
Self-Issued Wilderness Permits as a Use Measurement System

Robert C. Lucas and Thomas J. Kovalicky



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RESEARCH SUMMARY

Wilderness recreational use is difficult to measure. Many approaches have been tried, but all have limitations. Self-issued, mandatory permits are a relatively new system. Such a system was begun for the Spanish Peaks Primitive Area, Montana, in 1978. A rigorous evaluation was conducted to determine compliance by different types of visitors and for different types of permit station locations.

Virtually all use at the six major trailheads was counted and classified in terms of compliance and in terms of a number of variables believed to influence visitor compliance, using automatic electronic use-monitoring equipment.

Overall, 53 percent of the visitor groups obtained permits. Compliance varied widely among different trailheads, from 21 to 72 percent. Stations located up the trails away from the parking areas at the trailheads had higher compliance rates than those at the trailheads. Summer and fall compliance rates were identical. Compliance dropped sharply as visits became shorter. This was the factor most strongly related to compliance among the variables examined. Campers, whether hiking or riding, complied 72 percent of the time, and this varied little among trailheads. Day-users had only a 45-percent compliance rate, with wide fluctuations among trailheads. The briefer the day-use, the lower the compliance. Visitors staying less than 2 hours had only a 20-percent compliance rate, while those staying over 3 hours had a 65-percent compliance rate. Day-visitors riding horses had only a 25-percent compliance rate. Persons visiting the area alone had lower compliance than groups.

The self-issued permit system works best for the longer-term visitors, who have the most importance for management planning. The system appears, in its first year, to have produced slightly better data than voluntary trail registers used earlier. It approximates the performance of agency-issued permits in some areas, but falls short of the compliance obtained in other areas. The system appears to have promise as a use measurement system, although a decision to adopt self-issued permits also needs to consider other management objectives, as well as costs of all potential systems. Station location, design, maintenance, and compliance monitoring all need to be emphasized by managers to raise compliance rates and make a self-issuing permit system a useful management tool.

CONTENTS

INTRODUCTION

Wilderness management requires reasonably accurate sic data on recreational use. Most wilderness values sult from recreation use and so do most threats to the eservation of wilderness values. As a result, most wilder- ss management involves managing visitor use (Hendee d others 1978). This requires reliable data, including ormation about how much use occurs at different places thin a wilderness, what type of use it is (methods of vel, party size, lengths of stay, and perhaps types of tivities engaged in), and when it occurs.

Planning to modify use, to alter trail systems, or to add close campsites; estimation of ecological impacts; heduling public contact specialists; and so on, all pend on use data. Evaluating the success of manage- ent efforts in meeting objectives also requires reason- ly accurate use data.

With some exceptions, wilderness recreational use ta are low in accuracy. Methods that yield reasonably curate data at acceptable cost are needed, both for anagement and to provide basic data for research on ological impacts, crowding perceptions, use distribu- ons, and trends over time. Better use measurement was e of the research needs listed most often by respondents a recent survey of wilderness managers in all agencies ashburne in press).

Use Measurement Methods

Wilderness use is one of the most difficult types of creational use to measure. The typical wilderness has any access points, usually distant from Ranger Stations d difficult to check. Compared to developed sites, use light and variable (wilderness recreation is, by definition, w density). This makes it prohibitively expensive to serve all entry points--some would have no use at all on rtain days. Use is so widely dispersed that it is nearly possible to make a direct head count, as could be done developed auto-access campgrounds. Therefore, a riety of indirect ways of measuring wilderness use have en devised: sample observations, electronic counters, tomatic cameras, estimates based on data from trail gisters or mandatory permits, or guessing, based on ormal, unsystematic observations.[1]

A survey of wilderness managers (Washburne in ess) shows informal observation is the most common easurement technique (37 percent of all wilderness). rmits are almost as common (36 percent). The remain- r (27 percent) use trail registers, and about half of these some checking to calibrate or relate register data to tual use.

Observing a sample of trailheads on sample days oduces accurate estimates (Lucas and others 1971; cas and Oltman 1971), but the highly variable use makes liable sampling difficult and costly. Observers must near trails in all kinds of weather, often with long periods which there is no use to observe.

In addition to entry point sampling, traffic has been sampled at checkpoints on access roads (Lucas 1964). In many areas, one road serves several entry points and results in more use being sampled for the same effort than sampling at trailheads.

Automatic electronic trail traffic counters have been tried with varying success (Lucas and others 1971; James and Schreuder 1972). An improved model that projects an invisible infrared beam onto a reflector and registers a count when the beam is interrupted has been developed and tested successfully (Tietz 1973). (We used these counters in this study, and they worked well.) At best, however, the counters can indicate the number of large, moving objects passing since the last time the counter was read. The counters cannot indicate whether the objects were hikers, packhorses, elk, or cows; when they passed, or how they clustered into parties. There are counters that print out counts and times, but they are expensive. Length of stay or information about activities cannot be obtained from the counters. Neither can direction (entry or exit) or route of travel.

Automatic movie cameras, set to expose one frame at preset intervals, say every 30 seconds, have been used by the National Park Service (Marnell 1977) to estimate use of several wild rivers. Other recording systems employ a movie camera to film a few frames when triggered by a passing object that interrupts an infrared beam. In either case, group size and type of boat usually can be determined. To protect privacy, individuals are not identified, and only public areas through which visitors pass are filmed, not campsites or swimming areas. Such systems appear to have the potential for accurate use measurement, but are probably too expensive for routine, annual use at all entry points to typical wilderness areas with many entry points. Cameras avoid problems of discomfort caused by weather and boredom that afflict human observers, and they are much cheaper.

Many estimates of wilderness use are based on voluntary self-registration at trail registers. Trail registers provide much more complete information than traffic counters. Party size, method of travel, date of entry, length of stay, some data on destination (or itinerary) and activities, and visitor residence are usually obtained. The problem, of course, is that some visitors do not register (Lucas 1975, Lucas and others 1971; Wenger and Gregersen 1964). Some kinds of visitors--especially horsemen, hunters, people making very short visits, and lone individuals--are less likely to register than others. Thus, the resulting registration data not only underestimate use, but also provide biased estimates of its composition.

Efforts have been made to develop systems for basing estimates on voluntary trail register data (James and Schreuder 1971; Lucas and others 1971). In effect, adjustment factors are applied to raw data from the trail register cards to compensate for nonregistration. A sample of registration behavior is observed to develop the adjustment factors.

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re than a dozen studies of use estimation for wilderness and dispersed eation are reviewed by George A. James (1971).

It appears (Lucas 1975) that voluntary trail registration rates may be highly variable from wilderness to wilderness and perhaps over time. This makes it essential to carefully check registration rates before using them as a basis for use estimates. Using observers for field-checking registration is difficult and expensive, however, and is rarely done. Electronic traffic counters, or better, automatic cameras, are useful and less costly sources of information on true total use to compare to registration data. Checking would probably only need to be done at intervals of a number of years, reducing costs. Currently, use estimates based on trail registers have a large, but usually unknown, margin of error.

The most accurate wilderness use data come from mandatory visitor-permit systems (Hendee and Lucas 1973; Washburne in press). Most National Park Wildernesses and more than one-third of all National Forest wildernesses[2] require visitors to obtain permits, a practice also common in Canadian wilderness-type areas. Often, especially in National Parks, only campers must obtain permits; day-users are exempted. In almost all cases, permits must be obtained from the managing agency. In a very few wildernesses, permits are issued by cooperators, such as employees of nearby resorts. Permits provide all of the information obtained from trail registers, in addition to greater detail on planned routes of travel. Some visitors fail to get permits even though they are mandatory (Lime and Lorence 1974), just as some visitors do not register at trail registers. Compliance varies, although it is usually higher than for trail registers.

The agency-issued permit has its disadvantages. The costs of an agency-issued permit system are substantial, primarily for additional employees to issue permits. Obtaining a permit sometimes inconveniences visitors, who usually must visit an agency office, which is often out-of-the-way, during the hours it is open, which may require changes in travel schedules. In some places, permit applications can be made by mail or telephone and permits received by mail, or, when time is short, picked up outside offices after hours.

Managers of several National Forest wildernesses in Washington and Oregon have instituted a system in which visitors issue themselves mandatory permits at trailheads. This system, of course, is only used where use is not rationed. The visitors keep one copy of the permit, which may be checked for compliance by wilderness rangers in the area, and deposit a copy at the trailhead. Informal spot checks suggest that the system may result in higher compliance rates and more accurate data requiring less adjustment than either agency-issued permits or trail registers.

A fourth alternative would be mandatory self-registration. In addition to the copy of the registration form deposited at the registration station, a copy could be carried into the wilderness by the party, making compliance checking possible. Where data collection is the objective, and use control is not planned soon, this might be a more appropriate approach than a permit system which implies the potential for denial of a permit (Sprague 1979). However, to our knowledge such a system has not been used. It is questionable whether Federal agencies could use such an approach. By regulation, the Office of Management and Budget (OMB) must approve collection of information from the public by Federal agencies. There is legal authority for mandatory permits, and OMB approval has been obtained for voluntary trail registration systems, but Forest Service officials believe approval of mandatory registration might be difficult or impossible to obtain (personal communication from Roy Feuchter).

National Forest managers in Montana began using self-issued, mandatory permits in the Spanish Peaks Primitive Area, Gallatin National Forest, on July 1, 1978. This provided an opportunity to evaluate self-issued permits as a use measurement system in a rigorous way.

STUDY OBJECTIVES

The objective of the study was to determine how well a self-issued permit system measured recreational use. Strictly speaking, the study sought to determine the completeness of the use information supplied by visitors. This was **intended use** information because it was supplied before the visit. This study did not seek to determine how **actual** use deviated from **intended** use. It also did not concern itself with accuracy of such information as reported party size.

The study was intended to develop the following specific information:

1. What proportion of parties, classified on the basis of the characteristics below, obtain permits:
   a. Summer/fall visitor groups
   b. Day user/overnight camper groups
   c. Hikers/horseback riders
   d. Party size (single individuals/small parties/large parties.
2. How does permit station location affect compliance behavior by different types of visitors?

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[2] A survey of managers (Washburne in press) indicated about 35 percent of all National Forest Wildernesses based use estimates on permits in 1978.

Figure 1.--Double-panel trailhead information center used at major trailheads.

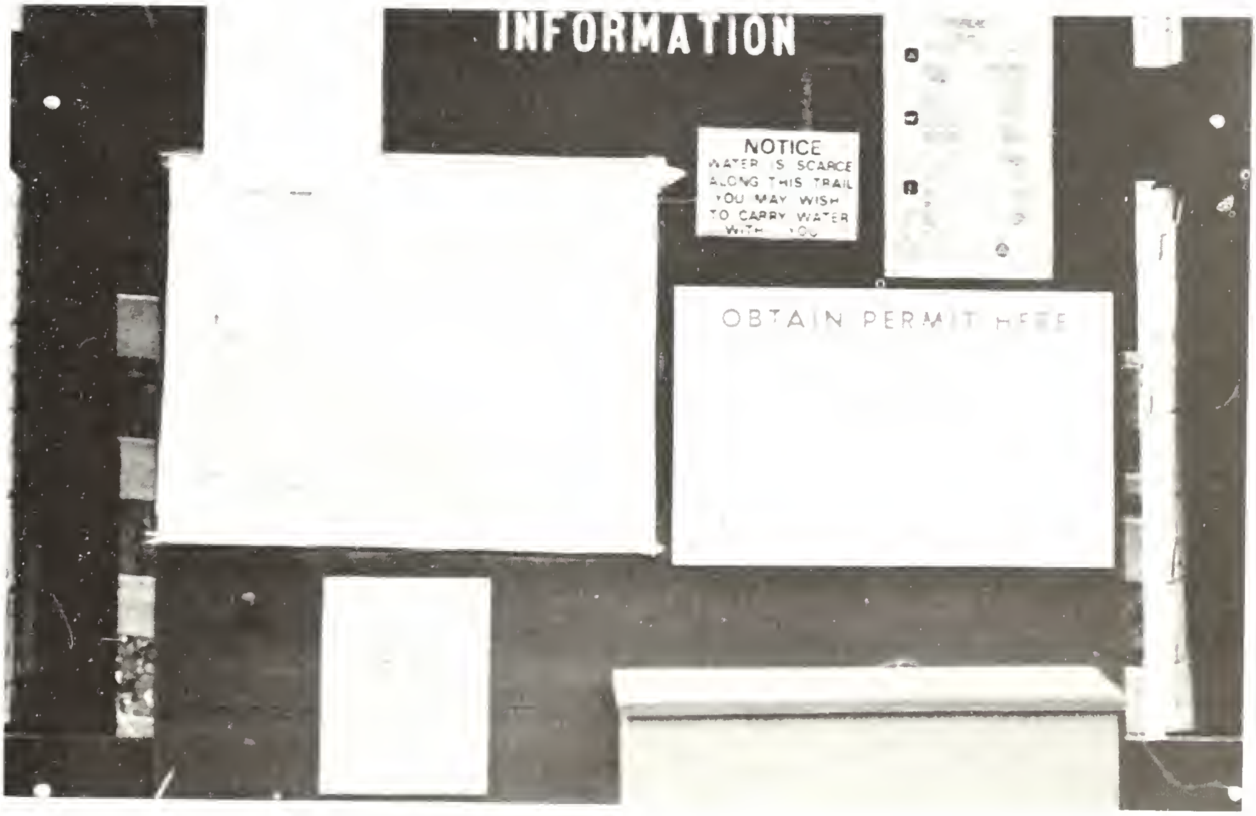

Figure 2.--Single-panel information center used at minor trailheads.

STUDY PROCEDURES

Self-Issued Permit System

Trailhead "information centers" incorporating the self-issuing permit facility were installed at all 11 trail entry points to the Spanish Peaks Primitive Area by the Gallatin/Bozeman Ranger District, Gallatin National Forest, before July 1, 1978. The information centers followed a new standard design for the Northern Region of the Forest Service, consisting of two sign panels at major entries and one sign panel at less-used trailheads (fig. 1 and 2). Standard Forest Service permit forms were used (appendix 1).

The Gallatin/Bozeman Ranger District, the Gallatin National Forest, and Northern Region headquarters informed the public about the new system, its purpose, and desired visitor behavior through press releases to local newspapers and personal contacts with key persons.

Sample Sites

In cooperation with the district ranger and his staff, the following six trailheads, shown in figure 3, were chosen for monitoring use and permit compliance:

1. Spanish Creek
2. Little Hellroaring Creek
3. Hellroaring Creek
4. Cascade Creek (Lava Lake)
5. Deer Creek
6. Hammond Creek

These were the most-used trailheads. Other access points received only very light use.

Observation Period

Sample sites were monitored from July 1, 1978, into the fall as long as possible. Observations ended at different trailheads from November 1 to November 8.

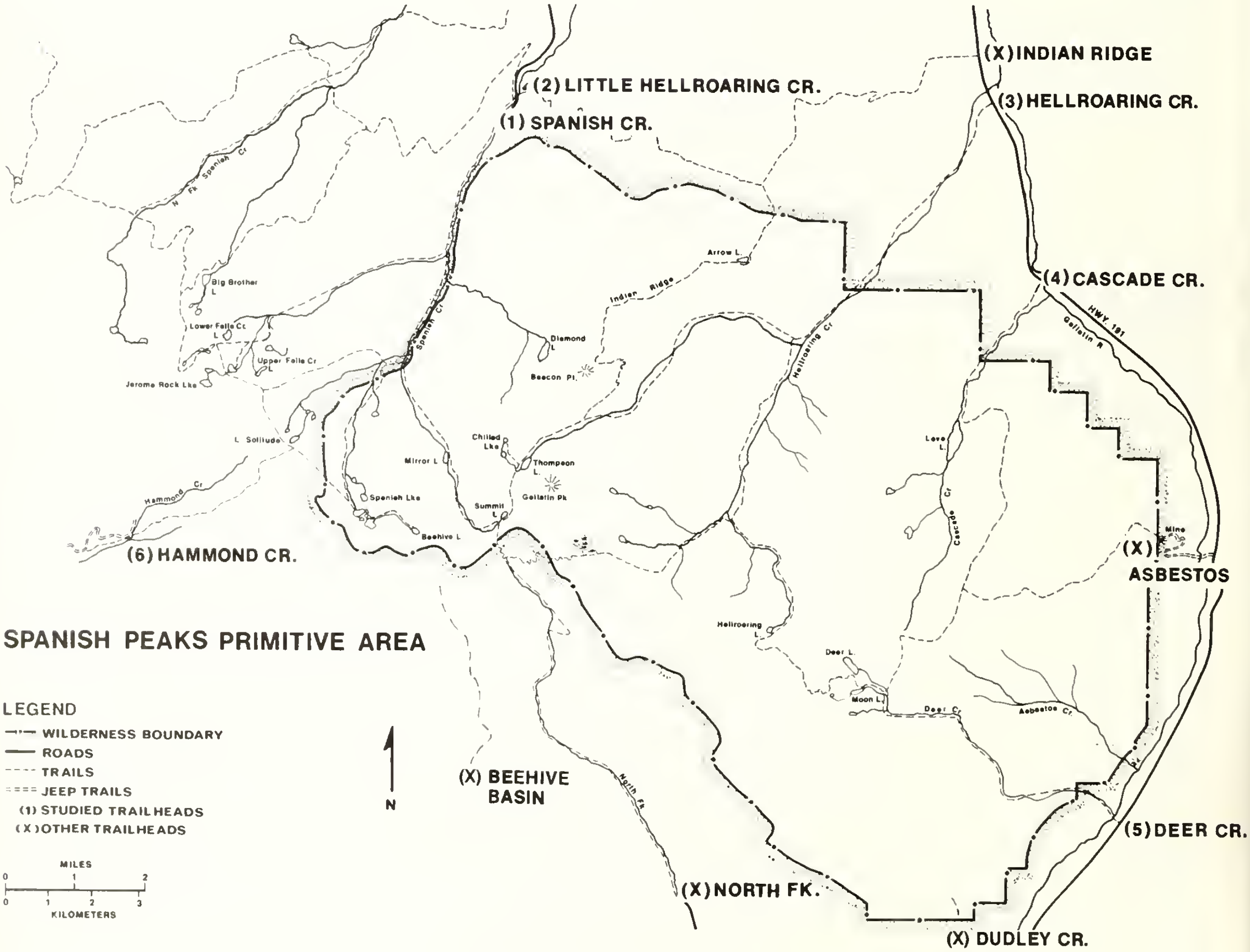

Figure 3.--System of trails and trailheads in the Spanish Peaks Primitive Area.

Observation Methods

Modified movie cameras (fig. 4) triggered by infrared trail traffic counters (fig. 5) were used to measure and classify recreational use. Wherever possible, the cameras were focused on the permit-issuing facility to observe compliance/noncompliance directly. Both camera and counters were camouflaged as well as possible. At one location (Spanish Creek), this was impossible because of the exposed location of the information center sign. In this case, the camera was placed farther along the trail to record all visitor use, which was compared to use accounted for by completed permits.

Figure 4.--Camera used to record trail traffic, mounted in a weatherproof box.

Figure 5.--Trail traffic counter used to activate the camera system.

The camera-counter systems were fabricated by the Forest Service's Missoula Equipment Development Center.[3] A prototype was tested at Spanish Creek in July and August 1977 and performed perfectly. The cameras could be adjusted to run for a variable time per triggering by the traffic counter (up to 252 seconds) and to expose frames at a selected interval (every 2 to 30 seconds). The current model also automatically exposed one frame per hour (24 hours per day) while turning on an internal red light to provide an indication of date and passage of time.

Parties were recorded both entering and leaving; the timing frames helped estimate approximate lengths of stay for day-users. For example, if one red dot separated entrance and exit, the party could only have been up the trail less than 2 hours. It was possible to identify very brief visits and provide additional confirmation of day-use/camper classifications that were based on the presence/absence of large packs or packstock.

Duration and spacing of exposures were set to insure enough information to record the entire party and determine if they obtained a permit (except where the camera was not focused on the information center), while using film at a rate that would not exhaust the film before the next servicing visit.

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[3] Information on the camera-counter system is available from the Equipment Development Center (Gasvoda 1978).

In all cases, film exposure intervals were set less than the time a person could move across the camera's field of view. A fast walker or a horse might go about 5 feet per second. If the field of view was 50 feet, this would require about 10 seconds. An exposure interval of 6 or 7 seconds provides some margin of error, and enough overlap to positively record the party composition. We used intervals from 4 to 10 seconds at the various locations where the permit station was in the camera's view.

Where the camera was focused on the permit station, 120 to 180 seconds from beginning to ending filming indicated clearly if the party complied, even if they had not always finished writing and depositing the permit when the camera shut off.

The movie camera used color, super-8 film cassettes that provided about 3,500 frames. Usually, each party triggered the camera twice (in and out). A party with several members retriggered the camera and exposed more film. (The camera initiated a new cycle for each triggering impulse). Thus, film consumption is somewhat greater than twice the number of frames selected for exposure per party, times the number of parties.

Heavily used Spanish Creek and Cascade Creek were visited for servicing at least twice a week and all other sampling locations at least once a week. If there was any chance that the film could be exhausted before the next visit, it was removed, labeled, and sent in for developing. When new film was installed, a few frames were exposed to photograph a card marked with the location and date.

Triggering the camera when persons passed was far superior to simple time lapse photography. With 10-second exposure intervals, film would be exhausted in about 10 hours and very few exposures would include visitors.

Film was viewed as soon as possible to identify any field equipment problems that might need to be corrected.

Protection of Privacy

Both the letter and spirit of privacy laws were fully observed. Forest Service legal counsel has advised that automatic cameras are legal for use as traffic measuring and classifying devices.

Cameras were located and focused so individuals could not be identified. (The pilot test in 1977 showed that individuals were indistinguishable. The two persons who installed the camera and then walked the trail could only distinguish themselves by clothing colors.) Film was kept secured by the field technician and was viewed only by her or authorized officials. After all data were recorded, the film was kept locked securely for 3 months for possible rechecking, and then it was all destroyed. Film was intended to be used only to record use, and this was what the public was told. Therefore, it was decided that it would not have been available for use as evidence in any proceedings against violators, if such a situation developed. (It did not.)

A press release to inform the public of the use of cameras was issued by Gallatin National Forest officers. The press release stated that cameras would be used to measure use, but did not indicate that they were focused on the permit stations. This, together with limited readership of the press release, should have avoided influencing visitors' permit issuance behavior.

Traffic Classification, Permit Compliance

A form was used to record observations from film (appendix 2). Method of travel (horseback riders, hikers, and hikers with packstock) was easily observed. Day-users and campers were classified primarily by noting whether people had large backpacks or packhorses. Day-users were classified by approximate length of stay, using the hourly marked exposures. Group size was classified as well as possible, but, in a few cases, parties were strung out and it was not possible to determine positively who was with whom. We attempted to identify hunters by rifles, but photo quality made this impossible in many cases.

If persons remained at the permit station, apparently filling out forms, and they were still doing so when the camera shut off, it was assumed that they had complied.

Permit Tabulation

Permits were collected whenever the field assistant visited a trailhead. The trailhead name was marked on all of the completed permits. Permits were kept in sequence to aid in estimating dates for any that lacked date of entry.

Permits were compared to the projected film to confirm compliance or noncompliance. For Spanish Creek, this was necessary to make the compliance classifications. At other locations, if parties entered in darkness (especially common in the fall), it was sometimes possible to reconstruct events with the use of permits if such parties exited during daylight hours, so they could be classified in terms of method of travel, party size, and so forth.

Permit Station Location

All permit stations were classified as "end-of-road" or "up-the-trail" (if out of sight of the parking area) for analysis of the effect of location.

ANALYSIS PROCEDURES

Variables Analyzed

Results are primarily descriptive and comparative. Tabulations were made for permit compliance related to the following single variables believed to influence visitor responses:

1. Trailheads
2. Summer/fall
3. Day-users/campers
4. Hikers/hikers with stock/horseback riders
5. Party size: classified as 1 person, 2 through 6 persons, 7 or more persons.

Tabulations for combinations of variables included e following (only one of which is reported here):

1. Summer/fall
   a. Day-use/camper
      (1) Hikers/hikers with stock/horseback riders
      (2) Party size
   b. Hikers/hikers with stock/horseback riders
   c. Party size
2. Hikers/hikers with stock/horseback riders
   a. Party size

Statistical Significance

The data constitute a complete census, not a sample. hus, "statistical significance" has no meaning. In a sense, **ny** difference is significant. The question is not how much atistical confidence can be placed on estimated complince rates or on differences among them, but, rather, hether or not differences are large enough to be nportant, and if compliance rates are acceptable.

Evaluation Criteria

Acceptability of visitor compliance with the permit ystem is a management decision, which needs to take ito account costs of the system over time, expected iture improvement or deteriorations of visitor compliance, ontributions to other objectives, and so forth.

One important consideration is the increase in complince for this system compared to voluntary self-registraon. Reported self-registration rates vary from 28 to 74 ercent (Lucas 1975). In the pilot test of equipment at panish Creek in August 1977, exactly 50 percent of 130 arties observed registered. Rates varied from 78 percent f overnight hikers (50 parties) to 0 percent of day-use orseback riders (16 parties). Day-hikers registered in 40 ercent of the cases, campers using horses in 43 percent of ne cases.

The permit system would be considered successful in athering basic use data, and superior to self-registration, compliance rates equaled or exceeded 75 percent overall nd at least 60 percent at each trailhead.

The less that the major types of uses vary in complince, the more feasible it will be to base total use estimates n an expansion of permit data. A simple ratio expansion ctor seems as accurate as more complex approaches ased on regression formulas (Lucas and others 1971), ut if compliance rates for common types of visitors vary an important extent, it would be necessary to classify ermits, and apply separate expansion factors to each to ccurately estimate the composition of use, as suggested Lime and Lorence (1974). This makes the procedure ore cumbersome for managers, and therefore, this ctor is of particular interest in the analysis.

RESULTS

Equipment Performance

The traffic counters and camera systems worked almost perfectly. A few days' observations were lost when one battery failed, but there were no other problems. False triggering of traffic counters, which exposes film with no visitors present, was a minor problem at only one location.

Vandalism was not a significant problem. One camera was discovered with the wires disconnected, but no damage was done. If such recreational use measuring systems are used in the future, brief explanatory cards on the cameras and traffic counters seem desirable to avoid puzzling visitors as to the nature and purpose of the equipment. This suggestion was also made by Leatherberry and Lime (1980) who used the same equipment to monitor a trail register in the upper peninsula of Michigan.

There were no complaints or adverse reaction to the camera system, despite a press release about the study carried by local news papers.

Compliance and Related Factors

1. **Overall**.--In 1978, 53 percent of the visitor groups to the Spanish Peaks issued themselves a permit. This fell short of the desired level (about 75 percent was hoped for) but should be judged in perspective. This was the first year of a new program. It went into effect on July 1, during the use season. It was a new system for Montana, one with which few visitors were familiar. One unusual location, discussed below, pulled the overall compliance rate down 2 percent.

2. **By trailheads**.--Compliance rates varied widely among trailheads (table 1). Cascade Creek was the highest (72 percent) and Hammond Creek the lowest (only 21 percent).

Table 1.--**Compliance by trailhead**

Trailhead	Number of parties entering[1]	Number of parties complying	Percentage complying
Spanish Creek	751	325	43
Little Hellroaring Creek	60	37	62
Hellroaring Creek	111	44	40
Cascade Creek	516	370	72
Deer Creek	142	94	66
Hammond Creek	94	20	21
Total	1,674	890	53

[1] Number of parties observed visiting the area (counted once, although they may have been observed entering and leaving).

Hammond Creek was a special case. The permit station was located about 3 miles from the Primitive Area boundary. Several trails from this trailhead did not lead to the Primitive Area. Many of the visitors did not enter the Primitive Area and thus did not require a permit. Many of them were on horseback rides for the day, while staying at a nearby dude ranch. Because the dude ranch was already covered by a special use permit from the Forest Service, the likelihood of the guides filling out another permit was probably low, regardless of the planned route.

The permit stations located some distance up the trail (Little Hellroaring, Cascade, and Deer Creeks, and Spanish Creek during the fall only, after the station there was moved at the end of summer) performed better, with 64 percent of the visitors obtaining permits there compared to 38 percent at the permit stations located at the trailhead near the road. If Hammond Creek is omitted, the comparison changes little, becoming 64 versus 41 percent. With the exception of Spanish Creek in the fall, all of the stations located up the trail met the desired level of at least 60 percent compliance at each location.

3. **By seasons**.--Summer and fall compliance rates were identical--both 53 percent (table 2). This was unexpected because previous studies (Wenger and Gregersen 1964; Lucas and others 1971) showed substantial drops in the fall, especially for hunters, who were common in the Spanish Peaks.

With the main exception of Deer Creek, fall and summer rates were substantially the same at each trailhead. Deer Creek, with considerable fall day-use, much of it by hunters who had poor compliance, dropped from 78 to 50 percent.

Spanish Creek improved 6 percent, probably related to the move of the information center and permit-issuing facility from the edge of a large, somewhat confusing parking lot up the trail about 100 yards.

4. **By length of stay**.--Compliance dropped sharply as visits became shorter (table 3). Overall, 72 percent of the campers (overnight visitors, whether hiking or using horses) obtained permits, compared to 45 percent of day-users. Campers complied at similar rates (68 to 79 percent) at all trailheads, but day-user compliance rates varied widely among locations (10 to 70 percent, or omitting Hammond Creek, 28 to 70 percent).

Again, the stations located up the trail performed best. The three locations with the highest compliance for campers were all up the trail. After the Spanish Creek station was moved up the trail, compliance by campers jumped from 63 to 81 percent. Day-users complied much better at up-trail locations (55 to 70 percent compliance except at Spanish Creek in the fall, which was only 33 percent) compared to 10 to 28 percent at roadside locations (26 percent for Spanish Creek in the summer).

Compliance for day-users also dropped as stays became more brief. Parties could be classified into approximate lengths of stay in most cases by noting the number of hourly red frames between their entrance and exit. If no red frame separated entrance and exit, their stay could not have exceeded one hour, for example.

The day visitors making longer stays, more than 3 hours, complied almost as well as campers, 65 percent compared to 72 percent for campers. Visitors staying 2 hours or less complied very poorly (20 percent or less compliance). Compliance of day-users was as follows:

Duration of stay	**Compliance**
Hours	Percent
1	17
1-2	20
2-3	43
3+	65

5. **By method of travel**.--There were substantial differences in compliance rates by visitors traveling different ways (table 4). Horseback riders' compliance was lowest (35 percent, or omitting Hammond Creek, 43 percent). The small sample of hikers leading packhorses--only 19 parties--complied best (84 percent). Hikers were intermediate (55 percent).

As related to compliance, method of travel and length of stay are strongly interrelated. (These data will be presented in a subsequent section).

6. **By party size**.--Single persons complied less frequently than larger parties (table 5), obtaining permits only 41 pecent of the time. Medium and large parties had about the same compliance rates (57 and 60 percent, respectively).

7. **Combined factors**.--Compliance was tabulated against combined variables. Table 6 presents the most meaningful of these, showing for each trailhead the compliance rate during summer and fall for day-visitors and campers, separated into hikers and horseback riders. Several relationships stand out:

a. Compliance by campers, both hikers and horse users, is relatively good almost everywhere (about 70 percent, overall), summer and fall.

The occasional lower compliance figures for campers in table 6 are, with one possible exception, all based on light use and few observations. Almost all of these anomalies are based on three or fewer observations. The 20 percent figure for Deer Creek horse campers in the fall is based on observations of only 5 parties. The one possibly significant exception is for fall hiking campers (in other words, backpackers) at Hellroaring Creek, where only 42 percent of 12 parties issued themselves permits. Except for this one situation, backpacker rates ranged, by season, from 63 to 80 percent. Horse campers, omitting values based on small numbers of observations, ranged by season, from 75 to 100 percent, and for the total use period, from 60 to 81 percent.

b. Camper compliance rates for hikers were better at up-trail locations (Little Hellroaring, Cascade, and Deer Creek and Spanish Creek in the fall) than roadside locations, but there was no clear difference for horse campers.

Table 2. -- **Compliance during summer and fall, by trailhead, percentage of total**

	Season			
	Summer[1]		Fall[2]	
Trailhead	**Number of parties**	**Percent complying**	**Number of parties**	**Percent complying**
Spanish Creek[3]	494	41	257	47
Little Hellroaring Creek	10	60	50	62
Hellroaring Creek	48	42	63	38
Cascade Creek	326	73	190	69
Deer Creek	82	78	60	50
Hammond Creek	78	21	16	25
Total	1,038	53	636	53

[1] July and August

[2] September, October, November

[3] The Spanish Creek information center-permit facility was moved from the parking area up the trail, just out of sight of the parking lot, on September 1, 1978

Table 3. -- **Compliance by length of stay, by trailhead, percentage of total**

	Length of stay			
	Day-users		Campers (overnight visitors)	
Trailhead	**Number of parties**	**Percent complying**	**Number of parties**	**Percent complying**
Spanish Creek	473	29	278	68
Little Hellroaring Creek	45	58	15	73
Hellroaring Creek	78	28	33	67
Cascade Creek	401	70	115	79
Deer Creek	75	55	67	79
Hammond Creek	77	10	17	71
Total	1,149	45	525	72

Table 4.--**Compliance by method of travel, by trailhead, percentage of total**

	Method of travel					
	Hikers		Hikers with stock		Horseback riders	
Trailhead	**Number of parties**	**Percent complying**	**Number of parties**	**Percent complying**	**Number of parties**	**Percent complying**
Spanish Creek	664	44	6	67	81	37
Little Hellroaring Creek	43	72	1	100	16	31
Hellroaring Creek	93	35	3	100	15	53
Cascade Creek	503	72	3	67	10	40
Deer Creek	108	65	6	100	28	64
Hammond Creek	42	36	--	--	49	8
Total	1,453	55	19	84	199	35

Table 5.--**Compliance by party size, by trailhead, percentage of total**

	Party size, number of persons					
	1		2-6		7 or more	
	Number of parties	Percent complying	Number of parties	Percent complying	Number of parties	Percent complying
Spanish Creek	153	36	574	45	22	55
Little Hellroaring Creek	20	80	38	50	2	0
Hellroaring Creek	42	17	67	55	1	0
Cascade Creek	91	54	410	76	15	93
Deer Creek	42	45	101	76	3	67
Hammond Creek	22	14	63	24	9	11
Total	370	41	1,253	57	52	60

Table 6.--**Compliance by method of travel, length of stay, and season combined, by trailheads, percent of total**

		Method of travel[1]			
		Hikers		Horseback riders	
Trailhead	**Season**	**Day**	**Campers**	**Day**	**Campers**
Spanish Creek	Summer	26	63	23	75
	Fall	33	81	33	88
	Total	29	67	26	81
Little Hellroaring Creek	Summer	100*	100	0*	0*
	Fall	70	63	36	100
	Total	71	75	29	50*
Hellroaring Creek	Summer	23	83	50	0*
	Fall	28	42	40	80
	Total	26	63	44	67
Cascade Creek	Summer	72	78	0*	100*
	Fall	67	84	50	50*
	Total	70	80	29	67*
Deer Creek	Summer	66	82	91	100
	Fall	27	78	29	20
	Total	51	80	67	60
Hammond Creek	Summer	25	64	3	100*
	Fall	0	100*	0	67*
	Total	21	69	2	75
Total		51	72	25	70

[1] 19 parties hiking with packstock are omitted from this table.

*Based on 3 or fewer observations

c. Day-hikers complied fairly well at most station locations up the trail.

Spanish Creek in the fall (after the station was moved) was still only 33 percent, and Deer Creek in the fall was only 27 percent. The other day-hikers' compliance rates for up-the-trail locations were all at least 66 percent.

d. Day-hikers complied very poorly at roadside locations. Compliance never reached even 30 percent in such cases.

e. Day horseback riders' compliance rates varied widely, but generally were very low (25 percent overall). Only at Deer Creek (almost three-fourths mile up the trail), did day horseback riders comply fairly well (67 percent).

DISCUSSION AND CONCLUSIONS

The self-issued mandatory permit system worked best
s a use measurement system for those types of visitors
iat most people would consider most critical for wilder-
ess management decisions--the campers and longer-
rm day-users. The system measured short-term day
sers poorly. Although, ideally, managers would like
omplete counts of all types of visitors, if weaknesses
xist, the short-term day-users are the least critical group
ecause of their relatively smaller impact on the area and
n other visitors. Use by day-use horseback riders, even
r long visits, was not well measured, and this probably
a more serious problem because of the greater potential
npacts by horses.

Self-Issued Permits Compared to Trail Registers

The self-issued permit system probably provides data that are better than voluntary self-registration. No direct comparison is possible, but table 7 presents available data on registration rates at trail registers, which can be compared generally to data in table 6 and earlier tables.

A test in Michigan, which alternated mandatory registration (using permit forms) and voluntary registration over 2 years at the same trail, found identical 67 percent compliance rates for both systems (Leatherberry and Lime 1980).

Table 7.--**Some reported registration rates for voluntary trail registers**

eas	State	Year	Source	Visitor type	Registration rate
					Percent
Three Sisters Wilderness Mountain Lakes Wilderness	Oregon	1961-62	Wenger and Gregersen 1964	Hikers	79
				Riders	40
				Total	74
Mission Mountains Primitive Area	Montana	1968	Lucas, Schreuder, and James 1971	Summer	74
				Fall	41
				Hikers	66
				Horsemen	44
				Day-use	63
				Campers	74
				Total	65
Banff National Park	Alberta	1968	Thorsell 1968	Total	35
Rawah Wilderness	Colorado	1970	James and Schreuder 1972	Total	89
Selway-Bitterroot Wilderness	Montana	1974	Lucas 1975	Day-use	19
				Campers	49
				Hikers	31
				Horsemen	11
				Total	28
Idaho Primitive Area	Idaho	1974	Personal Communication Earl Dodds, District Ranger	Total	18
Sawtooth Wilderness	Idaho	1975	Mullins 1975[1]	Day-hikers	85
				Camping hikers	87
				All horsemen	33
				Total	78
Waterton Lakes National Park	Alberta	1976	Scotter and Bernard[2]	Total	78
Spanish Peaks (Spanish Creek, August only)	Montana	1977	Lucas (unpubl.)	Day-hikers	40
				Day horsemen	0
				Camping hikers	78
				Camping horsemen	50
				Total	50

[1] Unpublished report by William H. Mullins, 1975, Sawtooth Wilderness visitors study. 18 p. USDA For. Serv., Sawtooth National Recreation Area, Ketchum, aho.

[2] Unpublished report by George W. Scotter and Joan L. Bernard, no date, Compliance rate at unmanned trail registers, Waterton Lakes National Park, Alberta, inada. 9 p. Canadian Wildlife Service, Edmonton, Alberta.

Trail registration rates appear highly variable, but lower in more recent observations than earlier cases, with the notable exception of the Sawtooth Wilderness. The studies show relatively poor registration by horsemen everywhere and to a lesser extent, by day-users. Day-users in the Sawtooth Wilderness, however, had an 85 percent compliance rate!

The 1977 pilot test data from Spanish Creek are difficult to compare directly to self-issued permits, because the trail register, which was checked only in August, was located about 500 yards up the trail, whereas the permit-issuing facility was located near the parking area. However, in general, it appears that self-issued permit compliance was substantially higher than voluntary registration by horsemen, about the same for backpack campers, and a little lower for day-hikers. From a management perspective, the data from the permits seem superior.

Self-Issued Permits Compared to Agency-Issued Permits

Published compliance data for agency-issued permits are available for just a few areas. In the Desolation Wilderness, California, where about 99 percent of the use is by hikers, in 1974 (the fourth year permits were required) about 40 percent of the day-users had permits, (Schechter and Lucas 1978) compared to 51 percent of the day-use hikers in the Spanish Peaks. About 85 percent of backpack campers in the Desolation Wilderness obtained permits from the agency offices, compared to 72 percent in the Spanish Peaks. Thus, the self-issued system in its first year worked a little better for day-users and a little worse for campers than a well-established agency-issued permit. If, however, only the compliance rate for campers at up-trail locations is considered, the Spanish Peaks compliance rate rises to 80 percent, not appreciably different.

The Boundary Waters Canoe Area, Minnesota, in 1971 (the sixth year of the permit system), had 88 percent compliance overall (Lime and Lorence 1974). The rate for day-users was 73 percent; for campers, 92 percent; both better than achieved in the Spanish Peaks. High compliance was attributed to enforcement, with citations and fines for noncompliance, 10 offices issuing permits, and about 100 local merchants (mostly resorts, sporting goods stores, and boat and canoe rental businesses) authorized to issue permits.

In the Great Gulf Wilderness, New Hampshire, in the summer of 1976 (the second year permits were required), 78 percent of all visitors were estimated to have obtained permits (Leonard and others 1978). Compliance by day-users was reported to be about 60 percent, and camper compliance 80 to 90 percent. Visitors were all hikers, so the figures compare to about 51 percent compliance for day-users in the Spanish Peaks and 72 percent for campers (or 80 percent for the superior up-trail locations). These small differences might be the result of the newness of the self-issued permit system in Montana.

The compliance rate in the Dry River Wilderness, also in New Hampshire, in 1975, the first year for permits, was 69 percent.[4] Again, all use was hiking, but no breakdown between day-users and campers was provided. These rates seem little different than the Spanish Peaks figures for hikers.

Compliance with agency-issued permits in the Three Sisters and Mount Jefferson Wildernesses, Oregon, were estimated at only 50 to 70 percent compliance (personal communication, S. Hanna), probably a little lower than the Spanish Peaks self-issued permits. On the other hand, the Glacier Peak and Pasayten Wildernesses in Washington and the Eagle Cap in Oregon estimate about 90 percent visitor compliance with agency-issued permits (personal communication, Bernard Smith).

The Spanish Peaks System Compared to Other Self-Issued Permit Systems

The Three Sisters and Mount Jefferson Wildernesses reported better than 90 percent compliance when they switched to self-issued permits. These compliance rates, of course, exceed those in the Spanish Peaks. Perhaps the earlier agency-issued permit set the stage for excellent acceptance of the more convenient self-issued permits. Most use was by hikers, probably contributing to high compliance rates. Also, permits were required at most wildernesses in the region, unlike the Spanish Peaks, which was the only National Forest area in the northern Rockies requiring permits.

Overall Evaluation

The self-issued, mandatory permit appears to have promise as a use-measurement system, recognizing that any system has other objectives, as well as costs. In its first year, it provided more complete data on some important types of users than trail registers, especially horsemen and fall visitors. During the second year (1979), compliance increased to about 90 percent at all locations except Spanish Creek, according to compliance checks by wilderness rangers (personal communication, John Dolan). It appears to be almost as complete in coverage as an agency-issued permit, and, if the Oregon reports are valid and reflect the general potential of the self-issued permit system, it can provide even more complete coverage.

A mandatory registration system has never been tested, so no comparison can be made. However, a special registration station that explained a research study was in progress and provided a justification or rationale for registering obtained excellent response rates. About 94 percent of all hikers and 67 percent of all horsemen registered (Lucas 1980). High compliance rates for voluntary trail registers reported by the Sawtooth Wilderness suggest that system may have the potential to perform better than it has in most places.

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[4] Unpublished report by the Northeastern Forest Experiment Station, no author, no date, Travel permit compliance in eastern wilderness: some preliminary results. On file at the Forestry Sciences Laboratory Durham, N.H.

Factors Affecting Compliance

Permit compliance is associated most strongly with visitors' length of stay. This was also true in Michigan (Leatherberry and Lime 1980). This had more effect on compliance than method of travel, which was only influential for day-users.

Summer and fall rates were essentially the same, unlike the case for trail registers, which have shown lower rates in the fall.

Lone visitors complied relatively poorly, as they also have done at voluntary trail registers (Wenger and Gregersen 1964; Lucas, and others 1971). This may be partly because of the brief stay of many lone visitors. One would think a person camping alone might have more motivation to register or obtain a permit to leave a record of his or her presence for security.

Locations away from the parking area, up the trail some distance, produced higher compliance rates by hikers, and at least as high compliance by horsemen. (This was also reported for the Sawtooth Wilderness). Day-use horsemen appeared to comply slightly better at up-trail locations, which seems somewhat surprising. One might expect better compliance at the parking area, where someone is usually ready before the others in the party and could easily register or write a permit while waiting, and it was not necessary to dismount to fill out a permit. However, actual visitor behavior did not bear this out. Several possible reasons can be suggested.

1. Signboards at the edge of parking lot may be lost in the clutter and confusion of cars and other signs. In contrast a sign up the trail stands out. (This reason also was cited for the Sawtooth Wilderness.)
2. Many groups have a leader recognized as the one to deal with registration or permit issuance. This person is unlikely to have free time at the parking area. He or she is overseeing preparations, checking equipment, and often distracted. After the party is on the trail, it may be much easier for the leader to focus attention on a sign and permit-issuing facility.
3. At the parking area people are anxious to start. After a little travel, and especially after climbing a hill, an excuse for a rest at a sign and permit station could be welcome, especially for hikers. Horsemen often find that saddles need adjusting after a short ride, making a stop necessary.
4. The up-trail location screens out some people making very brief visits, who rarely comply with the permit requirement. In a sense, this is more an apparent advantage than real, affecting the compliance **rate** rather than data on actual use.
5. An up-trail location can symbolize wilderness entry, and suggest an appropriate signing-in ceremony. By analogy, probably very few people fail to sign a mountain climbing register. For example, the most successful permit station in the Spanish Peaks, on the Deer Creek trail, was located furthest up the trail and right at the Primitive Area boundary.

MANAGEMENT IMPLICATIONS

Adoption of a Self-Issued Permit System

A self-issued permit system can be a useful wilderness management tool if managers are committed to the effort required to make it function effectively. Commitment by managers is probably the most critical factor in the success of either a permit or trail register system.

Adoption of a self-issued permit system must be based on objectives for each area and the estimated cost of a self-issued permit or alternative system. Use measurement is an important goal, but although it is the sole objective emphasized in this study, it is not the only one. Visitor contact and communications also are important, and these may involve receptionists in offices or visitor information centers, signs, brochures, and wilderness rangers. The role of each of these may vary depending on the type of permit or trail register system that is used.

As a use measurement system alone, self-issued permits have good potential. Rates of compliance compare well with alternatives, and provide more complete data on some types of visitors than trail registers provide. The system is probably less costly than agency-issued permits, and more convenient for visitors. Self-issued permits should cost about the same as trail registers, assuming both are well-maintained and serviced regularly at intervals appropriate for use levels.

The alternative of mandatory registration deserves consideration, unless the survey approval policy of the Office of Management and Budget is an insurmountable barrier. Where data collection, not use regulation, is the objective, the term "permit" might be considered by some to be a misnomer. It is possible (no data are available) that some visitors are irritated by the tone of Government control they perceive in permit systems and that they do not comply as a form of protest. If a mandatory registration system had a copy of the registration form to be carried by the visitor for compliance checking by wilderness rangers--and this would seem necessary--the distinction becomes purely one of name, and visitor reaction is difficult to predict.

Station Location

Locations up the trail are clearly superior to end of road, trailhead parking areas in obtaining visitor compliance; however, the added time and cost required to build such stations and to service and maintain them is a disadvantage. For example, a station 1 mile up the trail might require an extra 40 minutes to an hour each time it was checked. We experienced little vandalism in the Spanish Peaks, but what little occurred was unrelated to up-trail or trailhead location. Although not tested formally in the study, location very close to the edge of the trail (as at Cascade Creek, Deer Creek, and Little Hellroaring Creek) and in the line of sight of the trail, which curves around the station (as at Deer Creek), seems desirable

In areas with appreciable horse use, the station location should provide room for stock and include a hitching rail. The permit station should be designed to invite a stop to adjust cinches, stirrups, or packhorse loads. A sign near the trailhead could inform visitors, especially horsemen, of the distance to the station and point out that it is a good place to check saddles and other tack, somewhat like a highway sign, "rest area ahead."

Station Design

The station design tested included a map, both as a service and as an attractor, and consolidated all information in one place. Permit boxes were a conspicuous bright blue.

No design alternatives were tested, but bright colors and eye-catching design probably are helpful in influencing visitors to stop and leading them to filling out a permit. Red or orange permit boxes might have been more effective. Backpackers sometimes trudge along, eyes fixed a yard ahead of their feet, and both color and placement need to be designed to make the station impossible to pass by unnoticed.

Station Maintenance

The permit stations in the Spanish Peaks were visited frequently and kept well supplied with forms and pencils. Busy locations were usually visited every other day and even the most lightly used stations at least once a week.

Frequent maintenance is essential. No data can be obtained if a station runs out of forms, and the lack of pens or pencils will deter many visitors. The inability to obtain a required permit puts conscientious visitors in an awkward position. Do the visitors leave without a permit, or take the time to try to get one elsewhere? A poorly maintained station tells the visitor that the permit requirement (or registration) is not important to the agency.

The effect of vandalism can also be limited by frequent servicing. All permit forms, blank and completed (completed forms were exposed in the design used) were stolen from the Spanish Creek station about July 15. Only 2 days' worth of completed forms were lost. With infrequent maintenance this interruption would have been much more serious. Managers, although discouraged, should not use vandalism as an excuse to do nothing. Unfortunately, vandalism is a cost of doing business.

Monitoring Compliance

If a self-issued system is used, periodic monitoring of visitor compliance is essential. Monitoring should encourage better compliance over time. Fairness to those visitors who make the effort to comply would seem to require an enforcement effort. Monitoring is also necessary to check compliance rates, which must be estimated with reasonable accuracy to convert permit data into acceptable use measurements, and which can shift with time. This study suggests recording compliance based on length of stay, and at least for day-users, on method of travel.

Based on results, to estimate total actual use, permit data for the Spanish Peaks would be multiplied by about 1.4 for campers, by about 2.0 for day-hikers, and by about 4.0 for horseback day-visitors. Until more experience accumulates, the possibility of summer-fall differences needs to be checked, as well as possible differences in compliance between campers who hike and those who use horses.

The most efficient way to monitor compliance is to have wilderness rangers keep careful records of their compliance checks, and tabulate and analyze these records each winter, after the main use season. Wilderness rangers will tend to contact a larger proportion of visitors who penetrate the area than of the visitors who only travel in the periphery--especially, the brief, day-users. This will probably cause the rangers' compliance checks to overstate compliance for day-users. This may not be critical, but some trailhead checking could provide data for adjusting this compliance estimate if desired. The traffic counter-camera system is effective for monitoring use if carefully installed and well-maintained. It is an effective tool for accurate use measurement and classification.

Data Editing

Prompt editing, especially by people familiar with the area and its use, has numerous advantages. Incomplete or obviously inaccurate data can sometimes be corrected without resorting to guessing. Keeping reasonably current on editing and coding avoids an overwhelming job with insufficient time at the end of the season, just before the report is due.

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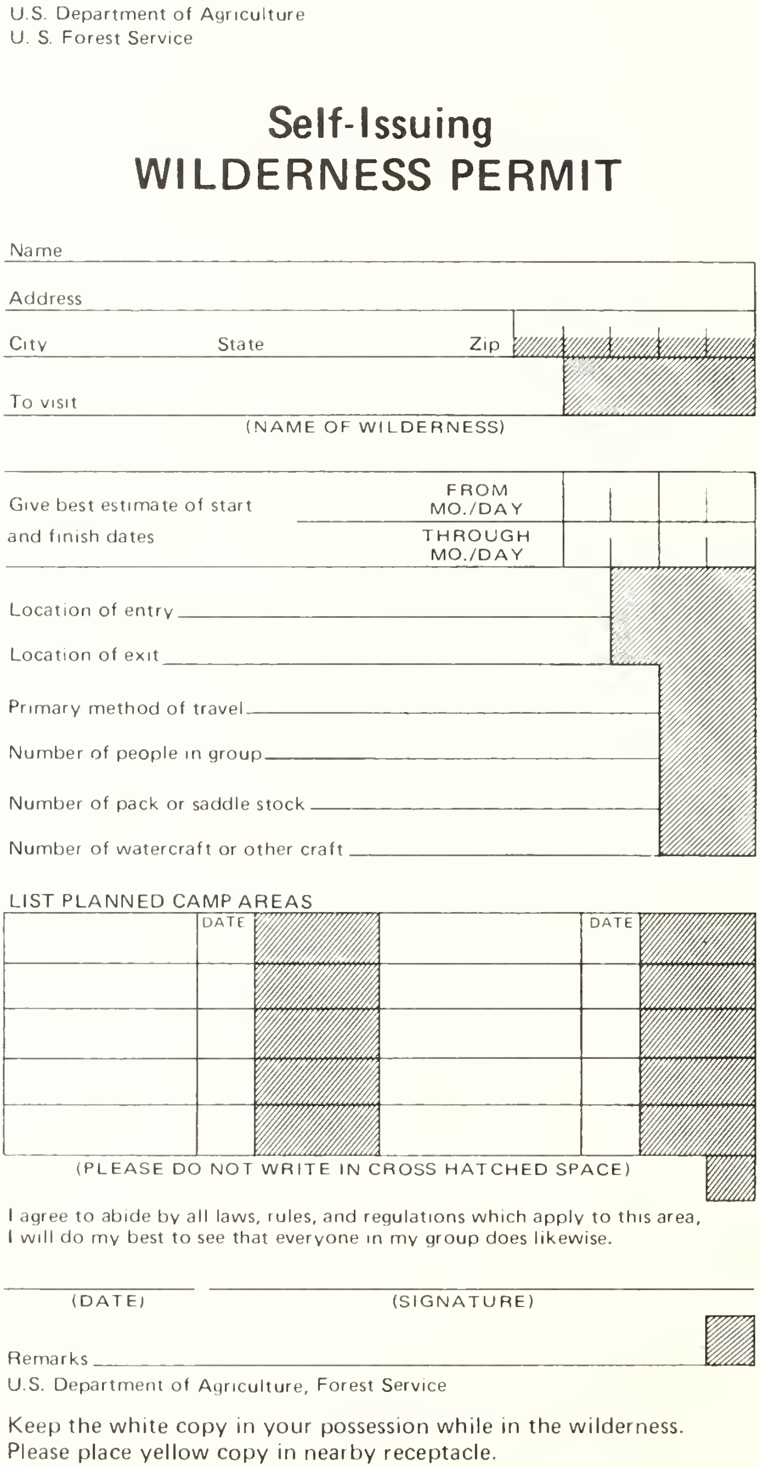
APPENDIX I

PERMIT FORM USED IN THE SPANISH PEAKS PRIMITIVE AREA



U.S. Department of Agriculture
U. S. Forest Service

Self-Issuing
WILDERNESS PERMIT

Name

Address

City State Zip

To visit
(NAME OF WILDERNESS)

Give best estimate of start and finish dates	FROM MO./DAY		
	THROUGH MO./DAY		

Location of entry

Location of exit

Primary method of travel

Number of people in group

Number of pack or saddle stock

Number of watercraft or other craft

LIST PLANNED CAMP AREAS

	DATE	▨		DATE	▨
		▨			▨
		▨			▨
		▨			▨
		▨			▨
		▨			▨

(PLEASE DO NOT WRITE IN CROSS HATCHED SPACE)

I agree to abide by all laws, rules, and regulations which apply to this area, I will do my best to see that everyone in my group does likewise.

(DATE) (SIGNATURE)

Remarks

U.S. Department of Agriculture, Forest Service

Keep the white copy in your possession while in the wilderness.
Please place yellow copy in nearby receptacle.

APPENDIX II

FORMS USED FOR CLASSIFICATION OF TRAFFIC AND COMPLIANCE

SPANISH PEAKS USE DATA, 1978

Trailhead Spanish Cr. (code in col. 6) Classification At trailhead.
Dates and approximate times covered from 8/19, 10:30a to 8/24, 11:15a

	Col. 1		2		3			4	5			
	Season		Length of Stay		Method of Travel			Party-size	Permit Compliance			
	Summer	Fall	Day	Overnight	Hike	Hike w/stock	Horseback	No. of People	Yes	No	Uncertain	
	Code 1*	2	1	2	1	2	3	Code direct	1	2	3	
1	1			2	1			2	1			
2	1			2	1			3	1			
3	1		1				3	4		2		
4	1			2	1			2	1			
5	1		1		1			2	1			
6	1		1		1			2	1			
7	1		1		1			1	1			
8	1		1		1			5		2		
9	1		1		1			9		2		
10	1		1		1			2	1			
11	1			2	1			2	1			
12	1			2	1			1	1			8/20
13	1		1		1			1		2		
14	1		1		1			3	1			
15	1			2	1			2		2		8/21
16	1			2	1			1	1			
17	1			2	1			2	1			8/22
18	1		1		1			1		2		
19	1			2	1			1	1			
20	1		1		1			2	1			
21	1		1		1			1		2		
22	1		1		1			6		2		
23	1		1		1			2		2		
24	1		1		1			8	1			
25	1		1		1			1		2		

	Day-use	Overnight	Hiker	Hike/stock	Horseback	1 person	2-6	7+	Total
No. of parties†	16	9	24		1	8	15	2	25
No. complied	7	8	15		0	4	10	1	15
% complied	44	89	63		0	50	67	50	60

* Put correct code number on line below

† Omit parties that could not be classified on permit compliance.

SPANISH PEAKS - 1978 - SELF-ISSUED PERMITS

LENGTH-OF-STAY FOR DAY-USERS

Trailhead Cascade Creek Date 7/27 — 8/3

Length of Visit	COMPLIANCE		
	Yes	No	Uncertain
≤ 1 hour (No dots)		𝍸	
≤ 2 hours (1 dot)	𝍷	𝍷𝍷𝍷	
≤ 3 hours (2 dots)	𝍷		
More than 2 dots	𝍸 𝍸𝍷 𝍸 𝍷𝍷		
Uncertain			

☆ U. S. GOVERNMENT PRINTING OFFICE: 1981—777-028/90 REGION NO. 8

Lucas, Robert C., and Thomas J. Kovalicky
1981. Self-issued wilderness permits as a use measurement system. USDA For. Serv. Res. Pap. INT-270, 18 p.
Intermt. For. and Range Exp. Stn., Ogden, Utah 84401

A self-issued, mandatory visitor permit system was evaluated as a use measurement system during its first year of operation in the Spanish Peaks Primitive Area, Montana. Overall, 53 percent of all visitor groups obtained permits. Length-of-stay was the factor most related to compliance. Overnight visitors (campers) complied well; day-visitors did not, especially those making brief visits. Self-issuing permit stations located up the trail performed better than those adjacent to parking areas. Self-issued permits appear to have advantages over voluntary trail registers for measuring use. Recommendations for raising compliance, which would also apply to trail registers, are presented.

KEYWORDS: wilderness, recreation, use measurements, permit systems, trail registers, Montana

The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

The Intermountain Station includes the States of Montana, Idaho, Utah, Nevada, and western Wyoming. About 231 million acres, or 85 percent, of the land area in the Station territory are classified as forest and rangeland. These lands include grasslands, deserts, shrublands, alpine areas, and well-stocked forests. They supply fiber for forest industries; minerals for energy and industrial development; and water for domestic and industrial consumption. They also provide recreation opportunities for millions of visitors each year.

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Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

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

United States
Department of
Agriculture

Forest Service

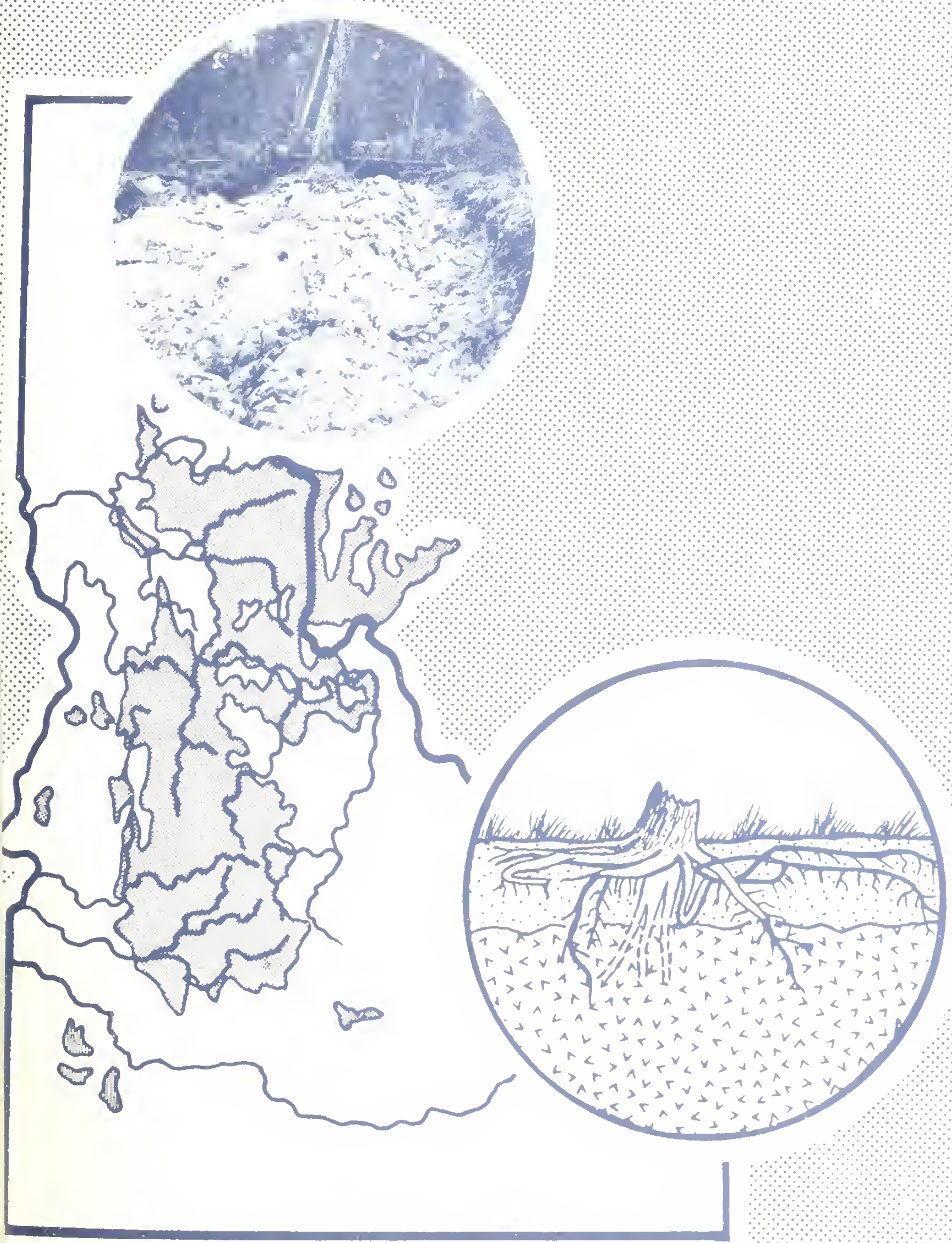
**Intermountain
Forest and Range
Experiment Station**

Research Paper
INT-271

May 1981

Forest Vegetation Removal and Slope Stability in the Idaho Batholith

Donald H. Gray
Walter F. Megahan



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RESEARCH SUMMARY

A study was conducted on two small watersheds in the Boise National Forest to determine the role of forest vegetation in maintaining more secure slopes in shallow, coarse-textured soils typical of the Idaho batholith. Both soil water piezometry and soil shear strength measurements were made in the watersheds.

Results of the field studies and supporting analyses indicate that forest vegetation often provides a critical margin of safety. Woody vegetation growing on slopes of the batholith contributes to stability by root reinforcement, by soil moisture depletion from interception and transpiration, by regulation of snow accumulation and melt rates, and by soil arching restraint between tree stems. Conversely, removal of vegetation from a slope by timber harvesting or wildfire results in a loss or reduction of effectiveness of these stabilizing mechanisms. Loss of vegetative stabilization in turn can lead to increased frequency of landslides as documented in this study.

Management implications of the study are discussed. Suggested measures and approaches include more stringent controls on size and location of clearcut units, greater use of "vegetation leave areas" or buffer zones particularly along haul roads and next to streams, and construction of hydraulic structures that divert water away from critical areas.

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Forest Vegetation Removal and Slope Stability in the Idaho Batholith

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INTRODUCTION

Slope Stability Problems in the Batholith

DESCRIPTION OF THE BATHOLITH

The Idaho batholith is a 16,000 mile^2 (41 000 km^2) mountainous area of granitic rocks located in central Idaho (see location map in fig. 1). Shallow, coarse-textured soils (loamy sands to sandy loams) typically develop on slopes that average 60 percent or more in many drainages. Soils of this type have been shown to be extremely erodible (Anderson 1954; André and Anderson 1961).

The granitic bedrock exhibits various degrees of weathering and fracturing. An idealized subsurface profile in a slope in the natural, undisturbed state, is shown in figure 2. The soil profile can be divided roughly into three major zones according to degree of weathering, indicated by surface soil (decomposed granitics and organic matter), fractured, disintegrated rock, and relatively competent, partly weathered bedrock. These zones vary in thickness, and changes in composition or texture are transitional rather than abrupt. A more precise delineation can be made by using a classification for granitic rocks developed by Clayton and Arnold (1972). Their classification criteria include apparent degree of mineral alteration and rock competency with respect to angularity of joint sets and response to a hammer blow.

The surface soil is almost without stones and is derived from granitic rock in a fairly advanced state of physical, if not chemical, weathering. This horizon usually consists of a sandy, coarse-textured soil with little or no intrinsic cohesion. In general it would be classified as an A-1-b soil under the American Association of State Highway Transportation Officials (AASHTO) Classification and as a SW-SM soil under the Unified Classification (Gonsior and Gardner 1971). Such relict features or vestiges of the original rock structure, as joint planes may persist in the soil. It is this part of the profile that is generally the most prone or vulnerable to both surficial and mass erosion (Durgin 1977).

Cyclonic storms and/or deep snowpacks that release large volumes of water to the soil within short periods are annual occurrences in the batholith region. Water supplied by these climatic events rapidly infiltrates the soil surface and continues downward until it reaches the zones of reduced hydraulic conductivity at the interface with the fractured, disintegrated bedrock. Continued inflow of water creates a saturated layer at this level, which in turn causes both buildup of a piezometric head and subsurface flow along the weathered bedrock surface (Megahan 1972). The subsurface flow zone is shown on figure 2. Depth of the soil piezometric surface is one of the most important factors influencing stability of steep mountain slopes mantled with shallow, noncohesive soils.

Figure 1.—Location map showing the Idaho batholith and study area.

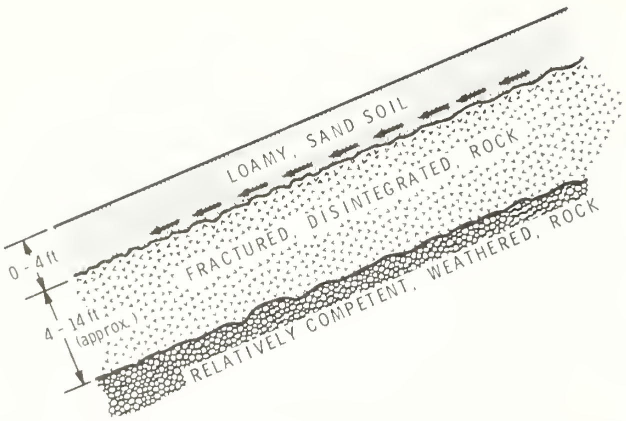

Figure 2. — Typical soil profile and slope geometry in the Idaho batholith (excluding swales, depressions, and other topographic lows). Arrows indicate the shallow subsurface flow zone.

DOCUMENTATION OF SLOPE FAILURES

The Idaho batholith area contains valuable timber reserves as well as other resources important to the regional and national economies. This has led to considerable development activity, particularly road construction and timber harvesting. The batholith is also a critical area with respect to surface and subsurface stability. Surface erosion and landslides are prevalent. Consequently, much of this development activity has increased the occurrence of landslides and provided large exposed areas from which sediment can readily be removed by surface erosion processes (Megahan and Kidd 1972).

Slope stability problems in the batholith have been studied and documented by a number of investigators in the past decade (Croft and Adams 1950; Gonsior and Gardner 1971; Megahan and Kidd 1972; and Megahan and others 1978). An inventory and analysis by Megahan and others (1978) of some 1,400 landslides on two National Forests reveals some interesting findings about the nature and cause of these slope failures.

The survey was carried out on the Clearwater and Boise National Forests and represents geologic conditions found in the western and central portions of the Northern Rocky Mountain physiographic province. Most of the area surveyed in the landslide inventory falls within the Idaho batholith. Portions of the Clearwater National Forest, however, are outside the batholith. Here, low grade metasediments (mostly quartzite) of the Belt Series predominate.

Almost three quarters (72 percent) of the slides inventoried were debris avalanches or debris slides. For a 3-year study period, a total of almost 15 acres (6 hectares) of forest land were lost to landslides each year on the Clearwater National Forest alone. Repair costs to simply clear debris from roads and replace road fill material averaged $56,000 per year. An average of 56,000 cubic yards/year (43 000 cubic meters/year) of slide material was delivered to active stream channels with adverse impacts on the fisheries resources of the region.

By far the most likely cause of accelerated landslide activity was road construction. Roads alone accounted for 58 percent of the landslides inventoried. In combination with logging and/or forest fires, roads accounted for a total of 88 percent of all landslides. Vegetation removal alone accounted for 9 percent of the landslide activity. Only 3 percent of the landslides occurred on "natural" or undisturbed slopes. These relationships are shown graphically in figure 3.

The Idaho batholith is not unique with regard to its hig incidence of slope failures. Numerous slides have occurred i granitic areas all around the world (Durgin 1977; Jones 1973). Granitic masses or batholiths commonly form the core of mountains that may have extreme topographic relief. Progressive physical, chemical, and biological weathering weakens th granitic rocks and make them susceptible to erosion and mas movement (Clayton and others 1979). Natural events such a intense rainstorms, earthquakes, or other perturbations ca then trigger slides at susceptible sites. Developmental activit such as road construction and timber harvesting can accelerat or intensify this process.

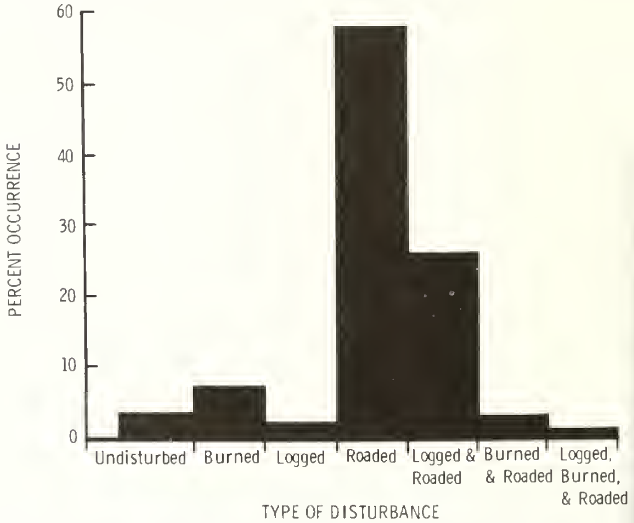

Figure 3. — Landslide occurrence by type of disturbance, western and central Northern Rocky Mountain physiographic province (from Megahan and others 1978).

Potential Effects of Timber Removal

STABILIZING INFLUENCE OF WOODY VEGETATION

Central to the purpose of this paper is the role of fores vegetation in maintaining more secure slopes. This questio has been analyzed in considerable detail by Gray (1970, 1978 who identified four principal mechanisms by which fores vegetation enhances stability, namely:

(a) Mechanical reinforcement from the root system.
(b) Regulation of soil moisture content and piezometri levels through transpiration, interception, and b affecting snow accumulation and rate of melting.
(c) Buttressing or soil arching action between the trun or stems.
(d) Surcharging from the weight of trees.

The effectiveness of these hydromechanical influences d pends upon soil and slope conditions at particular sites. Ro reinforcement and buttressing, for example, would be of litt avail in arresting deep-seated, rotational failures in cohesi soils. On the other hand, in shallow, coarse-textured soils whi are prone to debris sliding and avalanching along an incline bedrock surface, the situation is quite different; root reinforc ment and buttressing may contribute significantly to stability this case. Dramatic examples of such slope stabilization ponderosa pines are shown in figures 4 and 5. The importan of these "hydromechanical" contributions of forest vegetation the stability of slopes in the Idaho batholith is examined greater detail later in the paper.

Figure 4. — Ponderosa pine tree (*Pinus ponderosa* Laws) buttressing and restraining a slope in a road cut in granitic soil of the Idaho batholith. Note massive buttress roots in right foreground.

Figure 5. — Slope buttressing by ponderosa pine. Unbuttressed part of slope on left has failed. Mendocino National Forest, California.

CONSEQUENCES OF REMOVAL

One way of ascertaining the significance or contribution of forest vegetation to the stability of slopes is to examine the consequences of its removal. The concensus of investigators on this question is clear, namely, indiscriminate removal weakens soils and destabilizes slopes. This concensus applies not only to the Idaho batholith but to other forested slopes as well (Bishop and Stevens 1964; Rice and Krammes 1970; Swanston 1974; Swanson and Dyrness 1975; O'Loughlin 1974; Swanston and Swanson 1976; and Wu 1976).

The landslide inventory conducted by Megahan and others (1978) in the Boise and Clearwater National Forests revealed significant contributions of vegetation roots to stability of steep mountain slopes. Landslide hazard was observed to increase in direct proportion to the amount of vegetation removed because of root decay. The amount of residual vegetation, including both trees and shrubs, was an important factor regulating the increase in landslide hazards following timber cutting or forest fire. The rate of root decay relative to the rate of new root growth appeared to determine the time of occurrence of maximum landslide hazard following vegetation removal. On the average, landslide hazards were greatest 4 years after timber removal and remained high for about 6 years. By the end of 20 years, landslide hazards had returned to their predisturbance levels. These slide-vegetation relationships are shown graphically in figures 6 and 7.

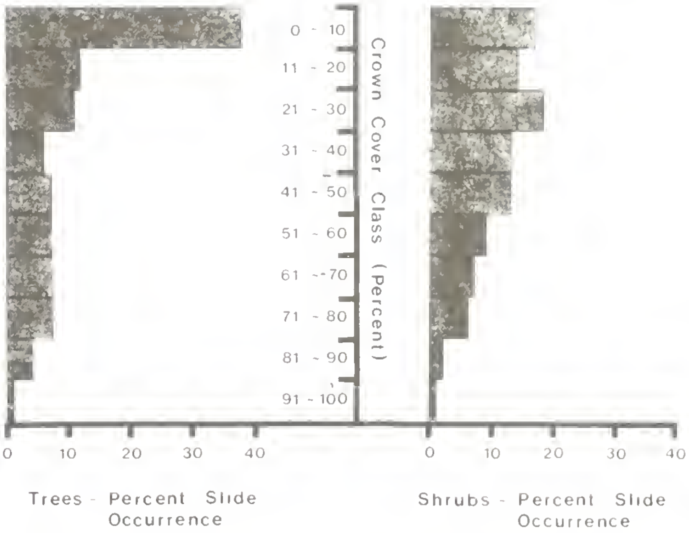

Figure 6. — Landslide occurrence by vegetation crown cover, western and central Northern Rocky Mountain province (from Megahan and others 1978).

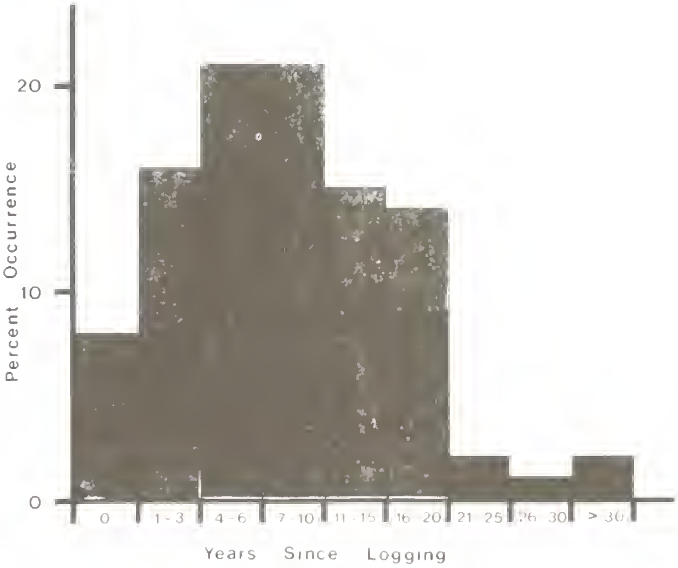

Figure 7. — Landslide occurrence by years since logging, western and central Northern Rocky Mountain province (from Megahan and others 1978).

DESCRIPTION OF PINE CREEK STUDY

The Pine Creek study was established originally to evaluate subsurface flow occurrence on representative granitic slopes and the effect of clearcutting and road construction on subsurface flow emerging on the face of road cut slopes.

Physiographic Setting

The Pine Creek drainage is a tributary to the Middle Fork of the Payette River above Crouch, Idaho. The study was installed on two small undisturbed watersheds of 2.4 and 0.8 acres (1.0 and 0.3 hectares). These microwatersheds are representative of first order drainages found in midelevation, fluvial landscapes of the Idaho batholith.

Slope gradients on the two study watersheds range from 35 to more than 70 percent and aspects range from northeast to northwest (see fig. 8). The soil is a Koppes loamy coarse sand and is a member of the sandy-skeletal mixed family of typic cryoborolls (Nelson 1976). Sandy loam to loamy sand soils overlie moderately weathered and fractured bedrock and range in depth from 6 inches (15 cm) on ridges to about 48 inches (122 cm) in drainage bottoms. Surface soils were almost entirely covered by litter up to 1 inch (2.5 centimeters) deep before disturbance. Soils are poorly developed, exhibiting only shallow A and C horizons. Average physiographic and soils data are summarized by watershed in table 1. A general view of the study watershed is shown in figure 9.

Vegetation on the watersheds before disturbance consisted of an overstory of ponderosa pine (*Pinus ponderosa* Laws.), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), and Engelmann spruce (*Picea engelmannii* Parry), and an understory of small trees and shrubs.

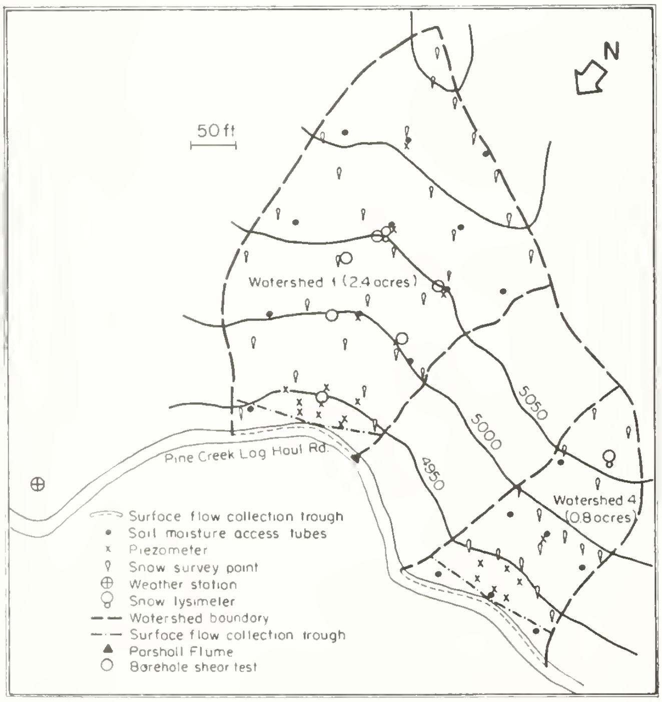

Figure 8. — Pine Creek study area showing location of instrument and data collection stations in the watersheds.

Annual precipitation in the vicinity averages approximately 32 inches (81 cm). A large portion occurs as snowfalls; consequently, a large snowpack accumulates often to a total depth in excess of 60 inches (152 cm), or 20 inches (51 cm) of water equivalent. During the spring, the snowpack melts in a relatively short time, contributing large volumes of water to the soil that generate subsurface flow and measurable piezometric heads.

Table 1. — Descriptive data for Pine Creek study watersheds Boise National Forest

Watershed	Average slope	Average soil depth	Average elevation	Average aspect (azimuth)	Average crown cover
	Percent	*Inches*	*Feet*	*Degrees*	*Percent*
Watershed No. 1 (clearcut)	52	32	5,050	337 NNW	63
Watershed No. 4 (uncut)	62	30	5,005	335 N	43

Figure 9. — View of Pine Creek study area, Watershed No. 1, Boise National Forest, Idaho. Arrows point to slope failures. (Photo taken July 1977.)

History of Land Use

The study was initiated in 1969 and proceeded on schedule until November 1972 when the larger watershed (No. 1) was clearcut. A total of 36 ponderosa pines, averaging 25.8 inches (65.5 cm) in diameter, and 126 Douglas-fir, averaging 13.4 inches (34.0 cm) in diameter, were removed as a result of the logging. The total volume of timber removal averaged 14,500 board feet per acre (203 m³/ha). Slash treatment included lopping, scattering, and some hand piling. On August 20, 1973, a wildfire swept through the Pine Creek drainage, including the two study areas. This unplanned event compromised some of the hydrologic studies, but also provided an opportunity to compare the postburn response of a cutover and adjacen undisturbed watershed.

Postfire Stability Problems

Following the wildfire, it was apparent that accelerated surface soil erosion (by rilling and rain splash) was occurring on the clearcut watershed. This was corroborated by studies conducted by Megahan and Molitor (1975). The erosion was entirely postfire; there was no evidence of surface erosion on the clearcut watershed before the fire. The clearcutting had a twofold effect: it removed protective canopy cover (an important source of postfire litter); and it increased surface fuel loading that led to a more intense burn on the clearcut watershed.

Mass erosion also occurred in 1974 and 1975 after the fire. It was manifested by progressive failures of cut slopes above the haul road that traversed the two watersheds (see fig. 9). Other landslides also occurred within the 2,200-acre (890-ha) Pine Creek burn (table 2). It is interesting that only 50 percent of these slides were road associated (most were rotational slumps in road cuts). The remainder were shallow, debris slides or flows with an average depth of 26 inches (66 cm). These slides occurred on natural slopes with an average gradient of 73 percent (36 degrees). Typical examples of both erosion and slope stability problems in the study watersheds are shown in figures 10 and 11.

Table 2. — Landslide study on the Boise National Forest (1975)

Slide identification number	Slides in the Pine Creek Burn							
	Slide type	Length	Width	Depth	Volume	Gradient	Soil depth	Cause
		Feet			*Cubic yard*	*Percent*	*Inches*	
BO-613-75	Debris slide	24	37	3	50	60	12	Road cut
BO-614-75	Debris slide	12	15	1.5	7-10	60-70	Missing	Not road associated
BO-615-75	Debris slide or flow	Missing	Missing	Missing	9	Missing	Missing	Road cut
BO-616-75	Debris flow(?)	15	15	6	10-12	75	18	Road cut
BO-617-75	Debris torrent/flow	200	10	1	200	65	16	Not road associated
BO-618-75	Debris avalanche	20	10	3	40	Missing	Fill failure	Road fill (culvert)
BO-619-75	Rotational slump	15	30	1	60	100	22	Road cut
BO-620-75	Rotational slump	35	57	1	220	80	Missing	Road cut
BO-621-75	Rotational slump and debris slide	30	110	2	350	70	14	Road cut
BO-622-75	Rotational slump	7	45	1	30	70	35	Road cut
BO-623-75	Debris avalanche	62	10	1	160	173	Missing	Not road associated
BO-624-75	Rotational slump	54	11	2	150	80	Missing	Road cut
BO-625-75	Debris flow	150	20	2.5	550	80	15	Not road associated
BO-626-75	Debris flow	75	30	2	240	85	23	Not road associated
BO-627-75	Debris flow	25	8	3	30	70	16	Not road associated
BO-628-75	Debris flow	90	10	2	140	70	15	Not road associated
BO-629-75	Debris flow	40	17	2	55	80	30	Not road associated
BO-630-75	Debris flow	65	22	2	125	70	16	Not road associated

Figure 10. — Slipout in slope above road cut, Watershed No. 1, Pine Creek study area, Boise National Forest, Idaho. (Photo taken July 1977.)

Figure 11. — Large gully in slope, Watershed No. 1, Pine Creek study area, Boise National Forest, Idaho. Gully was formed by subsurface flow emerging at cut face followed by piping and "spring sapping," which triggered localized slope failure. (Photo taken July 1977.)

STUDY DESIGN AND METHODS

Overall Experimental Design

As noted previously, the original purpose of the Pine Creek study was to evaluate subsurface flow occurrence on representative granitic slopes and the effect of clearcutting and road construction on subsurface flow. Hydrologic data collection on the study watersheds included water inflow, change in water storage, and outflow of water occurring as subsurface flow.

Subsurface flow was measured with collection troughs installed on the road at the base of the cut slope across the entire width of the watersheds. Estimates of water inflow into the watersheds and changes in water storage were obtained from a recording rain gage and snow lysimeter. In addition, 45 snow stakes and 23 neutron access tubes for soil moisture determination were located in a grid pattern on the study watersheds. Finally, 25 piezometers were located in suspected water-accumulation areas within the watersheds. All data collection sites or stations are shown in figure 8.

Some additional data were collected following the wildfire on the study area to evaluate the effects of burning on surface erosion rates. Data compilation included rill surveys, a network of erosion pins, and collection of eroded material in splash pans and in the subsurface flow collection troughs.

Piezometric levels or ground water conditions are also critical determinants of the mass stability of slopes. Accordingly, a conjunctive slope stability investigation was undertaken in the experimental watersheds in the summer of 1977. Estimates of soil shear strength (required for stability analyses) were obtained from in-situ borehole shear tests (see fig. 8 for locations) and from results of laboratory triaxial tests on granitic soils reported by other investigators (Lumb 1962; Gonsior and Gardner 1971; Hampton and others 1974[1]; Prellwitz 1975 USDA Forest Service 1977). The slope stability investigation also included an analysis of the contribution of forest vegetation to slope stability from root reinforcement, surcharging, and buttressing or soil arching action.

Piezometer Installation and Data Collection

A total of 25 piezometers were installed in the study watersheds: 14 in Watershed No. 1 and 11 in Watershed No. 4. The precise location of these piezometers is shown in figures 12 and 13. It should be noted that piezometer Nos. 10-14 and 9-11 in Watersheds 1 and 4, respectively, were lost in slope failures that occurred in 1974 and 1975 (see figs. 12 and 13 for location).

The piezometers were installed vertically by hand augering a 2-inch (5-cm) hole through the loamy sand soil to the surface of the underlying fractured, disintegrated rock. A typical piezometer installation is illustrated schematically in figure 14. The piezometers were read frequently during the active snowmelt period in late spring and at monthly intervals throughout the following summer and fall. Both the present and the maximum water depths were measured at each piezometer. The maximum reading between measurements was determined by noting the position of powdered cork on the aluminum rod. The powdered cork floats up as piezometric levels rise and adheres to the aluminum rod at the point of highest rise. This technique was employed by Swanston (1967) in his study of soil water piezometry in southeast Alaska.

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[1] Hampton, D., W. F. Megahan, and J. L. Clayton. 1974. Soil and rock propertie research in the Idaho batholith. USDA For. Sci. Lab. Rep., Boise, Idaho 121 p

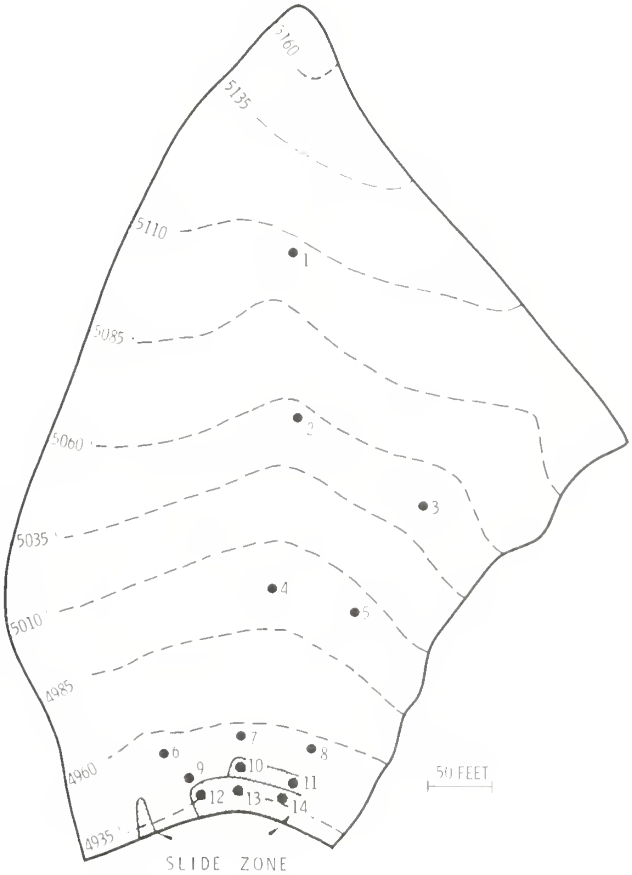

Figure 12. — Location of piezometers and limits of slide zone, Watershed No. 1, Pine Creek study area.

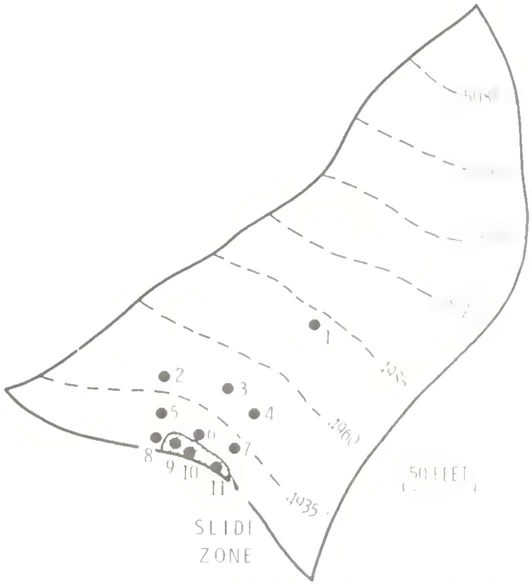

Figure 13. — Location of piezometers and limits of slide zone, Watershed No. 4, Pine Creek study area.

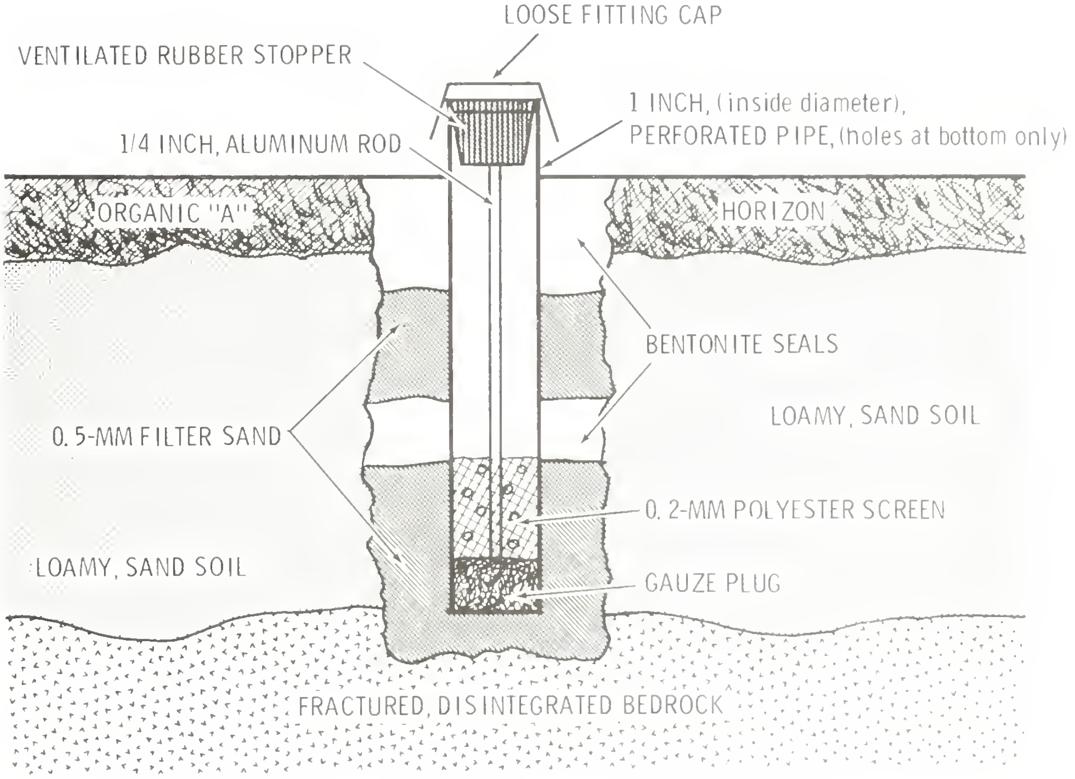

Figure 14. — Schematic illustration of typical piezometer installation, Pine Creek study area

Slope Stability Data Collection

IN-SITU BOREHOLE SHEAR TESTS

The borehole, direct shear test is a rapid method for obtaining in-situ shear strength parameters. Borehole shear tests avoid the need for recovering samples with all the attendant problems of sample disturbance and representative sampling (Handy and Fox 1967; Wineland 1975).

The method basically consists of lowering a shear head down a 3-inch (8-cm) diameter borehole to a desired depth in the soil profile (fig. 15), expanding the shear head against the sides of borehole with a known normal stress, and then recording the maximum shear stress required to crank the shear head up the hole (fig. 16). The test can be run at several depths in the borehole to provide an idea of how the soil shear strength parameters vary with depth.

The boreholes were drilled to the bottom of the soil horizon or disintegrated rock interface (fig. 2) using a 2-inch (5-cm) bucket auger. The holes were then widened to 3 inches (8 cm) in diameter using a thin-walled reamer. Occasionally undisturbed samples were taken with the reamer for density and moisture content determinations. These samples were also analyzed for their grain size distribution.

Figure 15. — Expandable shearing head of borehole device prepared for lowering down borehole.

Figure 16. — Borehole, direct shear test in progress in shallow, coarse textured soil developed on granitic rocks of the Idaho batholith. Pin Creek study area, Boise National Forest.

ROOT DISTRIBUTION AND STRENGTH TESTS

In order to make an assessment of the rooting contribution t soil shear strength and slope stability, it was necessary to obtai an estimate of both root distribution and root strength in th granitic soil of the study watersheds. This estimate wa obtained from results of studies in granitic soils of other watersheds in the Idaho batholith (Curtis 1964; Burroughs an Thomas 1977; and Megahan and others 1978).

Burroughs and Thomas (1977) measured the concentratio of intermingled lateral roots (Douglas-fir) in a vertical plane o trench midway between trees. Inclusion of all intermingled fresh roots up to 0.4 inch (1 cm) in diameter leads to a calculated "root area ratio" of 0.045 percent. Most of the roots counted fe into this size class. Roots in the size class 0 to 0.4 inch (0 to cm) comprised 96 percent of the roots counted in the sampl area. On the other hand, inclusion of fresh roots up to 3 inche (8 cm) in diameter increased the root area ratio to 0.174 percer even though these larger roots were not numerous. Root are ratios less than 1 percent may not seem significant with regar to slope stability, but, as shown later, even a few tenths of percent of root section in the soil is sufficient to provide substantial and critical amount of shear strength increase i shallow, coarse-textured soils.

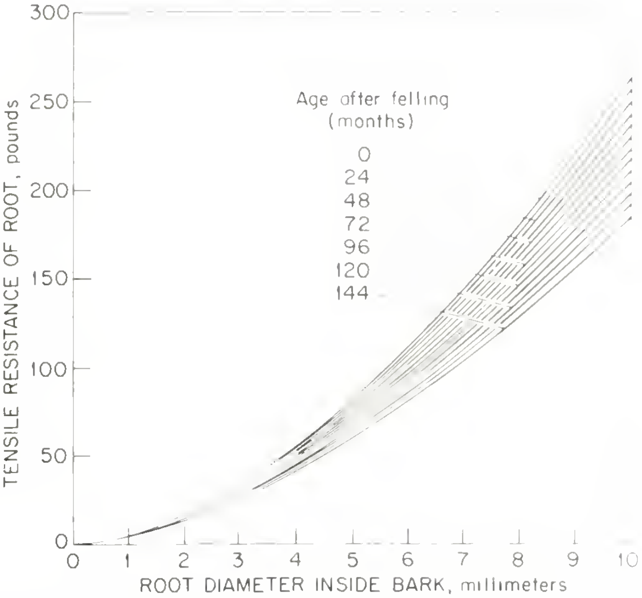

Figure 17. — Tensile resistance of roots of Rocky Mountain Douglas-fir as a function of age and size of root (from Burroughs and Thomas 1977).

Burroughs and Thomas (1977) also determined the tensile resistance of roots for various size classes and various elapsed times after cutting as shown in figure 17. Tensile resistance was only measured for Douglas-fir roots in the size interval 0 to 0.4 inch (0 to 1 cm). The tensile strength computed as tensile resistance divided by root cross sectional area (as distinct from resistance plotted in fig. 17) decreased from 3,280 lb/in^2 (22 600 kPa) for a 0.08-inch (2 mm) diameter root to 2,150 lb/in^2 (14 800 kPa) for a 0.4-inch (10 mm) root. The average tensile strength for roots in this size interval, that is, 0 to 0.4 inch (0 to 1 cm), was approximately 2,720 lb/in^2 (19 800 kPa). This variation in root tensile strength with root size has been observed by other investigators as well (Gray 1978; Wu 1976). This type of information makes it possible to compute the average tensile strength **per unit area of soil** for a Douglas-fir root-soil system. By using a simple root or fiber reinforcement model described in the next section, these data can in turn be translated into a shear strength increase or pseudo "root cohesion."

Unfortunately, Burroughs and Thomas (1977) only looked at the concentration of lateral roots. It is the vertical roots (tap and sinker roots) that will contribute most to sliding resistance of soils on steep, inclined slopes. Studies by Curtis (1964) on ponderosa pine indicate deep penetration of tap roots and sinker roots in a cylindrical zone around each tree in granitic soils of the batholith. The extent of vertical root penetration and concentration across the slope surface as a whole is not known precisely.

One way of estimating this concentration is simply to use root area ratios that can be calculated from root distributions measured by Burroughs and Thomas (1977). Those authors caution, however, that their measurements were restricted to lateral roots of Douglas-fir crossing a vertical plane midway between trees. On the other hand, they also state that the finer roots (0.4 inch [1 cm] and smaller) are found throughout the rooting zone of each tree root system. Furthermore, they note that these same roots " . . . will penetrate a shallow soil overlying a weathered or well-fractured bedrock or glacial till to anchor the soil-root mass."

More direct data on critical root distribution in granitic soils can be obtained from the landslide study by Megahan and others (1978). The size and frequency of roots exposed in a slide shear plane in a forested slope are summarized in figure 18. The dominant size class (modal value) of roots in the shear plane was 0.20 to 0.40 inches (0.51 to 1.02 cm) in diameter. The dominant (modal value) root density class was 6.5 to 10.5 roots per square foot (70 to 113 roots per square meter). This information yields root area ratios ranging from 0.14 to 0.93 percent using data from the modal class. Burroughs and Thomas (1977) found the same class to be dominant for Rocky Mountain Douglas-fir in their study, i.e., most of the roots they counted fell into the 0 to 0.4 inch (0 to 1 cm) size range.

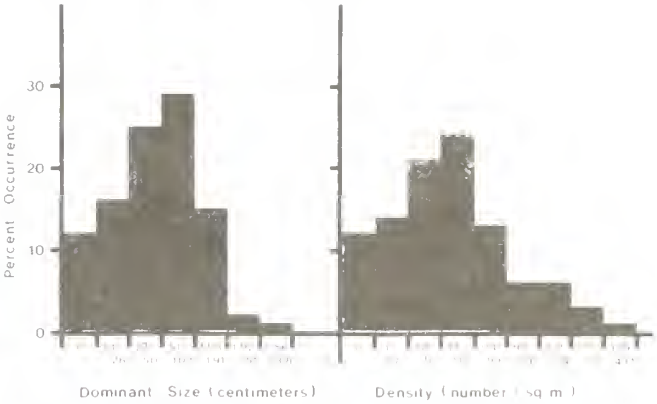

Figure 18. — Landslide occurrence by sheared roots at slide site (from Megahan and others 1978).

In contrast, the root area ratio (0.045 percent) calculated from their study for this size class was much lower than those computed from the data of Megahan and others (1978). The difference is most likely caused by the fact that Burroughs and Thomas (1977) counted only Douglas-fir roots in vertical planes midway between tree stumps, whereas in the other study all roots were counted in shear planes parallel to the slope, regardless of species. Wu (1976) measured root area ratios ranging from 0.05 to 0.17 and averaging 0.08 percent in his study of vegetative influence on landslide occurrence in Southeast Alaska. His root area ratios were measured at the contact between the B and C soil horizons, in soils developed on glacial till slopes supporting a spruce-hemlock forest.

Kozlowski (1971) observed that root structure as well as depth and rate of root growth are markedly influenced by the rooting medium or environment. The water-holding capacity or water availability in a soil is particularly important in this regard. Roots tend to avoid regions of high moisture stress and invade or permeate moist zones. In the case of shallow, coarse-textured soils of the Idaho batholith, the most favorable region for roots to exploit from a moisture standpoint is the zone close to the contact between the soil and the underlying fractured, disintegrated bedrock. In other words, one should expect a fairly high concentration of vertical or sinker roots across this contact.

This expectation is partly confirmed by McMinn (1963) in his extensive study of the characteristics of Douglas-fir root systems. Hydraulic excavation of root systems in Douglas-fir stands revealed a pronounced tendency towards steeply inclined or downward root penetration, not only from the central, deep root system, but also from semivertical roots (sinkers) from laterals. This trend was most pronounced in older tree stands.

From all the aforementioned studies, a root area ratio in the range of 0.05 to 0.15 percent can be considered a reasonable or preliminary lower bound estimate in a slope for purposes of stability calculations in forested, granitic slopes of the Idaho batholith. This topic will be considered further in a subsequent section dealing with root reinforcement and its contribution to slope stability.

TREE STEM SURVEY

Tree stem survey data from nearby experimental watersheds in the adjacent Silver Creek drainage were used for calculating slope surcharge from the weight of forest vegetation and for estimating buttressing or soil restraint from tree trunks firmly rooted to the underlying bedrock.

A stem count and inventory for five cutting units on two experimental watersheds in the Silver Creek drainage is summarized in table 3. The inventory included only stems 12 inches (30.5 cm) and over in diameter at breast height. Average tree spacings (S) were calculated assuming a simple cubic and triangular array. Average size of openings (B) between "vertical root cylinders" were calculated assuming the diameter of the root cyclinder (D_R) was approximately five times the stem or trunk diameter (D_T) at breast height. Field studies by Wu (1976) and Curtis (1964) indicate that this diameter ratio is reasonable. The various spacing relationships are illustrated schematically in figure 19.

Table 3. — Stem count and tree spacings for experimental watersheds, Silver Creek study area, Boise National Forest

Cutting unit	Total area	Total stem area	Number of stems 12 inches in diameter and over	Average stem diameter	Average stem[1] spacing	Estimated[2] root zone diameter	Estimated size of opening between root zones
	Acres	*Feet²*		*Feet*			
Control Creek No.3	96.6	2,690	960	1.89	66	9.4	57
4	51.5	3,503	1,567	1.69	38	8.4	30
5	19.5	1,635	778	1.64	33	8.2	25
6	21.1	2,215	880	1.79	32	8.9	23
K-1 Creek	36.7	1,731	620	1.88	51	9.4	41

[1] Based on simple, cubic array where spacing (S) = $\left[\text{(area cutting unit)}/\text{(number stems} > \text{12 in.)} \right]^{1/2}$.

[2] Assume $D_R = 5D_T$ (estimate based on data in Curtis [1964] and Wu [1976]).

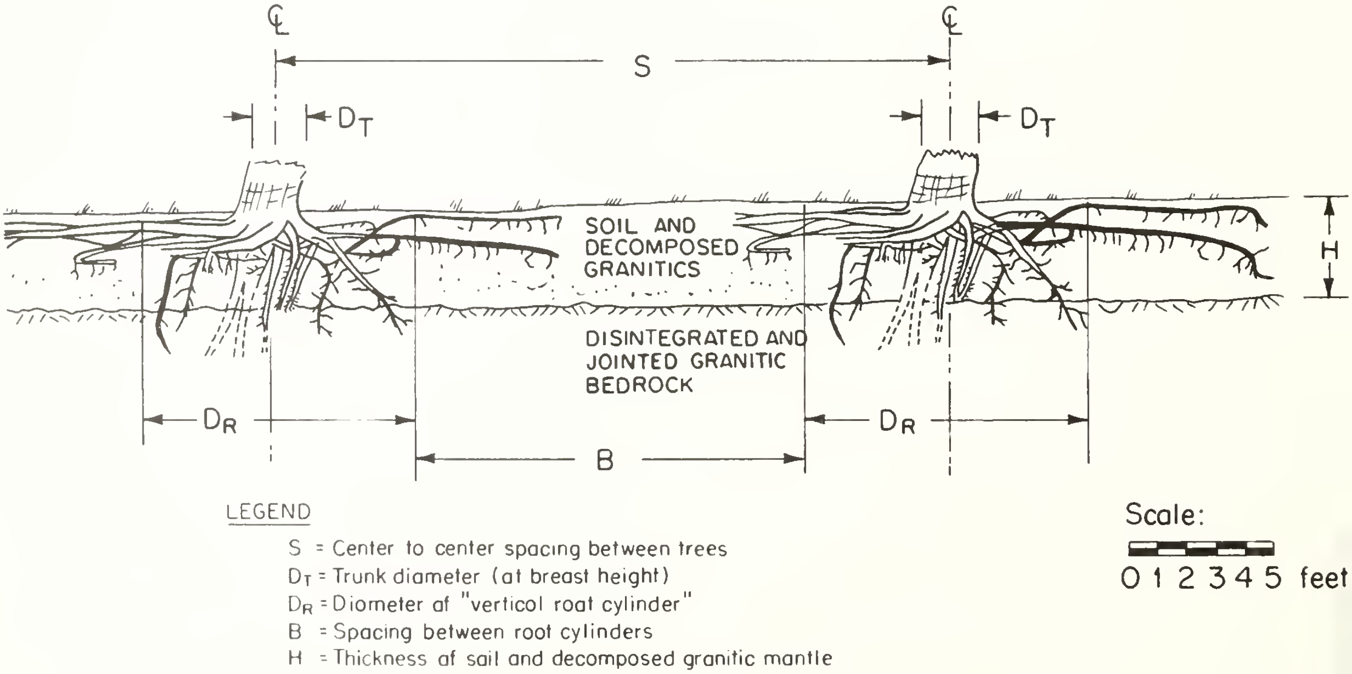

Figure 19. — Schematic diagram of spacing relationships between tree trunks and their "vertical root cylinders" in granitic slopes.

STABILITY MODELS FOR GRANITIC SLOPES

Infinite Slope Analysis — Natural Slopes

Slopes fail when the shear stress on any potential failure surface exceeds the shear strength. It is customary to express this balance of forces or stresses in terms of a ratio or factor of safety against sliding. This ratio or factor of safety is commonly defined as follows:

$$F = \frac{\text{shear resistance along critical surface}}{\text{shear forces promoting sliding on the surface}} \quad (1)$$

Most natural granitic slopes consist of a shallow, cohesionless soil mantle overlying an inclined bedrock contact. An idealized soil profile and slope geometry were shown in figure 2. The stability of such slopes can be determined by the so-called "infinite slope analysis." This model assumes that the thickness of the sliding mass is constant and relatively thin compared to its length. This also implies that the sliding surface is parallel to the slope and approximately planar over most of its area. The infinite slope model has been used previously and with good results to analyze the stability of slopes in the Idaho batholith (Gonsior and Gardner 1971; Prellwitz 1975).

According to the infinite slope model, the factor of safety against sliding can be expressed by the following mathematical equation:

$$F = \frac{\left[\frac{C_s + C_R}{\tan\phi' \cos^2\beta} + (q_o + \gamma H) + (\gamma_\beta - \gamma)H_W\right] \frac{\tan\phi'}{\tan\beta}}{[(q_o + \gamma H) + (\gamma_{SAT} - \gamma)H_W]} \quad (2)$$

F = factor of safety against sliding
H = thickness (depth) of soil mantle (in vertical direction)
H_W = height of piezometric surface above bedrock contact
C_s = effective cohesion of soil
C_R = shear strength increase from root reinforcement expressed as a pseudo cohesion
γ = moist density of soil (above piezometric surface)
γ_{SAT} = saturated density of soil
γ_β = buoyant density of soil ($\gamma_\beta = \gamma_{SAT} - \gamma_w$)
γ_w = density of water
q_o = vertical surcharge (from weight of vegetation)
β = slope angle or gradient
ϕ' = effective angle of internal friction of the soil

Equation 2 is a completely general expression for factor of safety, which takes into account the existence or presence of cohesion (C_s) in the soil, a slope surcharge (q_o), and a ground water table or piezometric surface in the slope (H_W). In the event hese are absent, the terms in which they appear are removed rom the equation. If the soil is completely dry, that is, in the absence of any piezometric surface ($H_W = 0$), dry density γ_{DRY}) may be substituted for moist density (γ) in equation 2.

The relative importance of the various parameters in equation 2, such as, cohesion as opposed to friction, and the effect on safety factor of a change in one variable, such as surcharge, is not intuitively obvious. The relative importance of each variable in the equation and direction of change that may be produced by altering input variables is best determined by conducting a sensitivity analysis using a realistic range of values for each input variable. This analysis is conducted for the study watersheds in a subsequent section of the report.

Slope vegetation and its removal affect several of the input variables in equation 2. Most noticeably or obviously affected will be the slope surcharge (q_o), piezometric height (H_W), and root cohesion term (C_R). Reduction in evapo transpiration as a result of clearcutting may also affect soil density (γ) in addition to the piezometric surface elevation. Based on the result of soil-root reinforcement studies conducted to date, the angle of internal friction of the soil (ϕ) is affected hardly at all by the presence or absence of roots (Gray 1978; Waldron 1977). The extent and consequences of forest vegetation and its removal on the stability of granitic slopes in the Idaho batholith are examined further in the next section of the report. Similar studies employing the infinite slope model have been conducted by Wu (1976), Brown and Sheu (1975), Gray (1978), and Ward (1976).

A simple theoretical model of a fiber-reinforced soil was developed by Wu (1976). This model was used by Wu to estimate the contribution of rooting strength to slope stability in analyses of both forested and cutover slopes in Southeast Alaska. A virtually identical model was developed independently by Waldron (1977) and evaluated in conjunction with direct shear tests run in the laboratory on root-permeated homogeneous and stratified soil.

A schematic illustration of the root reinforcement model proposed by Wu (1976) is shown in figure 20. The model essentially envisions an elastic root or fiber embedded in a soil matrix and initially oriented normal to the shearing surface. Deformation in the soil is resisted by tangential forces which develop along the fiber and which in turn mobilize the tensile resistance of the fiber. These tangential forces (τ on fig. 20) are produced by friction or by bonding between the fiber and surrounding soil matrix. The soil friction angle (ϕ) is assumed to be unaffected by the reinforcement. This model also assumes that tensile strength of the fibers or roots is fully mobilized during failure. This requires either fixity of the roots at their ends or roots that are long enough and/or frictional enough for the frictional or

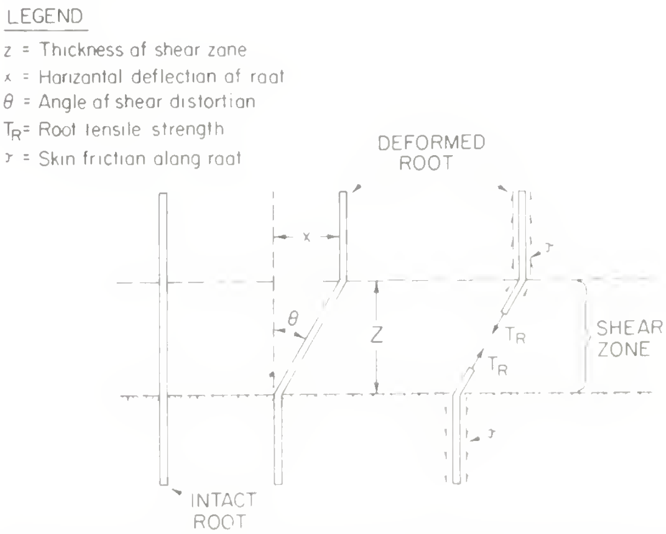

Figure 20. — Root reinforcement model. Flexible, elastic root is oriented in perpendicular direction to shear surface (after Wu 1976).

bonding strength between roots and soil matrix to exceed the tensile strength of the roots. This assumption appears justified from field examination of broken, exposed roots in shear planes of landslides (Wu 1976; Megahan and others 1978).

According to this model the tensile force that develops in the fiber can be resolved into a lateral component that directly resists shear and into a normal component that increases the normal or confining stress on the shear plane. Mathematically this translates into an increase in shear resistance or "root cohesion" C_R as follows:

$$C_R = t_R\,[\cos\Theta\tan\phi + \sin\Theta] \tag{3}$$

where C_R = shear strength increase from root or fiber reinforcement
Θ = angle of shear distortion
ϕ = angle of internal friction
t_R = average tensile strength of roots **per unit area of soil**

The average tensile strength of fibers or roots **per unit area of soil** (t_R) can be determined by multiplying the tensile strength of the roots (T_R) by the fraction of the soil cross section filled or occupied by roots (A_R/A). Thus:

$$t_r = T_R \cdot A_R/A \tag{4a}$$

where T_R = tensile strength of roots, psi
A_R/A = root area ratio or fraction of soil cross sectional area occupied by roots

This is an extremely useful and important relationship because it states that the root contribution to soil strength can be determined solely from measuring the tensile strength of the roots, T_R, and the fraction of the soil cross section occupied by roots, A_R/A. The root cross sectional area, A_R, can be found by counting the number of roots in different size classes, n_i, in a given soil cross sectional area, A, and then by summing the product of the root numbers in each size class times their corresponding average cross sectional area, a_i, for that size class. Thus:

$$t_R = T_R \frac{\Sigma\, n_i\, a_i}{A} \tag{4b}$$

where n_i = number of roots in size class i
a_i = average cross sectional area of roots in size class i, square inches
A = area of soil in sample count, square inches
T_R = average tensile strength of roots, psi.

This linear relationship expressed in equation 4 between root tensile strength per unit area of soil and root area ratio has been validated by Waldron (1977) for herbaceous plant roots (barley and alfalfa) and Wu (1976) for woody plants (spruce and hemlock).

In the case of natural root systems, the tensile strength tends to vary with the size or diameter of the root (Wu 1976; Burroughs and Thomas 1977; and Gray 1978). Accordingly, the root tensile strength term must be included inside the summation and the average root tensile strength **per unit area of soil** computed by the following relationship:

$$t_R = \frac{\Sigma\, T_i\, n_i\, a_i}{A} \tag{4c}$$

where T_i = tensile strength of roots in size class i.

Equations 3 and 4 and the model from which they are derived provide a basis for estimating the contribution of roots to soil shear strength. The only uncertain or indeterminate variable in the equations is the angle of shear distortion (Θ). This angle will vary with the amount of horizontal shear displacement and the thickness of the shear zone.

From results of laboratory direct shear tests conducted by Waldron (1977) on various root-permeated soils, the angle of shear distortion varied between 40 to 50 degrees. From the results of field observations of failures in root-permeated soil masses on slopes (Wu 1976), the angle appeared to vary between 45 and 70 degrees at most. By running a parametric variation or sensitivity analysis on equation 3, Wu (1976) showed that the bracketed term is relatively insensitive to all expected values of either friction angle (ϕ) or shear distortion angle (Θ). The bracketed term only varied from 0.92 to 1.31 for $20 \leqslant \phi \leqslant 40$ and $40 \leqslant \Theta \leqslant 70$. Thus assuming the midpoint of the range to be the most probable value for the bracketed term, the shear strength increase from root or fiber reinforcement may be estimated to an average or first approximation simply by

$$C_R \approx 1.12\, t_R \tag{5a}$$

or

$$C_R \approx 1.12\, T_R \cdot \frac{A_R}{A} \tag{5b}$$

or

$$C_R \approx 1.12 \frac{\Sigma\, T_i\, n_i\, a_i}{A} \tag{5c}$$

This simple theoretical model or relationship permits an estimate of rooting contribution to shear strength based solely on a determination of the root area ratio or concentration of roots in a soil cross section and on measurements of tensile strength or resistance of the roots themselves. The validity of the model is supported by results of direct shear tests run on root-permeated soils in both field and laboratory (Endo and Tsuruta 1969; Waldron 1977).

The root reinforcement model can be used to obtain estimates of root shear-strength increase or "root cohesion" (C_R) in granitic soils of the Idaho batholith. Root density and tensile strength data from the studies by Burroughs and Thomas (1977) and Megahan and others (1978) were employed for this purpose. Calculated "root cohesions" for Rocky Mountain Douglas-fir at various elapsed times after cutting are summarized in table 4. Root cohesions were calculated using equation (5a) and root tensile strength **per unit area of soil** data for Rocky Mountain Douglas-fir reported by Burroughs and Thomas (1977). They included data for all roots in the size interval 0 to 0.4 inch (0 to 1 cm). As noted previously inclusion of roots up to 0.4 inch (1 cm) in diameter corresponds to a root area ratio of 0.045 percent. This ratio is a reasonable **lower bound** estimate for root concentration across a potential failure surface in the shallow, coarse-textured granitic soils of the Idaho batholith. With increasing time after felling, both the number of roots and the tensile strength of the remaining roots decrease; this accounts for the decrease in root cohesion (table 4).

The tabulated data indicate that shear strength increases from root reinforcement up to 1.5 lb/in^2 (10.3 kPa) are possible in granitic soils for initial root area ratios as low as 0.045. Furthermore, the data show that some 60 to 70 percent of this strength is lost due to root deterioration or decay 5 to 10 years after cutting. This elapsed time coincides with the period of greatest landslide activity as observed by Megahan and others (1978), figure 7. With slightly higher root area ratios (up to 0.15 percent), which appear to be entirely possible based on data from Megahan and others (1978) and Wu (1976), the rooting contribution to soil shear strength increase will be still higher (assuming tensile strength of the roots remains the same).

Table 4. — **"Root cohesion" of soil at various elapsed times after felling Douglas-fir for root size class 0 to 1 centimeter**

Residual root cohesion[1] (C_R), lb/inch^2			
t = 0 (fresh)	t = 1 year	t = 5 years	t = 10 years
1.50	0.70	0.50	0.40

[1] Calculated from equation (5a) and root tensile strength data in Burroughs and Thomas (1977)

SOIL ARCHING RESTRAINT MODEL

Arching in slopes occurs when soil begins to move through and around a row of piles (or trees) firmly embedded or anchored in an unyielding layer. Under the right conditions, the trees are in effect both cantilever piles and abutments of "soil arches" that form in the ground upslope from the trees. The requirement of firm anchoring or embedment of trees in an unyielding layer of a slope can occur under the following conditions:

(1) Overlying an inclined bedrock contact in shallow residual soils or glacial till.

(2) In sandy slopes, where tree stem bases are deeply buried as a result of sand accretion.

Other conditions pertaining to spacing and diameter of the tree trunks, thickness and inclination of the yielding portion of the soil profile, and shear strength properties of the soil also determine arching effectiveness.

An arching theory developed for soil slopes by Wang and Yen (1974) is based on a semi-infinite slope model and rigid-plastic-solid soil behavior. Their theory was developed for a single row of embedded piles (of diameter d) spaced a distance (B) apart across a slope as shown schematically in figure 21. According to this theory, the average arching pressure (p) in a slope and the critical spacing (B_{CRIT}) for arching to occur are given by the following equations:

$$\frac{p}{\gamma H} = \left[\frac{(m\cos\beta\sin\beta - K_o\cos\beta\tan\phi - \frac{2C_s}{\gamma H}\cos\beta - m\cos^2\beta\tan\phi_1 - \frac{c_1}{\gamma H}m)}{2K_o\cos\beta\tan\phi}\right]$$

$$\times\left[\{1 - \exp(-2K_o n\cos\beta\tan\phi)\} + 1/2K_o\exp(-2K_o n\cos\beta\tan\phi)\right] \qquad (6)$$

$$\text{nd } B_{CRIT} = \frac{H K_o (K_o + 1)\tan\phi + \frac{2C_s}{\gamma}}{\cos\beta(\tan\beta - \tan\phi) - \frac{c_1}{\gamma H\cos\beta}} \qquad (7)$$

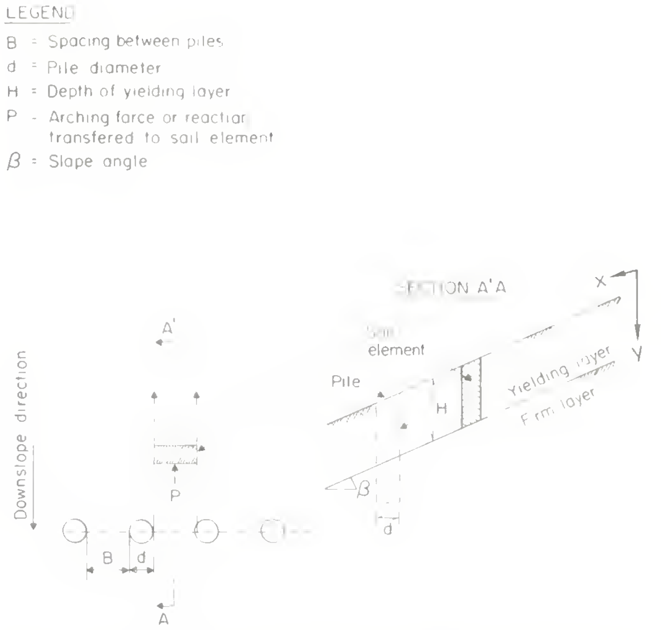

Figure 21. — State of plastic deformation and soil arching action around a row of piles (trees) embedded in a slope (from Wang and Yen 1974).

where B = clear spacing or opening between piles
B_{CRIT} = critical clear spacing between piles
C_s = cohesion in soil
c_1 = cohesion along basal sliding surface
H = depth of yielding or sliding plane
K_o = coefficient of lateral earth pressure at rest
m = B/H = relative width or dimensionless spacing
n = X/B = relative distance (in direction of slope)
p = average lateral pressure or arching pressure
β = slope angle
γ = unit weight of soil
φ and ϕ_1 = angle of internal friction in soil and along basal sliding surface, respectively.

The total force (P) developed against a pile of diameter (d) embedded in a slope with a thickness or depth of yielding soil (H) is given by:

$$P = \frac{K_o}{2}\gamma H^2 d + (\frac{K_o}{2}\gamma H - p)BH \qquad (8)$$

The load on each pile embedded in a slope is thus the summation of two loads, one from the pressure at rest of the soil immediately uphill from the pile, similar to the lateral pressure on a retaining wall. The other is the soil arching pressure transferred to the adjacent piles as if each pile is an abutment of an arch dam. When the average lateral pressure (p) approaches zero, arching action is a maximum.

RESULTS OF ANALYTICAL AND FIELD STUDIES

Piezometric Responses of Slopes to Vegetation Removal

A number of hydrologic processes are regulated by vegetation on a forested slope. For the present study area, important processes are snow accumulation and melt and factors affecting total evaporation losses including interception, transpiration, and direct evaporation from the soil. These processes in turn influence slope stability by helping to regulate the water content of the unsaturated soil moisture zone and the depth of any underlying piezometric surface. The net effect of vegetation removal is to reduce evapotranspiration losses and to increase snow accumulation and snowmelt rates thereby creating a tendency to raise the piezometric surface.

Increased soil moisture contents at the end of the growing season document the fact that evapotranspiration losses were reduced following clearcutting and fire on the study watersheds. Also snow survey and snowmelt lysimeter data verify increased springtime snow accumulation and snowmelt rates following timber removal (Megahan, unpublished data). The combined effect of an increased snowpack melting faster in conjunction with a greater carryover of fall soil moisture storage causes an increase in peak springtime piezometric depths compared to the forested condition (fig. 22). The piezometric data shown are the annual peak values for the piezometer on each watershed that registered the greatest water depth throughout the entire study period. The snowpack data are from the nearby Silver Creek study area that remained undisturbed throughout the course of the present study.

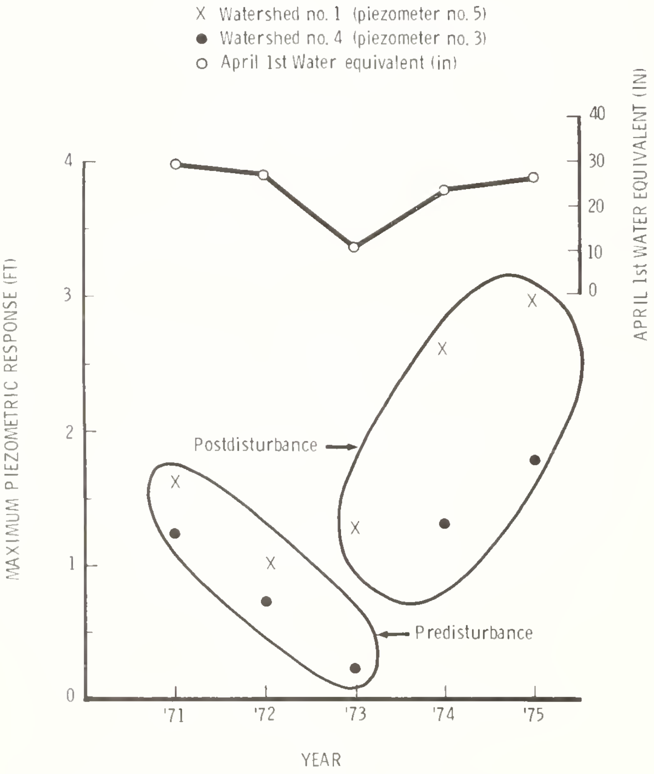

Figure 22. — Annual peak piezometric response for peak sample points on Watersheds No. 1 and No. 4 and corresponding snow accumulations.

The consistently greater piezometric responses on Watershed No. 1 as compared on Watershed No. 4 reflect the greater potential drainage area for piezometers on No. 1 relative to No. 4. Water depths on both drainages decreased from 1971 to 1972 in response to a smaller snowpack in 1972. The 1973 snowpack was unusually low (there was a 7 percent chance of having a snow water content equal to or less than the recorded value) and the piezometric levels on the undisturbed Watershed No. 4 dropped accordingly.

A similar trend in piezometer levels did not occur, however, on Watershed No. 1, which had been clearcut logged the previous November. Rather, the maximum piezometer level actually exceeded those recorded in 1972 when snow water contents were much greater (there was an 81 percent chance of having a snow water content equal to or less than the recorded value in 1972). The late fall cutting date for Watershed No. 1 prevented the development of differences in growing season soil moisture storages on the two study watersheds; therefore, the increased piezometric levels on Watershed No. 1 are mainly the result of differences in snow accumulation and melt during the previous winter and spring.

The following summer, the total soil moisture storage on Watershed No. 4 decreased more rapidly than on Watershed No. 1 because of reduced evapotranspiration losses caused by the timber removal on Watershed No. 1. By mid-August of 1973, 49 percent more water was stored in the 12- to 60-inch (30- to 152-cm) depth on Watershed No. 1 (a total of 5.8 inches [14.8 cm] on Watershed No. 1 and 3.9 inches [9.9 cm] on Watershed No. 4). On August 20, 1973, both watersheds were burned in a wildfire that killed all nonsprouting vegetation. In the spring of 1974, piezometric levels were greatly increased on Watershed No. 1 relative to predisturbance levels even though the April 1 snow accumulation was less than the two prelogging years studied. The difference reflects both changes in evapotranspiration losses and in snow accumulation and melt rates. Piezometric levels also increased on Watershed No. 4, but probably not to the maximum because of the development of a partial soil moisture deficit prior to the fire. April 1 snow depths increased slightly in 1975, relative to 1974, but still were below pretreatment amounts. Large increases in piezometric levels occurred on both study watersheds in response to combined effects of decreased evapotranspiration and snow accumulation and melt.

These data do not lend themselves to rigorous statistical analysis because of limited sample sizes. A simple graphical analysis relating the annual peak piezometer depth to the corresponding April 1 snow water content is informative, however, because it suggests the relative effects of vegetation removal on piezometric levels (fig. 23). A simple linear regression was fitted to the three predisturbance data points for Watershed No. 4. In spite of the limited data points, the regression had an r square value of 0.85 and a standard error of 0.27 feet (0.09 m). The regression coefficient was significantly different from zero at the 85 percent confidence level. By using the snow water contents for 1974 and 1975 to predict the piezometric levels for these years and by comparing predicted to measured piezometric values, we can estimate increases of about 65 percent and 100 percent in soil water levels for 1974 and 1975, respectively. A similar analysis is not possible for Watershed No. 1 because there are only two pretreatment data points. If the assumption is made, however, that the regression slope is the same as for Watershed No. 4 and that the regression line

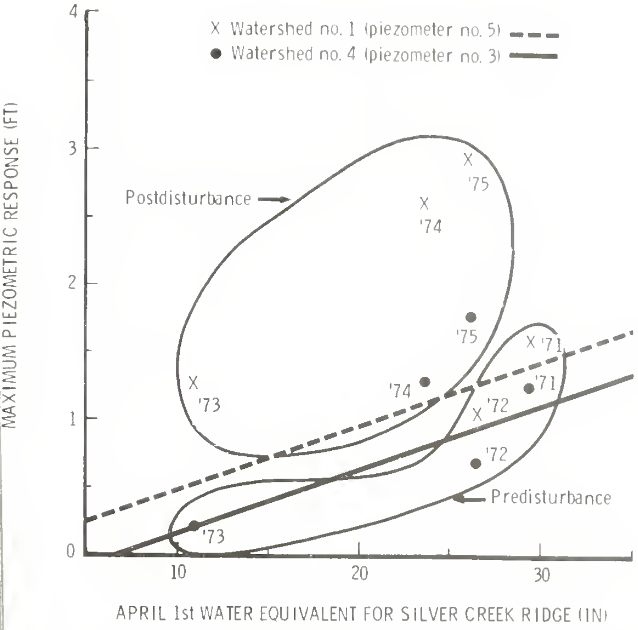

Figure 23. — Annual peak piezometric response for peak sample points on Watersheds No. 1 and No. 4 versus annual April 1 snow water content in inches.

asses through the average for the two pretreatment years dashed line, fig. 23), we obtain estimates of changes in soil oisture levels of 140, 134, and 140 percent for 1973, 1974, nd 1975, respectively, for Watershed No. 1.

Estimated increases in maximum piezometric levels range om 65 to 140 percent following clearcut timber harvest and/or ildfire. We want to emphasize the fact that these increases are ot statistically significant. The increases, however, are relavely consistent for both watersheds for all postdisturbance ears over a wide range of climatic conditions. Moreover, the ocumented onsite hydrologic responses of increased soil oisture carryover and increased snow accumulation and melt ates following vegetation removal would tend to cause ineased piezometric levels. Everything considered, we feel that eak piezometric levels were increased about 100 percent as e result of clearcutting and relatively intense wildfire on the udy area.

Stability Relationships

OIL SHEAR STRENGTH

The results of borehole shear tests and field density easurements in Watershed No. 1 are summarized in table 5. oil friction angles (ϕ) not only tended to vary with location, but th depth as well. Friction angles varied from 29 to 39 degrees, nd generally increased with depth to a limiting value of 38 to degrees at the contact between soil (decomposed granitics) nd fractured, disintegrated bedrock. The friction values rerted in table 5 are station averages for the surface soil alone. o cohesion was detected in any of the borehole tests. The adation of a composite sample taken from the 24- to 36-inch 1- to 91-cm) depth of the soil horizon in Watershed No. 1 is own in figure 24. The soil consists of 10 percent fine gravel, percent sand, and 4 percent by weight silt size material; it uld be classified as a well-graded sand (SW), according to e Unified Classification system. In-situ densities ranged from to 101 lb/ft^3 (1.47 to 1.62 g/cm^3) with an average value of 96 lb/ft^3 (1.54 g/cm^3). Densities tended to increase with depth as did the friction angle of the soil. Only the mean density (96 lb/ft^3) is tabulated in table 5. Subsequent sensitivity analyses showed that such small variations in soil density from station to station had a negligible influence on calculated slope stability; hence the reason for tabulating only the mean.

Table 5.—Summary of soil-slope data for granitic soil in the Pine Creek study watershed

Slope or soil parameters	Station number 1	2	3	4	5	6
Friction angle,[1] degrees	34	29	29	34	32	37
Slope angle, degrees	30	28	29	32	31	40
Soil depth, inches	30	36	30	30	30	48
Soil density,[2] lb/ft^3	96	96	96	96	96	96
Dry density,[2] lb/ft^3	88	88	88	88	88	88
Saturated density,[2] lb/ft^3	117	117	117	117	117	117
Cohesion, lb/inch^2	0	0	0	0	0	0

[1] In-situ borehole shear test. No cohesion intercept detected.

[2] Mean value based on several measurements of field density and water content at different stations.

The soil shear strength parameters, densities, void ratios, and gradations measured in the Pine Creek study watersheds are comparable to those reported by Gonsior and Gardner (1971) during extensive field and laboratory tests of granitic soils in the Zena Creek timber sale area in the Payette National Forest. Most of the soils investigated by them had slightly higher silt size fractions and so were classified as well-graded silty sands, or SW-SM materials, according to the Unified Classification.

Gonsior and Gardner (1971) conducted numerous direct shear and triaxial compression tests to investigate the effect of unit weight and moisture content upon the shear strength of granitic soils. Their test results showed that strengths based upon effective stress parameters exhibited negligible variation over a wide range of conditions. For design purposes, they recommended 35 and 0 as reasonable values for the angle of internal friction (ϕ) and soil cohesion (C_s), respectively. Shear strength envelopes measured in triaxial compression indicated slight residual cohesive strength (on the order of 2 lb/in^2 [14 kPa]) in most tests on saturated specimens. Gonsior and Gardner (1971) advise, however, that some of the cohesion measured in triaxial tests on saturated specimens could be accounted for by partial saturation, a curved failure envelope, or by membrane resistance; no corrections were made for this factor.

These findings are also corroborated by Lumb (1962) who examined the influence of variation in cohesion and friction angle with void ratio and degree of saturation. His tests were run on both undisturbed and remolded samples of decomposed granite with fine, medium, and coarse gradation. Considerable "apparent cohesion" was manifest in partially saturated specimens as a result of capillary forces. As expected, apparent cohesion tended towards zero at full saturation (that is, below a piezometric surface) in all soils tested, fine or coarse grained.

Undoubtedly, some residual soil cohesion does exist in granitic soils; borehole shear test results notwithstanding. In the first

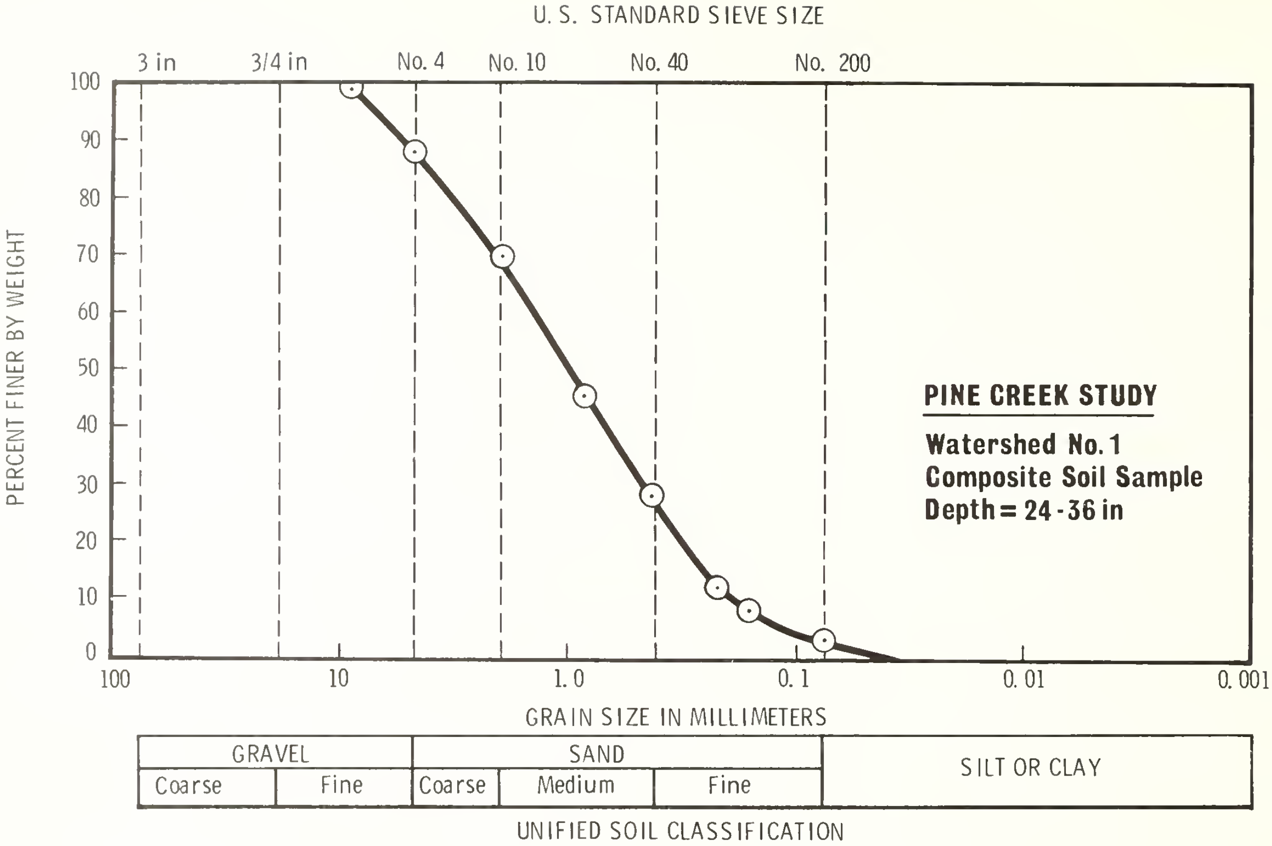

Figure 24. — Grain-size distribution of composite soil sample from Watershed No. 1.

place, the borehole shear test often yields low or nonexistent values of cohesion (Wineland 1975). Secondly, full or complete saturation is required to eliminate apparent cohesion as a result of capillary action. Lastly, some cohesion must be present to explain the stability of what otherwise would often be a failed slope, particularly in the case of cut slopes.

Analysis of actual failures in both natural and cut slopes in the Idaho batholith by Gonsior and Gardner (1971) suggests that cohesion up to 0.9 lb/in² (6.2 kPa) may be mobilized. A similar value was reported by Prellwitz (1975) in his analysis of granitic slopes in the batholith. Prellwitz (1975) suggests that a cohesion of 0.76 lb/in² (5.2 kPa) is reasonable for soils above the phreatic surface and 0.35 lb/in² (2.4 kPa) below for SW-SM materials.

Much higher cohesions have been reported in laboratory triaxial tests on some granitic soils of the batholith (Hampton and others 1974).[1] Sample sites in this study were purposely selected to provide a wide range in the weathering properties of granitic rocks with the sampling heavier in the more weathered rocks. Higher cohesion would be expected under these conditions because more advanced chemical weathering of the bedrock has occurred, causing formation and accumulation of clay colloids. Hydrolysis of mica and feldspars leads to formation of clay minerals such as illite and kaolinite. The absence of strong solution and eluviation leads to their accumulation. These factors may combine to produce a finer grained, more cohesive, and correspondingly less frictional soil as shown by the results of triaxial compression tests in figure 25.

Highly weathered bedrock conditions are relatively rare in the Idaho batholith because they are generally associated with shear zones and zones of secondary hydrothermal alteration. Accordingly, high cohesion values such as those shown in figure 25 probably occur on less than 5 percent of the upland slopes of the batholith. Such soil conditions were not present in the Pine Creek study watersheds as evidenced by the shear strength test results reported in table 5.

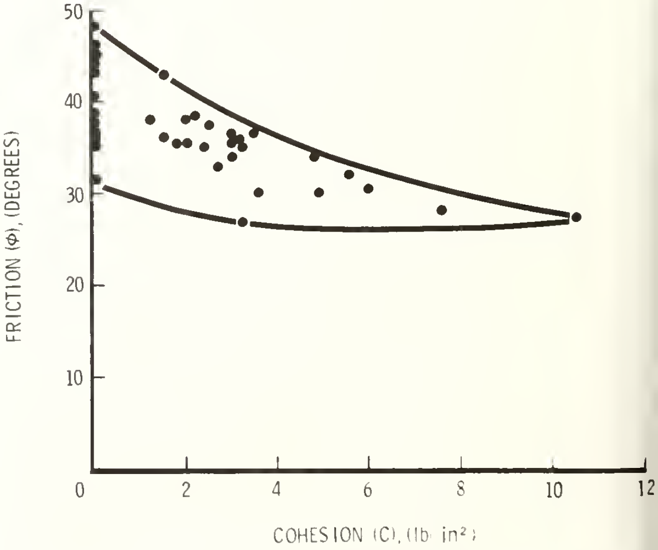

Figure 25. — Relationships between angle of internal friction and cohesion for various batholith soils (from Hampton and others 1974, footnote 1).

SOIL ARCHING RESTRAINT

Preliminary analyses of field data obtained from forested, sandy slopes on the Idaho batholith indicate that these slopes meet theoretical criteria for arching restraint between trees. Tree spacings, or more importantly the width of openings between "vertical root cylinders" are of the right order of magnitude for soil arching to manifest itself according to the Wang-Yen theory (Wang and Yen 1974). Tree trunks and their associated "vertical root cylinders," which are firmly anchored to bedrock (fig. 19), potentially can behave as arch abutments.

Openings between vertical root cylinders appear to average around 30 feet (9.1 m) based on stem counts in forested plots on the nearby Silver Creek study area (table 3). These data were obtained from large survey units which include some unforested areas in streams, brush, and rock outcrop. On a smaller more localized scale, spacings are considerably less, particularly in groves of trees (fig. 26). Based on these last field observations, the width of opening between vertical root cylinders in the slopes averages about 6 to 7 ft. (1.8 to 2.1 m).

The maximum allowable opening or critical distance (B_{CR}) between piles (or trees) embedded in a slope can be calculated from soil arching theory. This critical distance is shown plotted in figure 27 using the soil arching theory for slopes derived by Wang and Yen (1974). The critical distance is plotted versus cohesion for various assumed values of residual friction and cohesion (ϕ_1, c_1) along the basal sliding surface. Other soil and slope parameters used in the analysis are typical of shallow coarse-textured, granitic soils overlying a steep bedrock rock contact ($\beta = 40°$, $\phi = 35°$, $H = 3$ ft [0.9 m] $\gamma = 100$ lb ft^3 [1.6 g cm^3]).

The soil arching analyses show that the critical distance in a shallow mantle is very sensitive to cohesion, particularly cohesion along the basal sliding surface (c_1). If no cohesion is assumed, and the residual friction (ϕ_1) along the basal sliding surface is one-half the peak friction (ϕ), then the critical spacing is 4 ft (1.2 m). On the other hand, if a cohesion (C_s) of only 0.35 lb/in^2 (2.4 kPa) is assumed with the residual cohesion (c_1) along the basal sliding surface a mere 12 percent of this value, then the critical spacing increases to 21 ft (6.3 m). This distance usually approaches or exceeds the size openings between "vertical root cylinders" observed in the field, particularly in groves of trees (fig. 26). Based on his analysis of granitic slopes in the batholith, Prellwitz (1975) suggested that 0.35 lb in^2 (2.4 kPa) is a reasonable lower limit for cohesion of soils beneath the phreatic surface. With slightly higher values of cohesion, the critical distance increases further thus insuring that soil arching effects will be manifest. These values of cohesion in granitic soils are well within reason. Possible sources of cohesion or apparent cohesion include root reinforcement, cementation, clay binder, and capillary stresses (above the phreatic surface).

Figure 26. — Row of ponderosa pine trees at spacings sufficiently close to manifest soil arching restraint between trees. Silver Creek study area, Boise National Forest.

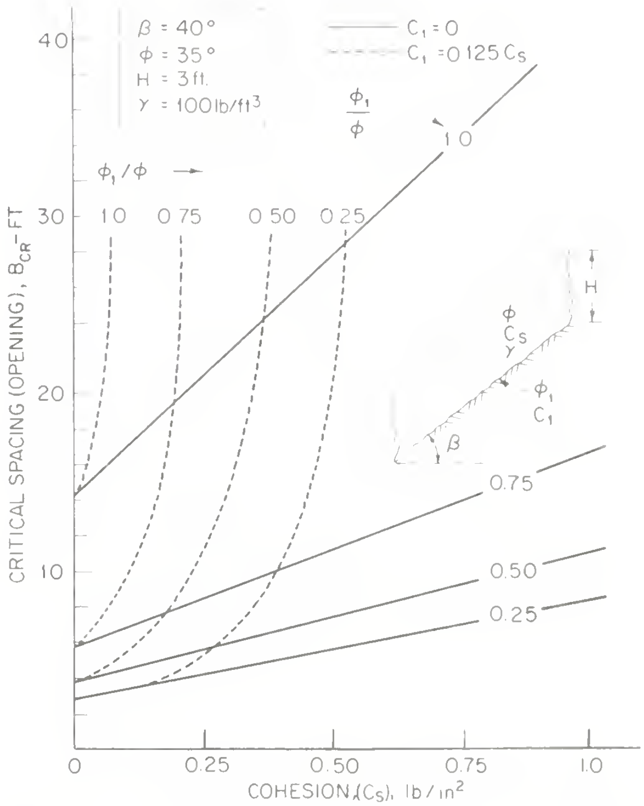

Figure 27. — Theoretical critical openings (B_{CR}) versus cohesion for piles (trees) embedded in a steep, sandy slope ($\beta = 40°$, $\phi = 35°$, $H = 3$ ft.). Influence of cohesion and friction along the base (ϕ_1, c_1) is also shown.

SENSITIVITY ANALYSES

The relative importance of various soil-slope-hydrologic parameters on slope stability and the direction of change in slope safety factor that may be produced by altering these parameters may be determined by conducting sensitivity analyses or parametric variation studies. These same studies also permit evaluation of effect of vegetation removal on slope stability through the influence of removal on the parameters themselves.

There are several types of slope sensitivity analyses that can be conducted. All are based in the present case on the infinite slope model and on the effect of altering input variables on the general stability relationship expressed in equation 2.

Table 6 includes a summary of stability relationships for each of the stations or locations where borehole shear tests were conducted. Shown in table 6 are calculated factors of safety for each station based on existing or measured values of soil depth

Table 6. — **Summary of stability calculations at different stations for granitic soil in the Pine Creek study watershed, Idaho**

Stability calculations	**Station number**					
	1	**2**	**3**	**4**	**5**	**6**
Factor of safety[1] (F)	1.2	1.04	1.0	1.1	1.04	0.9
Critical piezometric level[2] (H_{cr}), inch	6.5	2.1	0	3.2	1.7	N/A
Required cohesion for stability, lb/inch^2						
H_w/H = 0 (dry)	0	0	0	0	0	0.12
= 0.5	0.14	0.24	0.23	0.20	0.20	0.53
= 1.0 (saturated)	0.40	0.52	0.46	0.45	0.46	0.93

[1] Based on infinite slope model (equation 2.)

[2] Piezometric height (above failure surface) at which F = 1.0 for slope and soil parameters given in table 5.

(H), local slope angle (β), soil density (γ or γ_D), friction angle (ϕ), and soil cohesion (C_s). The calculated factors of safety are close to unity and suggest the slope is only marginally secure. The calculations are based on zero cohesion ($C_s = 0$) and dry slopes ($H_W = 0$). Critical piezometric levels (still assuming zero cohesion) are also shown. The slope should theoretically fail at the critical piezometric level (F = 1.0). These critical piezometric levels are on the order of a few inches. The fact that the entire slope did not fail when pieometric levels in excess of these critical values developed in the slope (figs. 22 and 23) means that some cohesion must be present. Required cohesion to prevent failure at various piezometric levels is also calculated and tabulated. Values range from 0.4 to 0.9 lb/in^2 (2.8 to 6.2 kPa) at full saturation ($H_W = H$). These residual cohesions are consistent with values reported by Gonsior and Gardner (1971) and Prellwitz (1975). These observations are based, of course, on the assumption that the infinite slope model adequately represents stability conditions in granitic slopes of the Idaho batholith. Limitations of the infinite slope theory in this regard are discussed by Hartsog and Martin (1974), but do not appear to apply in this case.

The influence of both friction and cohesion on the factor of safety of a typical granitic slope with a shallow soil mantle is shown in figures 28 and 29. A slope thickness of 36 inches (92 cm), slope gradient of 35°, and soil densities of 88 and 117 lb/ft^3 (1.4 and 1.9 g/cm^3), dry and saturated, respectively, were selected for the analysis. Factor of safety is plotted against cohesion for various values of friction and piezometric elevation in the slope. As shown in the figures, stability is far more sensitive to soil cohesion than to friction angle, particularly when slope becomes fully saturated ($H_W = H$). It is also clear from this analysis that some cohesion must exist in steep slopes in order to provide the critical margin for stability when piezometric levels rise in the slope. Little cohesion is required to maintain a stable slope. Only 0.66 lb/in^2 (4.6 kPa) is needed at a friction angle of 19° and a slope angle of 35° ($\tan\phi/\tan\beta = 0.50$) when $H_W/H = 0.5$ (fig. 28). For these same conditions of slope and friction angle, at full saturation, ($H_W/H = 1.0$), the required cohesion is 0.88 lb/in^2 (6.1 kPa) (fig. 29).

The influence of a rise in piezometric surface on the factor of safety (all other factors held constant) can also be determined.

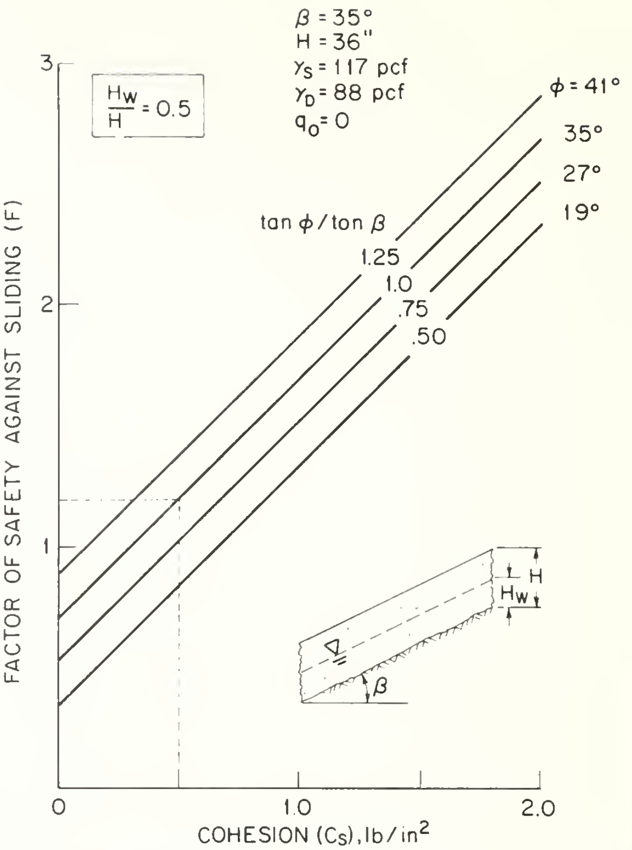

Figure 28. — Influence of cohesion on the stability of a sandy residual soil resting on an inclined bedrock contact. $\frac{H_W}{H} = 0.5$.

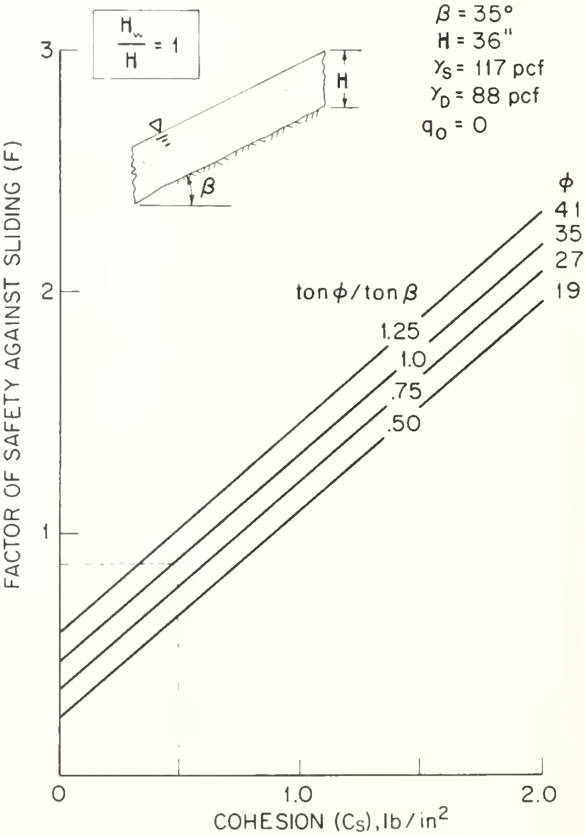

Figure 29. — Influence of cohesion on the stability of a sandy residual soil resting on an inclined bedrock contact. $\frac{H_W}{H} = 1$.

In this example, a cohesion of 0.5 lb/in² (3.4 kPa) and a friction angle of 35° are assumed. When the piezometric surface doubles in height, the factor of safety drops below one. This relationship is shown by the dashed lines in figures 28 and 29, respectively.

Yet another type of sensitivity analysis (Simons and others 1978)[2] can be employed that not only reveals the sensitivity, but also the direction of change in slope safety factor corresponding to a change in any input variable in the infinite slope equation. This approach is useful for examining the influence of vegetation removal on slope stability and the influence of changes in such variables as surcharge, the effects of which are more obscure or counter-intuitive.

This approach is conducted in four steps. First, a realistic range of values (ΔX_i) is selected for each input variable (X_i). Second, a base safety factor is computed by using the median values for all variables. Third, each input parameter is changed across its range of values and a new factor of safety is computed for each altered input. Fourth, the results are plotted as a relative percentage.

This sensitivity analysis was conducted for the range of input variables and their median values shown in table 7. These medians are believed typical of conditions for natural slopes in forested watersheds in the Idaho batholith. The ranges include conditions believed typical of conditions in both forested and cutover watersheds. In order to conduct the sensitivity analysis, the factor of safety equation was rewritten in a slightly different form as follows:

$$F = \frac{\dfrac{2(C_s + C_R)}{\gamma_w H \sin 2\beta} + \left[\dfrac{q_0}{\gamma_w H} + \left(\dfrac{\gamma_{SAT}}{\gamma_w} - 1\right) M + \dfrac{\gamma}{\gamma_w}(1\text{-}M)\right] \dfrac{\tan \phi'}{\tan \beta}}{\left[\dfrac{q_0}{\gamma_w H} + \left(\dfrac{\gamma_{SAT}}{\gamma_w}\right) M + \dfrac{\gamma}{\gamma_w}(1\text{-}M)\right]} \qquad (9)$$

where M = relative ground water height $\left(= \dfrac{H_w}{H}\right)$

able 7. — Range of input variables and their estimated medians for soil and slope conditions in watersheds of the Idaho batholith

Input variable	Range	Median
Variables not particularly influenced by vegetation:		
β	20-40°	30°
ϕ'	27-42°	35°
H	12-48 in	30 in
γ	90-120 lb/ft³	100 lb/ft³
γ_{SAT}	110-140 lb/ft³	120 lb/ft³
C_s	0-2 lb/in²	0.75 lb/in²
Variables strongly influenced by vegetation:		
q_o	0-200 lb/ft²	20 lb/ft²
C_R	0-1.5 lb/in²	0.5 lb/in²
M	0-1	0.25

The results of the sensitivity analysis shown in figure 30 revealed that some inputs have a linear effect on F while others, notably H and β, have strongly nonlinear effects. Factor of safety is quite sensitive to both root (C_R) and soil cohesion (C_S). In contrast, the slope safety factor is relatively insensitive to changes in density (γ) and surcharge (loss) q_o. Changes in soil friction (ϕ) do not have nearly as much influence on safety factor as changes in cohesion (C_S and C_R). This finding corrobrates the results shown in figures 28 and 29. The influence of relative ground water height (M) or piezometric elevation is intermediate in effect, except at very high ground water elevations (M ⟶ 1) where safety factors decrease sharply.

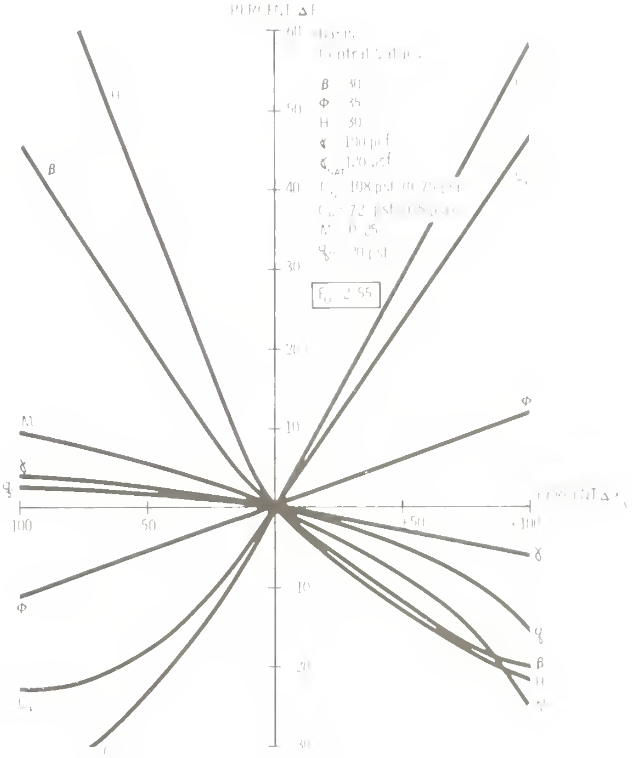

Figure 30. — Percent change in slope safety factor versus percent change in input variables. Base safety factor (F) was computed using the median or central value for all variables (table 7).

CONSEQUENCES OF VEGETATION REMOVAL

The preceding sensitivity analyses can be used to help evaluate the consequences of vegetation removal on the stability of slopes in the Idaho batholith. The input variables most strongly influenced by vegetation are M, q_o, and C_R. Removal of slope vegetation tends to decreased root cohesion (C_R), increased piezometric levels (M), and decreased slope surcharge (q_o). The net effect of these changes is to adversely affect stability, their extent and significance will be explored further. An exception appears to be surcharge that decreases following clearcutting, which should improve stability based on the sensitivity analysis previously discussed. On the other hand, this improvement is marginal; moreover, it can be shown that at low values of cohesion and high ground water elevations surcharge has a beneficial influence (Ward 1976).

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[2] Simons, D. B., R. M. Li, and T. J. Ward. 1978. Mapping of potential landslide reas in terms of slope stability. Report prepared by Eng. Res. Cent., Colo. State niv. for USDA For. Serv., Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 4 p.

Impact of Foliage Loss

Removal of slope vegetation results in a temporary but significant loss of foliage available for interception and transpiration of water. This in turn leads to wetter conditions and higher piezometric levels in a slope. Results of the Pine Creek study support this conclusion (figs. 22 and 23) as do results of other hydrologic investigations on effects of timber removal (Gray and Brenner 1970; Bethlahmy 1962; Brenner 1973). The impact of vegetation removal on soil moisture changes in a slope appears to be most critical the first year after cutting. Studies by Hallin (1967) showed that, after 3 years, low vegetation that invades a cutover site is nearly as effective as old-growth timber in depleting moisture.

The results of soil water piezometry studies in Watersheds Nos. 1 and 4 indicate that removal of vegetation by clearcut logging can increase piezometric levels as much as 100 percent. Critical piezometric levels shown in table 6, that is, the minimum head required to cause slope failure assuming no soil cohesion, were frequently exceeded. The occurrence of slides in the slope above the road cut in both watersheds (figs. 10-13) and in other watersheds in the vicinity (table 2) reflects the low margin of safety under high piezometric conditions. On the other hand, the absence of massive and pervasive slope failures suggests that some residual cohesion must be present. Required cohesions for local stability in Watershed No. 4 for different piezometric heads are also shown in table 6. These cohesions could be provided in whole or in part by root reinforcement.

Impact of Root Decay

The importance of cohesion on stability was clearly established in the preceding sensitivity analyses. The root reinforcement model coupled with root tensile strength and root distribution data show that live roots can provide a large fraction of the total or apparent cohesion present in granitic soils in the batholith. Conversely, studies of root strength loss with time after cutting (Burroughs and Thomas 1977) and landslide frequency with time after cutting (Megahan and others 1978) indicate progressive loss of root cohesion following clearcutting. Megahan's data suggest that landslides are most frequent 4 to 10 years after logging. These data are consistent with findings of other investigators (for example, Bishop and Stevens 1964; Swanston and Walkotten 1970). The time of minimum stability represents a crossover point between the growth and decay curves of root systems of slope vegetation. Root strength decline after tree felling is undoubtedly both species and site dependent (Burroughs and Thomas 1977). The timing or occurrence of slope failures is thus dependent on the amount of residual stand on the slope and the rate of establishment of new vegetation relative to the root strength decline of previously cut trees (Kitamura and Namba 1966).

Loss of Buttressing and Soil Arching Action

Analysis of spacing relationships and rooting morphology of trees in forested slopes of the Idaho batholith indicate the soil arching between trees may play an important role in restraining soil movement. Several examples of buttressing action by embedded tree trunks and root systems were observed (figs. 4 and 5). Gonsior and Gardner (1971) reported similar examples in their analyses of slope failures in the Idaho batholith. They recommended, in fact, that barriers of live trees should remain undisturbed immediately below the toe of fill slopes and above the cut slope.

Removal of all large diameter stems by clearcutting, of course, gradually eliminates any soil arching restraint or soil arching action. The stumps will temporarily provide restraint, but when the roots rot and decay these anchor points or "arch abutments" will actually become zones of weakness in the slope. This will occur because as roots rot and disappear voids with no shear strength will be left behind, or infilling with weak colloids may occur in the old root channels. In addition, former root channels may provide entry points for water and thus facilitate rapid buildup of pore pressures.

Loss of Surcharge

The sensitivity analysis reported showed that decreasing the vertical surcharge (q_o) by removing slope vegetation has a beneficial influence on stability, but only a slight one. Under certain conditions, surcharge can actually enhance stability. Ward (1976) showed that this occurs under the following circumstances:

$$(C_s + C_R) < \gamma_w H_W \tan \phi \cos^2\beta \qquad (10)$$

This relationship shows that surcharge is beneficial for low cohesion values, high piezometric levels, and relatively gentle slopes. Assuming the worst case of maximum rise in piezometric surface ($H_W = H$) and substituting the median values in table 6 for the variables on the right-hand side of equation (10), a limiting total cohesion of 0.57 lb/in^2 (3.9 kPa) results. This cohesion is quite possible as an upper, limiting value in many granitic slopes. In such slopes, surcharge from the weight of trees would have at best a beneficial influence and at worst a negligible effect as critical, saturated conditions develop in the soil.

MANAGEMENT IMPLICATIONS

Measures to Minimize Mass Erosion Hazard

LOCATION AND SIZE OF CLEARCUT AREAS

The preceding analyses and findings indicate that many slopes in the Idaho batholith are in a state of marginal or metastable equilibrium. Such slopes are vulnerable to both surficial and mass erosion when vegetation is removed by clearcutting or by wildfire. In many instances, road construction associated with timber harvesting appears to have a greater impact than vegetation removal alone (fig. 3). On the other hand, both may have synergistic and cumulative impacts on stability that are hard to distinguish and separate. The slope failures observed in the slope above the road cut in Watershec No. 1 (figs. 10 and 11) are a case in point. The failures appear tc be associated with the road cut, but may have been caused ir part by wetter conditions in the slope above and by loss of some root cohesion as a result of vegetation removal.

It is not possible at this point to formulate precise rules fo location and size of clearcuts to minimize mass erosior hazards. The following guidelines are suggested instead:

1. Limit size of clearcut units;
2. Stagger location of clearcut units or blocks both in space and in time;
3. Leave buffer zone of trees above and below haul roads;
4. Leave buffer zone of undisturbed vegetation along all streams.

SELECTION LOGGING VERSUS CLEARCUTTING

The analyses and findings reported here clearly recommend leaving as much residual timber stand as possible from the point of view of preventing surficial and mass erosion. The greater the amount of standing timber, the smaller the amount of soil root cohesion loss, the smaller the rise in piezometric levels in a slope, and the greater the amount of effective buttressing and soil arching action by residual vegetation. All these beneficial influences are favored by a selection logging system as opposed to clearcutting.

SITE PREPARATION AND ABANDONMENT PROCEDURES

There are a number of measures that are routinely employed n conjunction with timber harvest operations to minimize slope stability problems. These measures are usually specified in arious State and Federal forest practice rules. They include uch procedures as the seeding and scarifying of roadbeds, emoval of temporary road fills, construction of waterbreaks, isposal of slash, and establishment of "vegetation leave reas."

The concept of vegetation leave areas is of particular concern nd interest in view of the findings reported here. Trees and oody vegetation should be left undisturbed in critical areas uch as steep, slide-prone slopes. Vegetation should also be eft intact as much as possible along the margins of haul roads nd streams. Gonsior and Gardner's (1971) recommendation ears repeating in this regard, namely, that barriers of live trees hould remain undisturbed immediately below the toe of fill lopes and above cut slopes. This recommendation should be eighed, however, against the likelihood of trees falling across oads, owing to possibility of greater vulnerability to root dam- ge and windthrow after right-of-way-clearing.

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eneral Slope Hazard Rating Scheme

The recommendation to leave vegetation intact and in-place critical areas during timber harvest operations requires that me procedure be employed to identify slopes prone to high ass erosion hazard. Several schemes have been devised for entifying hazardous slopes (Radbruch-Hall 1976; Ward 1976; d Simons and others[2]). Most of these methods consist of mapping information on slope gradient, soil type, geology, hydrology, and past landslide occurrence. This information is integrated by linear combination or factor overlay techniques (Hopkins 1977) to produce a composite map of relative slope hazard.

An alternative approach is to base slope hazard ratings on a geotechnical model employing principles of limiting equilibrium. Geotechnical models such as the infinite slope analysis used here (equation 2) explicitly account for the primary factors in landslide occurrence such as soil strength, ground water influences, vegetative effects, and slope inclination. Geotechnical models represent actual field conditions; hence, they can be used to analyze the response of a hill slope to temporally and spatially varying factors. The geotechnical models or slope stability analyses are routinely used by engineers to evaluate the stability of a particular hillslope, determine the influence of a particular slope modification, and to assess the effectiveness of a particular slope protection measure.

One of the main difficulties with geotechnical models for slope hazard analysis is that they are deterministic. As such they do not satisfactorily take into account uncertainity and variability in the input parameters. A way around this dilemma has been developed by Wu (1976), Ward (1976), and Simons and others[2] by casting the stability equation or factor of safety equation in a probabilistic framework. Instead of computing a single valued safety factor for a slope, one computes a probability of failure. Calculated probabilities can then be grouped into three hazard classes as suggested by Simons and others[2], namely

1. High probability when $P[F < 1] > 60$ percent;
2. Medium probability when $30 < P[F < 1] < 60$ percent;
3. Low probability when $P[F < 1] < 30$ percent.

where $P[F < 1]$ is the cumulative probability that the safety factor (F) is less than or equal to one.

Computation of the probability of failure requires knowledge of the mean and variance of input variables in the safety factor equation. This type of information is seldom available without extensive testing. This difficulty can be overcome by assuming that the input variables are uniformly distributed, random variables. With this assumption the mean of a random variable is simply found as

$$\bar{X} = \frac{X_a + X_b}{2}$$

and the variance as

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where X_a and X_b are the lower and upper limits on the variable X. Thus, probability of failure can be estimated solely from knowledge of the range in each variable, information which is readily available. Simons and others[2] show that the assumption of a uniform distribution provides a conservative estimate of probability of failure. The authors also provide a well-documented example or application of their method for identifying potential landslide areas in terms of their probability of failure.

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CONCLUSIONS

The following main conclusions can be drawn from the results of the Pine Creek study in particular and about the role of forest vegetation on stability of slopes in the Idaho batholith in general:

1. Soils that develop on granitic rocks of the batholith are typically shallow, coarse-textured soils (loamy sands to sandy loams) that are found on steep slopes that average 60 percent or more in many drainages.
2. Batholith soils tend to be highly erodible and prone to mass soil movement particularly when disturbed by road construction and timber harvesting.
3. Forest vegetation on the batholith helps to maintain more secure slopes by a series of stabilizing mechanisms. These include mechanical reinforcement by root systems; soil moisture depletion by interception, transpiration, and regulation of snow accumulation and melting; and by buttressing and soil arching action behind embedded tree trunks.
4. Removal of forest vegetation without regard to slope stability can result in loss of the stabilizing influences of forest vegetation. Results of the Pine Creek study show that vegetation often provides the margin of safety between a secure and failed slope.
5. The factor of safety against sliding in slopes of the batholith is very sensitive to cohesion. Almost all, or at least a significant fraction of this cohesion, can be provided by root reinforcement in batholith soils.
6. Several measures are recommended to mitigate the impact of vegetation removal on slope stability. These measures include selection logging in preference to clearcutting, limitation of size of clearcut units, establishment of vegetation leave areas in critical areas, and careful integration of diversions and drainage measures with vegetation leave areas.
7. Live barriers of trees should be left when reasonably feasible below the toe of fill slopes and above cut slopes. Buffer zones of vegetation should also be left along the margin of streams.
8. Critical areas or slopes of high landslide potential can be identified by calculating a probability of failure that takes into account the uncertainty and variability in the input variables in a geotechnical model on which the assessment is based.

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Gray, Donald H., and Walter F. Megahan.
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The Intermountain Station includes the States of Montana, Idaho, Utah, Nevada, and western Wyoming. About 231 million acres, or 85 percent, of the land area in the Station territory are classified as forest and rangeland. These lands include grasslands, deserts, shrublands, alpine areas, and well-stocked forests. They supply fiber for forest industries; minerals for energy and industrial development; and water for domestic and industrial consumption. They also provide recreation opportunities for millions of visitors each year.

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Forest and Range
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Research Paper
INT-272

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RESEARCH SUMMARY

A classification system is presented for aspen (*Populus tremuloides* Michx.) dominated forests on the Bridger-Teton National Forest in western Wyoming. Twenty-six aspen community types are defined and described. A diagnostic key that utilizes indicator plant species is provided for field identification of the community types. Vegetation composition, environment, productivity, relationship to surrounding vegetation, and successional status are discussed. Tables are provided for detailed comparisons.

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INTRODUCTION

Intensive multiple use management for the resources produced by wildlands requires that we be able to categorize land units according to their potential productivity and likely response to management. This is especially true n the mountainous West where abrupt changes in environment create both striking and subtile differences n the land's capability to produce vegetation. Classifying ands for management purposes is not new. Resource nanagement, however, has entered a new era. Classification systems used in the past, such as cover type classiication, are often no longer adequate for the intensive nanagement needed to satisfy current and future demands or the multiple resources wildlands are capable of producing. As a consequence, a substantial effort has been under way in recent years, especially in the Forest Services Region 1 (the Northern Region) and Region 4 the Intermountain Region) to develop the types of classifications now essential for management.

The Bridger-Teton National Forest, the largest National Forest within the contiguous United States, lies ust south of Yellowstone National Park and immediately west of the Continental Divide in western Wyoming (fig.). It is highly mountainous terrain with part of five nountain ranges and eight rivers falling within its orders. The north-south oriented Wyoming and Salt River Ranges, which make up the southern portion of the orest, are composed of faulted and thrusted beds of ediment. The Teton Range, directly to the north, consists f highly glaciated Precambrian granites. Both the Gros entre and Wind River Ranges are angled in a outheasterly direction and are glaciated. The Gros Ventre nountains are uplifted sediments, while the Wind River ange has an exposed granite core. The southern portion f the volcanic Yellowstone Plateau occupies the northern nd of the Forest. The rivers form part of four major rainage systems. The Snake, Buffalo, Gros Ventre, oback, Salt, and Greys Rivers are part of the Columbia system, and the Green and New Fork Rivers flow into the Colorado system. The Missouri and Bear River watersheds also drain a small portion of the Forest. Elevations within the Forest range from 5,663 ft (1 726 m) on the Snake River at Alpine to peaks well over 13,800 ft (4 200 m) in the Wind River Range.

The great diversity in topography, soils, elevation, and microclimate on this Forest create a broad range of major vegetation formations: grasslands, shrublands, forb meadows, aspen groves, coniferous forests, and alpine tundra. A detailed habitat type classification partitioning the natural variability within the coniferous forest formation on the area has been developed by Steele and others.[1] A habitat type classification has also been developed recently which is appropriate to much of the nonforest shrublands (Bramble-Brodahl 1978; Hironaka and Fosberg 1979). A detailed natural classification for the aspenlands on the Forest has been lacking, however. Reed (1971) placed the aspenlands in the Wind River Mountains, only a portion of the Forest, into a single *Populus tremuloides/Symphoricarpos oreophilus* habitat type, but substantial variability in species composition and successional status is encompassed by this type.

Scattered aspen groves form a very important element in the vegetation complex on the Bridger-Teton Forest. These groves are esthetically pleasing, highly valued multiple use areas, providing good watershed protection, abundant livestock forage, and habitat for many forms of wildlife. Habitat and esthetics are two values that are particularly significant here because of the heavy recreational use on the Forest. The lack of a suitable natural classification for these aspenlands prompted the cooperative effort between the Bridger-Teton National Forest and the Intermountain Forest and Range Experiment Station that culminated in this publication.

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[1] Steele, R., D. Ondov, S. V. Cooper, and R. D. Pfister. Forest habitat types of eastern Idaho-western Wyoming. USDA For. Serv., Intermt. For. and Range Exp. Stn., Ogden, Utah. (In preparation)

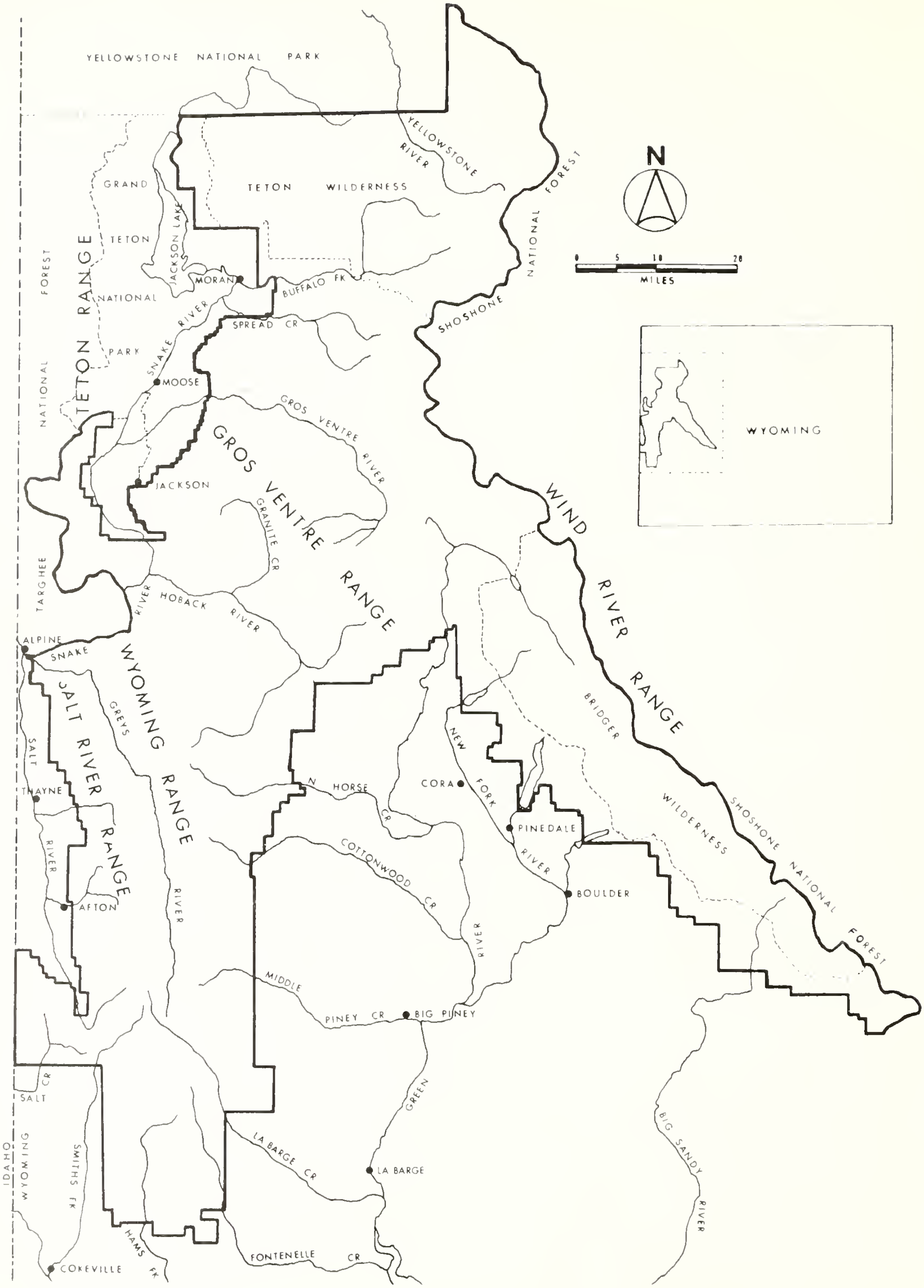

Figure 1.--The Bridger-Teton National Forest in relation to the major physiographic features of western Wyoming.

METHODS

A community type rather than habitat type approach was selected for defining the aspen communities on the Bridger-Teton Forest. Habitat types (Daubenmire 1952) are aggregations of land units capable of supporting similar climax plant communities, regardless of current successional status. This approach to classification is based upon the composition of climax plant communities. Community types are aggregations of similar plant communities based upon existing floristic composition, regardless of successional status. Both approaches view the plant community as an environmental integrator; the community type approach, however, avoids the presumption of climax. Community types may be either climax types or successional stages leading to a climax type. This is usually what the resource manager must deal with on a day-by-day basis.

Community types are used in this study because aspen is generally regarded as a seral species which is slowly replaced by conifers. Loope and Gruell (1973) determined that nearly all of the aspen clones in the Jackson Hole area of Wyoming had their origin following natural forest fires between 1850 and 1890; most of these stands are now actively succeeding to conifers. Aspen also can be replaced by grasslands or shrublands if regeneration s suppressed (Krebill 1972; Schier 1975). It also is ecognized as a climax dominant in parts of western Wyoming (Reed 1971; Beetle 1974). A community type classification will allow resource managers to identify and categorize aspen communities regardless of successional status. These community types can then be linked o existing habitat type classifications, or used as guides n developing such classifications. Meanwhile, the community type classification can be used as a mapping ool and as a basis for resource management planning.

The study area for developing the classification was he entire Bridger-Teton National Forest, with the exception of the Bridger and Teton Wildernesses. These areas were excluded because of travel and time constraints. Aspen is noticeably absent from the upper elevations in these wilderness areas (Reed 1976).

Field Methods

One hundred eighty-six aspen (*Populus tremuloides*) tands were sampled during the summer of 1978. Stands were subjectively chosen to describe as much representa-ve variation as possible. Concentrations of aspen within he study area were first determined from aerial photographs. A schedule was then prepared to optimize the use f time, and yet cover the entire study area. Only stands aving 50 percent or more of the canopy consisting of spen were sampled; those communities having greater han 50 percent of the canopy consisting of conifers were assumed to represent conifer communities sampled y Steel and others (see footnote 1). The normal procedure f stand selection was to travel a preselected route topping briefly to examine stand composition, and keeping a mileage log of apparent changes. At the end of the travel route the log was inspected and representative stands were selected for sampling. A selected stand was sampled by a single 4,036 ft² (375 m²) plot corrected for slope. The sample plot center was subjectively located within the stand to assure total community representation and avoidance of obvious ecotones that occurred at margins or openings.

Within each sample plot, ocular estimates were made of the canopy coverage of the vascular ground vegetation by species. These ocular estimates were checked for calibration, using a series of 50 microplots and practice layouts of subunits of known percentages. All unknown vascular species were collected for later identification.

Overstory canopy coverage, both total and by species, was also estimated ocularly. The following three size classes were used to evaluate the relative importance of each tree species: less than 3.9 inches (1 dm), 3.9 to 11.8 inches (1 to 3 dm), and greater than 11.8 inches (3 dm) diameter at breast height (d.b.h.). Tree species were also counted by 2.0 inches (0.5 dm) d.b.h. size classes. Trees between 0.3 and 4.5 ft (0.1 and 1.37 m) tall were counted on a 1,076 ft² (100 m²) circular subplot. Seedlings were also counted on this subplot. Age and height of at least three relatively free-growing "dominant" trees of each species were measured in each stand.

For each sample plot, the following environmental factors were recorded: slope, aspect, elevation, position, and configuration. Evidence of the successional status and perturbations were also recorded, including location of conifer seed sources, juxtaposition to neighboring communities, animal and disease disturbances, and fire history. Regolith classes (DeGraff and others 1977) and bedrock for each plot were determined. Neighboring conifer communities were keyed to habitat types according to Steele and others (see footnote 1).

Current aboveground biomass production of the vascular undergrowth on each sample plot was estimated ocularly and compared to a daily reference plot. Undergrowth biomass on the reference plot was determined from a series of three sets of five microplots, each 5.4 ft² (0.5 m²) in area. The three sets were randomly distributed within the 4,036 ft² (375 m²) sample plots, but the five microplots within each set were grouped regularly to provide within-set visibility for ranking estimates. Total current year's biomass on each of four microplots was ranked as a percentage of the fifth. The fifth microplot was then clipped, bagged, and taken to the laboratory for drying. The undergrowth biomass on the four to six sample plots measured on the same day was estimated as a percentage of this daily reference plot. Seasonal variation was accounted for by subjectively rating each sample plot according to the proportion of the expected current year's maximum biomass represented by the existing biomass.

Overstory aboveground biomass was determined from d.b.h. size class data using Zimmermann's (1979) regression equations. *Pinus* and *Pseudotsuga* were treated as *Picea* because of the similarity of growth forms and biomass components.

A separate effort to map conifer habitat types and aspen community types on the Bridger-Teton Forest beginning in the summer of 1979 provided validation of the aspen classification as well as additional insights to successional pathways.

Data Analysis

The goal of the analysis was to develop a community type classification. Three independent approaches, described by Mueller-Dombois and Ellenberg (1974), were merged to form the final classification: similarity indices, cluster analyses, and association tables.

Similarity between stands was computed with Sorenson's K index as used by Dick-Peddie and Moir (1970) and Dyrness and Franklin (1974). Similarity was based upon species canopy cover, with a minimum value of 3 percent qualifying for inclusion. This minimum-value constraint was imposed to eliminate species which could be considered as accidentally occurring with the community. Similarity values range from 0.00 to 1.00, with 1.00 indicating identical species and canopy cover values. A minimum value of 0.30 was selected to signify relatively high concordance; values above 0.30 comprised only 2.13 percent of the total 17,205 comparisons.

A cluster analysis (Sokal and Sneath 1963) of the 186 stands was then performed using the Sorenson's K similarity indices. This analysis was facilitated by using Marshall and Romesburg's (1977) CLUSTAR computer program with the "unweighted pair group method using arithmetic averages." A dendrogram showing the clustering relationships between stands can be found in Youngblood (1979).

The numerical techniques above are largely objective. They, however, fail to recognize vegetation unions and species that might have indicator value for certain environmental conditions, and overweigh species that have broad ecological amplitude. Therefore the association table method (Mueller-Dombois and Ellenberg 1974) was also used because it enables subjective recognition of floristic similarities through species fidelity, constancy, and coverage.

The final groupings for the classification were based on all three methods. The juxtaposition of each sample plot as determined by each method was compared for agreement. Where conflicts arose between placements, the final placement was based upon site characteristics of the different groups.

Average cover and constancy were computed for all species within each of the 26 groups (appendix A1 and A2). A dichotomous key was then developed which would separate each sample plot into its respective group. These groups are considered community types. The community types were named after the dominant and codominant trees in the overstory and the single species that indicate the best representative union of the undergrowth. Overstory and undergrowth names are separated by a slash.

Taxonomic Considerations

The flora of the Bridger-Teton National Forest is very diverse because of wide variability in climatic conditions and the union of at least three major floristic elements (Porter 1962). A Northern Rocky Mountain element enters from southern Montana and Yellowstone National Park and contains species characteristic of the Columbia Plateau. The Great Basin element extends eastward from Utah and southern Idaho, and is found throughout the southern portion of the Forest. A Southern Rocky Mountain element extends northward from Colorado, and is found along the Wind River and Wyoming Ranges.

Nomenclature usually follows Hitchcock and Cronquist (1973); Harrington (1954) was used occasionally when problems arose in the southern portion of the Forest. Taxonomic difficulties were experienced with field identification of a number of species and require clarification for the user of this community type classification.

Symphoricarpos albus and *Symphoricarpos oreophilus* can be difficult to separate unless one notes the small, hollow pith in 1- or 2-year old stems of *S. albus*. The rhizomatous *S. albus* is confined to mesic, forested sites within the northern part of the study area. The somewhat clumpy *S. oreophilus* is more widespread and often occurs on open, drier slopes and ridges.

Positive identification of *Thalictrum fendleri* and *Thalictrum occidentale* depends upon the availability of mature achenes. The dioecious habit of these two species complicates the already difficult situation. Generally, *T. occidentale* is a Northern Rocky Mountain species of cool mesic forests while *T. fendleri* is found more often in the Southern Rockies on warm, moist, and open sites.

Osmorhiza chilensis and *Osmorhiza depauperata* also are nearly impossible to distinguish without mature fruits. These have been combined under the name *O. chilensis*, in the assumption that they are ecologically similar.

In the absence of mature flowers, *Rosa woodsii* and *Rosa nutkana* are difficult to separate because of frequent interspecific hybridization. The morphological characteristic of sepals exceeding 0.8 inch (2 cm) was therefore used to differentiate *R. nutkana* from the smaller flowered *R. woodsii*. *R. woodsii* usually has clustered flowers, while *R. nutkana* is most commonly found with only a solitary flower terminating the lateral branches of the season. These two species are combined for simplicity under *R. woodsii*.

COMMUNITY TYPES

The classification separates three cover type groups into 26 community types. Cover type represents the overstory layer. The name reflects the one or two most dominant overstory species in the community as indicated by amount of canopy cover. Since tree reproduction is an important element reflecting site differences, tree canopy cover for defining "cover type" includes both the overstory and reproduction in the understory. A cover type is considered pure *Populus tremuloides* if there is less than 15 percent canopy cover of either *Pseudotsuga menziesi* or of the combined cover of *Abies lasiocarpa* and *Picea engelmannii*. When either *P. menziesii* or *A. lasiocarpa* and *P. engelmannii* occur with more than 15 percent cover the cover type name is binomial.

The undergrowth is named after the single species which depicts the most representative union of undergrowth species. It is usually named after one of the undergrowth dominants, but it does not necessarily imply the species with the greatest canopy cover. A listing o community types by cover types is given in table 1.

Table 1.--Aspen community types (c.t.) by cover type groups on the Bridger-Teton National Forest

- *Populus tremuloides-Abies lasiocarpa* cover type
  - *P. tremuloides-A. lasiocarpa/Prunus virginiana* c.t.
  - *P. tremuloides-A. lasiocarpa/Ligusticum filicinum* c.t.
  - *P. tremuloides-A. lasiocarpa/Pedicularis racemosa* c.t.
  - *P. tremuloides-A. lasiocarpa/Berberis repens* c.t.
  - *P. tremuloides-A. lasiocarpa/Shepherdia canadensis* c.t.
  - *P. tremuloides-A. lasiocarpa/Arnica cordifolia* c.t.
  - *P. tremuloides-A. lasiocarpa/Rudbeckia occidentalis* c.t.
- *Populus tremuloides-Pseudotsuga menziesii* cover type
  - *P. tremuloides-P. menziesii/Spiraea betulifolia* c.t.
  - *P. tremuloides-P. menziesii/Calamagrostis rubescens* c.t.
- *Populus tremuloides* cover type
  - *P. tremuloides/Ranunculus alismaefolius* c.t.
  - *P. tremuloides/Equisetum arvense* c.t.
  - *P. tremuloides/Heracleum lanatum* c.t.
  - *P. tremuloides/Prunus virginiana* c.t.
  - *P. tremuloides/Ligusticum filicinum* c.t.
  - *P. tremuloides/Spiraea betulifolia* c.t.
  - *P. tremuloides/Calamagrostis rubescens* c.t.
  - *P. tremuloides/Juniperus communis* c.t.
  - *P. tremuloides/Berberis repens* c.t.
  - *P. tremuloides/Shepherdia canadensis* c.t.
  - *P. tremuloides/Arnica cordifolia* c.t.
  - *P. tremuloides/Astragalus miser* c.t.
  - *P. tremuloides/Thalictrum fendleri* c.t.
  - *P. tremuloides/Rudbeckia occidentalis* c.t.
  - *P. tremuloides/Artemisia tridentata* c.t.
  - *P. tremuloides/Symphoricarpos oreophilus* c.t.
  - *P. tremuloides/Wyethia amplexicaulis* c.t.

The vegetation key (table 2) can be used to identify the three cover types and the community types within each. Use of this key requires the ability to identify four tree species, eight shrubs, twelve forbs, and two grasses. The key was designed only for those stands where at least 50 percent of the tree canopy cover consists of *Populus tremuloides*. The key is intended for use in aspen communities on the Bridger-Teton National Forest; applicability to other areas has yet to be determined.

A brief description of the general characteristics and noteworthy features of each community type is provided. These descriptions are sequenced in the order in which they appear in the key. Summary tables of constancy and canopy cover of important species within these community types can be found in appendixes A1 and A2. Estimated undergrowth and overstory productivity values are given in appendixes B1, B2, and B3.

The dichotomous key is designed to classify community types from canopy-cover values. Problems encountered in relating the values in the key to the estimated cover for a given aspen stand can usually be resolved by comparing the stand values with the written description and with the constancy-cover data in appendixes A1 and A2.

TYPE DESCRIPTIONS

Populus tremuloides-Abies lasiocarpa/ Prunus virginiana Community Type

(*Potr-Abla/Prvi* c.t.)

A single stand with undergrowth dominated by *Prunus virginiana* and having *Abies lasiocarpa* reproduction is used to tentatively define the *Potr-Abla/Prvi* c.t. It was found in the Salt River Range east of Bedford, Wyo. It occurs on a south-facing slope in the lower portion of the *A. lasiocarpa* zone. This sample plot is believed to be a successional stage which would eventually lead to an *A. lasiocarpa/Berberis repens* climax community (Steele and others, see footnote 1), except for periodic disturbance by snowslides. Floristically, this plot differs from the more common *Potr/Prvi* c.t. by the presence of *A. lasiocarpa* rather than *Pseudotsuga menziesii* in the understory.

Populus tremuloides-Abies lasiocarpa/ Ligusticum filicinum Community Type

(*Potr-Abla/Lifi* c.t.)

The *Potr-Abla/Lifi* c.t. was commonly encountered throughout the Wyoming and Gros Ventre Ranges on a variety of aspects on moderately steep slopes at midelevations in the *Abies lasiocarpa* zone. Sample plots ranged in elevation from 7,850 to 8,050 ft (2 393 to 2 454 m). This community type is believed to be a seral stage leading eventually to either an *A. lasiocarpa/Arnica cordifolia* or *A. lasiocarpa/Ribes montigenum* climax community (Steele and others, see footnote 1). We also regard this community type to be a later stage in development from a *Potr/Lifi* c.t.

The undergrowth of the *Potr-Abla/Lifi* c.t. is structurally and floristically identical to the *Potr/Lifi* c.t.; there appears to be no immediate change in undergrowth as a result of the slow invasion by *Abies lasiocarpa*. The tall forbs that characterize the *Potr-Abla/Lifi* c.t. consist of *Ligusticum filicinum* or *Osmorhiza occidentalis*, commonly associated with *Thalictrum fendleri*, *Geranium viscosissimum*, and *Rudbeckia occidentalis*. Generally, undergrowth production is moderately high.

The overstory of the *Potr-Abla/Lifi* c.t. is marked by the gradual invasion of *Abies lasiocarpa*. The complete conversion to a mature conifer stand may take several hundred years. Overstory production is characteristically low.

Table 2.--Vegetation key to aspen cover types and community types (c.t.) on the Bridger-Teton National Forest

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Key To Cover Types:

- I. *Abies lasiocarpa* and/or *Picea engelmannii* present, with at least 15 percent cover. .... *Populus tremuloides-Abies lasiocarpa* cover type (Go to A)
- I. *A. lasiocarpa* and/or *P. engelmannii* less than 15 percent cover II
  - II. *Pseudotsuga menziesii* with at least 15 percent cover .... *Populus tremuloides-Pseudotsuga menziesii* cover type (Go to B)
  - II. *P. menziesii* less than 15 percent cover .... *Populus tremuloides* cover type (Go to C)

Key To Community Types:

- A. (*Populus tremuloides-Abies lasiocarpa* cover type)
  - 1. *Ranunculus alismaefolius* at least 25 percent cover .... Go to C
  - 1. *R. alismaefolius* less than 25 percent cover 2
    - 2. *Prunus virginiana* at least 10 percent cover .... *Populus tremuloides-Abies lasiocarpa/Prunus virginiana* c.t. (p. 5)
    - 2. *P. virginiana* less than 10 percent cover 3
  - 3. *Ligusticum filicinum* at least 10 percent cover or *Osmorhiza occidentalis* at least 25 percent cover .... *Populus tremuloides-Abies lasiocarpa/Ligusticum filicinum* c.t. (p. 5)
  - 3. *L. filicinum* less than 10 percent cover and *O. occidentalis* less than 25 percent cover 4
    - 4. *Pedicularis racemosa* at least 10 percent cover .... *Populus tremuloides-Abies lasiocarpa/Pedicularis racemosa* c.t. (p. 9)
    - 4. *P. racemosa* less than 10 percent cover 5
  - 5. *Berberis repens* at least 10 percent cover or *Pachistima myrsinites* at least 20 percent cover .... *Populus tremuloides-Abies lasiocarpa/Berberis repens* c.t. (p. 9)
  - 5. *B. repens* less than 10 percent cover and *P. myrsinites* less than 20 percent cover 6
    - 6. *Shepherdia canadensis* at least 10 percent cover .... *Populus tremuloides-Abies lasiocarpa/Shepherdia canadensis* c.t. (p. 9)
    - 6. *S. canadensis* less than 10 percent cover 7
  - 7. *Arnica cordifolia* at least 10 percent cover .... *Populus tremuloides-Abies lasiocarpa/Arnica cordifolia* c.t. (p. 10)

Table 2 continued.

7. *A. cordifolia* less than 10 percent cover 8

  8. *Rudbeckia occidentalis* or *Nemophila brevifolia* at least 10 percent cover .... *Populus tremuloides-Abies lasiocarpa Rudbeckia occidentalis* c.t. (p. 10)

  8. *R. occidentalis* and *N. brevifolia* less than 10 percent cover ...... (Return to A, using half the designated cover values.)

B. (*Populus tremuloides-Pseudotsuga menziesii* cover type)

1. *Spiraea betulifolia* at least 10 percent cover .... *Populus tremuloides-Pseudotsuga menziesii Spiraea betulifolia* c.t. (p. 11)

1. *S. betulifolia* less than 10 percent cover 2

  2. *Calamagrostis rubescens* at least 10 percent cover ... . *Populus tremuloides-Pseudotsuga menziesii Calamagrostis rubescens* c.t. (p. 11)

  2. *C. rubescens* less than 10 percent cover .... (Undescribed communities in the cover type.)

C. (*Populus tremuloides* cover type)

1. *Ranunculus alismaefolius* at least 25 percent cover .... *Populus tremuloides Ranunculus alismaefolius* c.t. (p. 11)

1. *R. alismaefolius* less than 25 percent cover 2

  2. *Equisetum arvense* at least 50 percent cover .... *Populus tremuloides Equisetum arvense* c.t. (p. 12)

  2. *E. arvense* less than 50 percent cover 3

3. *Heracleum lanatum* at least 10 percent cover .... *Populus tremuloides Heracleum lanatum* c.t. (p. 12)

3. *H. lanatum* less than 10 percent cover 4

  4. *Prunus virginiana* at least 15 percent cover .... *Populus tremuloides-Prunus virginiana* c.t. (p. 12)

  4. *P. virginiana* less than 15 percent cover 5

5. *Ligusticum filicinum* at least 10 percent cover or *Osmorhiza occidentalis* at least 25 percent cover .... *Populus tremuloides Ligusticum filicinum* c.t. (p. 13)

5. *L. filicinum* less than 10 percent cover and *O. occidentalis* less than 25 percent cover........... 6

  6. *Spiraea betulifolia* at least 10 percent cover .... *Populus tremuloides Spiraea betulifolia* c.t. (p. 14)

Table 2 continued.

6. *S. betulifolia* less than 10 percent cover 7

7. *Calamagrostis rubescens* at least 10 percent cover or *Carex geyeri* at least 25 percent cover .... *Populus tremuloides*/*Calamagrostis rubescens* c.t. (p. 14)

7. *C. rubescens* less than 10 percent cover and *C. geyeri* less than 25 percent cover 8

8. *Juniperus communis* at least 25 percent cover .... *Populus tremuloides*/*Juniperus communis* c.t. (p. 15)

8. *J. communis* less than 25 percent cover 9

9. *Berberis repens* at least 10 percent cover .... *Populus tremuloides*/*Berberis repens* c.t. (p. 15)

9. *B. repens* less than 10 percent cover 10

10. *Shepherdia canadensis* at least 10 percent cover .... *Populus tremuloides*/*Shepherdia canadensis* c.t. (p. 16)

10. *S. canadensis* less than 10 percent cover 11

11. *Arnica cordifolia* at least 15 percent cover .... *Populus tremuloides*/*Arnica cordifolia* c.t. (p. 16)

11. *A. cordifolia* less than 15 percent cover 12

12. *Astragalus miser* at least 10 percent cover .... *Populus tremuloides*/*Astragalus miser* c.t. (p. 16)

12. *A miser* less than 10 percent cover 13

13. *Thalictrum fendleri* at least 15 percent cover .... *Populus tremuloides*/*Thalictrum fendleri* c.t. (p. 18)

13. *T. fendleri* less than 15 percent cover 14

14. *Rudbeckia occidentalis* or *Nemophila brevifolia* at least 10 percent cover .... *Populus tremuloides*/*Rudbeckia occidentalis* c.t. (p. 19)

14. *R. occidentalis* and *N. brevifolia* less than 10 percent cover 15

15. *Artemisia tridentata* at least 10 percent cover .... *Populus tremuloides*/*Artemisia tridentata* c.t. (p. 19)

15. *A. tridentata* less than 10 percent cover 16

16. *Symphoricarpos oreophilus* at least 10 percent cover .... *Populus tremuloides*/*Symphoricarpos oreophilus* c.t. (p. 19)

16. *S. oreophilus* less than 10 percent cover 17

Table 2 continued.

17	*Wyethia amplexicaulis* at least 10 percent cover	*Populus tremuloides/ Wyethia amplexicaulis* c.t. (p. 20)
17	*W. amplexicaulis* less than 10 percent cover	(Undescribed communities, (p. 21)

Populus tremuloides-Abies lasiocarpa/ Pedicularis racemosa Community Type

(*Potr-Abla/Pera* c.t.)

The *Potr-Abla/Pera* c.t. is a minor type found in the southern portion of the Wyoming and Salt River Ranges. It occurs at upper elevations in the *Abies lasiocarpa* zone; the sample plots ranged from 7,900 to 8,600 ft (2 408 to 2 622 m) in elevation. It is most commonly found on cool, northern aspects and moderately steep terrain. We believe this community type is a successional stage leading to an *A. lasiocarpa/Pedicularis racemosa* climax. Neighboring communities are usually mature conifer stands which belong to the *A. lasiocarpa/P. racemosa* habitat type. The *Potr-Abla/Pera* c.t. may be more common farther south and west in the Caribou and Wasatch National Forests, where Henderson and others (1976) and Steele and others (see footnote 1) found the *Abla/Pera* habitat type more abundant.

The *Potr-Abla/Pera* c.t. is recognized on the basis of having a sparse forb layer dominated by the indicator species, *Pedicularis racemosa*. The otherwise impoverished undergrowth may consist of traces of *Arnica cordifolia*, *Carex rossii*, *Symphoricarpos oreophilus*, *Shepherdia canadensis*, and *Pachistima myrsinites*. Average productivity of undergrowth is low.

Abies lasiocarpa regenerates quickly in the *Potr-Abla/Pera* c.t. *Picea engelmannii* may also be present. Within the *Abla/Pera* habitat type, *Picea engelmannii* and sometimes *Pseudotsuga menziesii* are common seral trees (Steele and others, see footnote 1). Overstory productivity appears to be fairly high.

Deer use the *Potr-Abla/Pera* c.t. for summer cover; moose browse the *Abies* reproduction in winter which can slow conifer invasions. This type appears to have little or no value for domestic grazing.

Populus tremuloides-Abies lasiocarpa/ Berberis repens Community Type

(*Potr-Abla/Bere* c.t.)

The *Potr-Abla/Bere* c.t. was found scattered throughout the Salt River Range and Wyoming Range portions of the Forest. Sample plots were on relatively gentle terrain, on all but northern exposures, and at elevations ranging from 5,900 to 8,700 ft (1 800 to 2 652 m). Several sample plots in the Wyoming Range were in communities maintained in a seral condition through repeated snowslides.

This community type is considered an intermediate successional stage leading to the climax *Abies lasiocarpa/Berberis repens* type described by Steele and others (see footnote 1). It is similar to the *Potr/Bere* c.t. which is considered an earlier stage in the sere. *Berberis repens* dominates a low shrub layer in the *Potr-Abla/Bere* c.t. *Pachistima myrsinites* is more common here and has a slightly higher coverage than in the *Potr/Bere* c.t. Other undergrowth characteristics are shared with the *Potr/Bere* c.t. The increased presence of *A. lasiocarpa* or *Picea engelmannii* distinguish this type from the *Potr/Bere* c.t.

Productivity appears to decrease with the increase of *Abies lasiocarpa* in the *Potr-Abla/Bere* c.t. when compared to the *Potr/Bere* c.t. This decrease may be the result of an increase in competition for light and moisture. Undergrowth and overstory productivity in the *Potr-Abla/Bere* c.t. are generally low.

Kerr and Henderson (1979) describe an *Abies lasiocarpa-Populus tremuloides/Berberis repens* community for the Manti-LaSal National Forest in Utah. Their type is very similar to the *Potr-Abla/Bere* c.t. It differs only in the relative proportion of conifers in the overstory, and a larger forb component in the undergrowth.

Populus tremuloides-Abies lasiocarpa/ Shepherdia canadensis Community Type

(*Potr-Abla/Shca* c.t.)

The *Potr-Abla/Shca* c.t. (fig. 2) was found throughout the Gros Ventre Range and in the northern portion of the Wyoming Range. It usually occurs on northerly exposures, on moderately steep slopes, and at elevations varying from approximately 7,050 to 8,300 ft (2 149 to 2 530 m). Surrounding communities are usually seral or mature conifer stands belonging to the *Abies lasiocarpa/Arnica cordifolia* habitat type (Steele and others, see footnote 1).

This community type is closely related to the *Potr/Shca* c.t., and is considered a later stage in succession which will eventually lead to an *Abies lasiocarpa/Arnica cordifolia* climax community. The presence of either *A. lasiocarpa* or *Picea engelmannii* as codominant with *Populus tremuloides* in the overstory marks the principle difference between the *Potr-Abla/Shca* c.t. and *Potr/Shca* c.t. *Pinus contorta* may also be present but demonstrates little potential for fully occupying these sites. A comparison of constancy and canopy cover data (appendixes A1 and A2) indicates that as succession proceeds from a *Potr/Shca* c.t. to a *Potr-Abla/Shca* c.t., such species as *Rosa woodsii*, *Bromus ciliatus*, *Epilobium angustifolium*, *Fragaria vesca*, *Geranium viscosissimum*, and *Lupinus argenteus* tend to decrease in abundance.

Figure 2.--Populus tremuloides-Abies lasiocarpa/Shepherdia canadensis *community type in the Hoback River drainage, Gros Ventre Range.*

Big game, especially elk and moose, appear to utilize this type extensively. Browsing by moose often tends to suppress the growth of *Abies lasiocarpa* and subsequently slows succession.

Populus tremuloides-Abies lasiocarpa/ Arnica cordifolia Community Type

(*Potr-Abla/Arco* c.t.)

At the southern end of the Forest, three stands were examined which were subsequentially categorized as the *Potr-Abla/Arco* c.t. This type occurs primarily on northerly exposures and is believed to represent an intermediate stage in succession between the early seral *Potr/Arco* c.t. and an *Abies lasiocarpa/Arnica cordifolia* climax.

The presence of *Abies lasiocarpa* as a codominant species in the canopy is the primary distinction between the *Potr-Abla/Arco* c.t. and *Potr/Arco* c.t. Undergrowth of both community types is dominated by *Arnica cordifolia*. The undergrowth of the *Potr-Abla/Arco* c.t., however, has more *Carex rossii* and *Osmorhiza chilensis*, and less *Symphoricarpos oreophilus* than the *Potr/Arco* c.t. Undergrowth productivity here was lowest of all classified types, whereas overstory productivity was moderate to high.

Ruffed grouse apparently find communities within this type acceptable for nesting sites, probably because of variability in tree diameter classes which provides abundant overhead cover.

Populus tremuloides-Abies lasiocarpa/ Rudbeckia occidentalis Community Type

(*Potr-Abla/Ruoc* c.t.)

The *Potr-Abla/Ruoc* c.t. is a later seral stage of the more common *Potr/Ruoc* c.t. It is found on the same variety of aspects and slopes as the *Potr/Ruoc* c.t., although the elevational range of 8,100 to 8,450 ft (2 469 to 2 576 m) is slightly higher, resulting in more successful conifer establishment. More mesic sites that abut the *Potr-Abla/Ruoc* c.t. are mature conifer stands in the *Abies lasiocarpa/Arnica cordifolia* habitat type (Steele and others, see footnote 1), while drier communities are *Artemisia* steppe or the *Potr/Syor* c.t.

The undergrowth of the *Potr-Abla/Ruoc* c.t. usually lacks a shrub layer and graminoid species have low constancy. The prominence of *Rudbeckia occidentalis*, which helps define the type, is believed to be at least partially caused by abusive grazing. The average undergrowth biomass of the stands examined was low.

Picea engelmannii and *Abies lasiocarpa* represent the climax overstory species. There is a high degree of vigor of conifer growth in the *Potr-Abla/Ruoc* c.t. due to the mesic site characteristics and the normally deep soil profile.

Kerr and Henderson (1979) have previously described an *Abies lasiocarpa-Populus tremuloides/Rudbeckia occidentalis-Sambucus racemosa* community type from central Utah.

Populus tremuloides-Pseudotsuga menziesii/Spiraea betulifolia Community Type

(*Potr-Psme/Spbe* c.t.)

The *Potr-Psme/Spbe* c.t. is a later seral stage of the more commonly found *Potr/Spbe* c.t. It occurs at middle to low elevations within the *Pseudotsuga menziesii* zone in the lower Greys and Snake River drainages, more commonly on the cooler, northerly slopes than the *Potr/Spbe* c.t.

Pseudotsuga menziesii is a slow invader in the *Potr-Psme/Spbe* c.t. The scattered individuals present should do little to change the floristic composition of the undergrowth. It may take several hundred years for *P. menziesii* to completely dominate the site, and any periodic fire, especially when the *P. menziesii* are still fairly young, will serve to prolong the occupation of the site by *Populus tremuloides*. Barring such disturbance, this community type will probably succeed to a *P. menziesii/Spiraea betulifolia* or possibly a *P. menziesii/Symphoricarpos albus* climax.

The undergrowth of the *Potr-Psme/Spbe* c.t. is identical to that of the *Potr/Spbe* c.t. Multiple layers of shrubs account for almost all the ground cover. A single sample plot having a dominance of *Physocarpus malvaceus*, along with the indicator *Spiraea betulifolia*, may be an intergrade between the more mesic *Pseudotsuga menziesii/P. malvaceus* and the warmer *Pseudotsuga menziesii/S. betulifolia* habitat types described by Steele and others (see footnote 1).

Annual production of the undergrowth and overstory averaged moderate to high in this type.

Populus tremuloides-Pseudotsuga menziesii/Calamagrostis rubescens, Community Type

(*Potr-Psme/Caru* c.t.)

The *Potr-Psme/Caru* c.t. is a minor type on the Bridger-Teton Forest. It occurs at low elevations in the *Pseudotsuga menziesii* zone along the Buffalo and Hoback Rivers. The sample plots ranged in elevation from 6,600 to 7,770 ft (2 012 to 2 368 m) on northern aspects, and had moderately steep slopes.

This community type is considered an intermediate successional stage between an early seral *Potr/Caru* c.t. and the climax *Psme/Caru* type found in the area (Steele and others, see footnote 1). The establishment of *Pseudotsuga menziesii* in the canopy marks the distinguishable difference between the *Potr-Psme/Caru* c.t. and he earlier seral *Potr/Caru* c.t. This type usually occurs because of fires that remove the *P. menziesii* overstory and promote vigorous suckering of *Populus tremuloides*. *Pseudotsuga menziesii* becomes established again about 50 years after the *P. tremuloides* canopy closes. More apid seedling establishment is presumably prevented because of the thick *Calamagrostis rubescens* sod and drought. Average overstory production is low to moderate.

The undergrowth in the *Potr-Psme/Caru* c.t. is generally indistinguishable from that of the *Potr/Caru* c.t. *Calamagrostis rubescens* creates a sward and represents most of the total ground cover. *Aster conspicuus* may occur with relatively high coverages, and *Thalictrum fendleri*, *Epilobium angustifolium*, and *Fragaria vesca* have high constancy. Undergrowth production is very high.

Climax *Pseudotsuga menziesii/Calamagrostis rubescens* communities are widespread throughout much of central and southern Idaho, western Wyoming, and northern Utah (Steele and others, see footnote 1; Henderson and others 1976). Steele found several communities on the Caribou National Forest in southeastern Idaho dominated by *Populus tremuloides* with an understory of *C. rubescens* in which he considered *P. menziesii* to be climax. Cooper (1975) sampled similar communities on the Targhee National Forest just west of the Bridger-Teton Forest.

Populus tremuloides/Ranunculus alismaefolius Community Type

(*Potr/Raal* c.t.)

This is a localized edaphic type found in moist depressions along streams or seepage areas. It is found at high elevations in the *Abies lasiocarpa* zone along the Wyoming Range. Sample plots ranged from 8,400 to 8,700 ft (2 560 to 2 652 m) elevation and had either eastern or western aspects. The type appears to be associated with grazing disturbance on gentle slopes or flat benches with a high water table. The underground moisture may result from late melting snowbanks that feed natural seepages. Alluvial deposits of fine-textured silts and clays accumulate to form deep layers of organic muck. Adjacent upland communities frequently belong to the *Abies lasiocarpa/Ribes montigenum* habitat type (Steele and others, see footnote 1). Open forb meadows of *Wyethia amplexicaulis* or tall forbs may also border the type. The *Potr/Raal* c.t. is usually confined to areas of less than 1.24 acres (0.5 ha).

The type is characterized by having a high coverage of the indicator species *Ranunculus alismaefolius*. Shrubs are absent, except for scattered *Ribes montigenum* or *Lonicera involucrata* on raised hummocks. *Carex microptera* or *Carex aquatilis* may be found in areas of surface water. Other forbs that may be found include *Trifolium longipes* and *Claytonia lanceolata*. Because the *Potr/Raal* c.t. is easily disturbed by either sheep or cattle, *Rudbeckia occidentalis* or *Nemophila brevifolia* may also occur.

The successional status of the *Potr/Raal* c.t. is unclear. *Abies lasiocarpa* and *Picea engelmannii* are present outside the areas of high ground water, either on raised hummocks or adjacent slopes. *Populus tremuloides* reproduces successfully as evidenced by multiple age classes on the sample plots. Given a time span of several hundred years, *A. lasiocarpa* may eventually colonize enough hummocks and raised microsites to lower the water table, allowing more rapid conifer invasion. Any disturbance might offset the invasion and prolong the *Potr/Raal* c.t.

Undergrowth productivity in the *Potr/Raal* c.t. is low to moderate, because of the stature of the dominant forbs. This type may have a wide range of overstory biomass depending upon the proportion of conifers present.

Populus tremuloides/Equisetum arvense Community Type

(*Potr/Eqar* c.t.)

This is a local edaphic type resulting from annual flooding by small streams or springs. The plots sampled were in the Wyoming and Wind River Ranges, but the type may be found throughout the Forest when edaphic conditions are adequate. Sites are at middle to high elevations in the *Abies lasiocarpa* zone and either on a flat streambank terrace or an alluvial bench. Surrounding communities are usually dominated by *Salix* spp. or conifers.

The understory is characterized by an almost complete cover of the indicator species *Equisetum arvense*. A wide variety of accompanying forbs and grasses may be present, depending upon the number of raised microsites and the depth of the water table.

The *Potr/Eqar* c.t. is believed to be seral to the *Picea/Equisetum arvense* habitat type as described by Steele and others (see footnote 1) and may be the result of fires. *Abies lasiocarpa* may be present on raised hummocks, and *Pinus contorta* may be a common associate in the seral stage. Pfister and others (1977) described a *Picea/Equisetum* habitat type for Montana, in which *Populus tremuloides* is seral.

The *Potr/Eqar* c.t. has low to moderate undergrowth productivity, depending upon the amount of wet-site graminoids. Overstory productivity is moderately high and is strongly influenced by the amount of conifers found on the site.

Populus tremuloides/Heracleum lanatum Community Type

(*Potr/Hela* c.t.)

The *Potr/Hela* c.t. is found on mesic, middle elevation sites within the *Abies lasiocarpa* zone. Sample plots range in elevation from 8,050 to 8,720 ft (2 454 to 2 658 m). It can be found scattered throughout the Wyoming, Salt River, and Gros Ventre Ranges on gentle easterly slopes or flat alluvial benches. Soils are fine textured and may become spongy with abundant moisture and accumulations of organic matter. Surrounding forest communities on somewhat drier sites may be either *A. lasiocarpa/Ribes montigenum* or *A. lasiocarpa/Arnica cordifolia* habitat types, as described by Steele and others (see footnote 1). Upland sites with abundant moisture may belong to the *A. lasiocarpa/Actaea rubra* habitat type. Open meadows of *Artemisia* or mixed tall forbs may also border the *Potr/Hela* c.t.

The *Potr/Hela* c.t. is characterized by having high coverage of the indicator species *Heracleum lanatum*. Common associates include *Pedicularis bracteosa*, *Thalictrum fendleri*, *Geranium richardsonii*, and *Elymus glaucus*. Shrubs such as *Ribes lacustre* or *Lonicera involucrata* may be present in trace amounts. Indicators of overgrazing, such as *Rudbeckia occidentalis* and *Nemophila brevifolia*, may also be found. *Heracleum lanatum* is very sensitive to grazing and its presence generally indicates a natural, undisturbed condition (Houston 1954).

Abies lasiocarpa and *Picea engelmannii* are only minor associates of *Populus tremuloides* in the *Potr/Hela* c.t. Neither of these conifer species seems capable of dominating the site for several centuries. All of the sample plots had multiple age classes of *P. tremuloides*, and the older ages were in excess of 150 years and 20-inch (5 dm) d.b.h. *Populus tremuloides* suckers were abundant as were large downed logs. Thus the *Potr/Hela* c.t. might be considered stable for several hundred years.

This is one of the more productive types for undergrowth biomass. Overstory biomass also is fairly high, reflecting the abundant moisture and deep soils. The type has one of the highest average tree basal areas of all aspen community types found.

Populus tremuloides/Prunus virginiana Community Type

(*Potr/Prvi* c.t.)

The *Potr/Prvi* c.t. is found in the *Pseudotsuga menziesii* zone along the Greys, Snake, and Gros Ventre Rivers. The type is normally found on warm, south-facing slopes of gentle topography at elevations ranging from 5,750 to 7,550 ft (1 753 to 2 301 m). It occurs either as isolated clumps in moist depressions surrounded by *Artemisia-Symphoricarpos* meadows or enclosed by *P. menziesii* forests.

Prunus virginiana is the principal component of a shrub-dominated undergrowth. Common associates include *Amelanchier alnifolia*, *Berberis repens*, *Symphoricarpos oreophilus*, and *Rosa woodsii*. *Acer grandidentatum* may also be present. A wide variety of forbs and graminoids may be found under the dense shrub layer; these include components of the drier, open meadows, such as *Potentilla glandulosa* and *Geranium viscosissimum*, or species more common under a closed forest canopy, such as *Calamagrostis rubescens*, *Elymus glaucus*, or *Osmorhiza chilensis*.

Pseudotsuga menziesii regenerates slowly in the *Potr/Prvi* c.t., and these sites may eventually become climax *P. menziesii/Berberis repens* or *P. menziesii/Calamagrostis rubescens* types as described by Steele and others (see footnote 1). *Pinus contorta* may also be present. The *Populus tremuloides* trees are usually even-aged, and many of the sample plots lacked sucker reproduction. This type appears to be most well developed along the Wyoming-Idaho border near Palisades Reservoir where several stands manifest stable conditions.

The type is important as a visual resource because of its occurrence at low elevations near existing major highways and its contrast of colors in the fall to neighboring conifer stands. The presence of *Acer* in the understory makes the contrast even more dramatic. Both deer and elk may use the *Potr/Prvi* c.t. for cover in winter and ruffed grouse may frequent the type.

Undergrowth productivity is very high because of the multiple layers of shrubs, forbs, and graminoids. Overstory production is also high.

Populus tremuloides/Ligusticum filicinum Community Type

(*Potr/Lifi* c.t.)

The *Potr/Lifi* c.t. is one of the most widespread types on the Bridger-Teton Forest. It occurs throughout the Wyoming, Hoback, Gros Ventre, and Wind River Ranges. Sample plots were found on all aspects and slopes from 7,000 to 8,850 ft (2 134 to 2 698 m) in elevation, but most often on midslope benches or alluvial terraces. The *Potr/Lifi* c.t. frequently forms continuous narrow to broad bands of *Populus tremuloides* separating open *Artemisia* or forb meadows from coniferous forests in the *Abies lasiocarpa* zone. These *Populus* stands may sometimes exceed several hectares in size. The conifer communities usually represent the *A. lasiocarpa/Arnica cordifolia*, or at higher elevations, the *A. lasiocarpa/Ribes montigenum* habitat types (Steele and others, see footnote 1).

The *Potr/Lifi* c.t. is characterized by having a dense, tall forb undergrowth consisting of *Ligusticum filicinum* or *Osmorhiza occidentalis* (fig. 3). *Geranium viscosissimum, Thalictrum fendleri, Valeriana occidentalis*, and *Delphinium occidentalis* are common associates and usually have high coverages. Shrubs are usually absent, and *Elymus glaucus* is the only graminoid with high coverage.

Abies lasiocarpa or *Picea engelmannii* may be present on the site as seedlings or saplings and represent the eventual climax overstory. Conifer establishment may be restricted because of the dense forbs. Cooper (1975) states that conifer invasion may be slowed by intense competition with forbs for light and moisture, and that the dead shoots and decaying leaf matter of forbs may have a smothering effect during fall and winter.

Big game frequently use the *Potr/Lifi* c.t. Many of the sample plots had *Populus tremuloides* stems damaged from browsing by elk. Some of the sample plots were near areas of high elk concentration during late winter and spring, and these areas had received extremely heavy use. Moose also use the type for cover and sometimes may retard the rate of conifer invasion by browsing the young *Abies*.

The tall forb undergrowth is moderately to highly productive, depending upon the degree of previous disturbance. Overstory production is moderate.

Houston (1954) rated *Populus tremuloides* sites with *Delphinium* spp. (tall), *Osmorhiza occidentalis*, and *Valerianna occidentalis* as good to excellent range. A *P. tremuloides*/tall forb community consisting of *Thalictrum fendleri, Senecio serra, Geranium viscosissimum, V. occidentalis*, and *O. occidentalis* has previously been described on the Humboldt National Forest by Lewis (data on file at Forest Service's Region 4). Morgan (1969) has described similar communities in Colorado that include *Ligusticum porteri*.

Figure 3.--Populus tremuloides/Ligusticum filicinum *community type on the Hoback drainage, Gros Ventre Range.*

Populus tremuloides/Spiraea betulifolia Community Type

(*Potr/Spbe* c.t.)

This community type is usually found along the lower Snake and Greys Rivers, in the lower to middle *Pseudotsuga* zone. Sample plots ranged in elevation from 5,750 to 6,100 ft (1 753 to 1 859 m). It normally occupies north to west aspects on fairly steep slopes, but can occur on southern aspects with more gentle slopes. Surrounding communities usually belong to the *Pseudotsuga menziesii/Spiraea betulifolia* habitat type on warm slopes and to the *P. menziesii/Symphoricarpos albus* or *P. menziesii/Physocarpus malvaceus* habitat types (Steele and others, see footnote 1) on more northern aspects.

The *Potr/Spbe* c.t. has a dominant multilayered shrub component and a minor forb and grass component (fig. 4). It is characterized by the high constancy and coverage of *Spiraea betulifolia*, but this may be overtopped by *Amelanchier alnifolia*, *Symphoricarpos albus*, *Rosa woodsii*, or *Prunus virginiana*. A third layer of *Pachistima myrsinites* or *Berberis repens* may underlie the *S. betulifolia*. *Smilacina stellata*, *Thalictrum fendleri*, and *Calamagrostis rubescens* may be present with low coverages.

Pseudotsuga menziesii seedlings or small saplings are usually present and should eventually dominate the site. When this conifer is abundant enough to begin influencing the site, a later seral stage, the *Potr-Psme/Spbe* c.t. is recognized. Cooper (1975) considered similar communities on the Targhee National Forest in eastern Idaho to be seral to his broadly defined *P. menziesii/Symphoricarpos albus* habitat type.

Undergrowth productivity is high, reflecting the dominance of dense shrubs, while overstory production of *Populus tremuloides* is only moderate.

Populus tremuloides/Calamagrostis rubescens Community Type

(*Potr/Caru* c.t.)

The *Potr/Caru* c.t. is the most widespread type described by this study. It is found throughout the Gros Ventre, Hoback, and the Teton Ranges and along the west flank of the Wyoming and Salt River Ranges. The type also extends westward along the Snake River into Idaho. It appears to reach its optimum development in the Spread Creek area of the Gros Ventre Range. The *Potr/Caru* c.t. is found on a variety of aspects and slopes, although it occurs most often on lower slopes or flat alluvial benches with northern aspects, sites which are usually cool and dry. The sample plots ranged in elevation from 6,200 to 8,500 ft (1 890 to 2 591 m) and occurred on moderately steep slopes. Soil parent materials include glacial tills along the Buffalo River and Spread Creek, alluvial benches along the Gros Ventre and Hoback Rivers, and colluvial deposits of sandstone and shale in the southern areas.

The *Potr/Caru* c.t. often appears as fairly large, homogeneous stands of *Populus tremuloides*. It usually occurs within the middle to lower *Pseudotsuga menziesii* zone and may border mature *P. menziesii* stands belonging to the *P. menziesii/Calamagrostis rubescens* habitat type (Steele and others, see footnote 1). It may also occur as isolated groves in the lower timberline zone and be surrounded by *Artemisia* steppe. When *Abies lasiocarpa* represents the lowest conifer in the area, neighboring communities may belong to either the *A. lasiocarpa/C. rubescens* community type or the *A. lasiocarpa/Berberis repens* habitat types (Steele and others, see footnote 1).

The undergrowth of the *Potr/Caru* c.t. is characterized by a dense sward of the indicator species, *Calamagrostis rubescens*. Either *Elymus glaucus* or *Bromus ciliatus* may be mixed with the *C. rubescens*. Along the Salt River

Figure 4.--Populus tremuloides/Spiraea betulifolia *community type along the Snake River near Alpine, Wyoming.*

Range, *C. rubescens* may alternate in dominance with *Carex geyeri*. Often a low shrub layer, consisting of *Rosa woodsii*, *Symphoricarpos oreophilus*, *Berberis repens*, or *Amelanchier alnifolia* may overtop the graminoids. Forbs are usually sparse, although *Thalictrum fendleri*, *Geranium viscosissimum*, *Aster conspicuus*, and *Lupinus argenteus* have fairly high constancy.

This type represents a confusing mixture of successional trends. Along the lower Buffalo and Hoback Rivers, *Pseudotsuga menziesii* is found as seedlings or saplings and should represent the climax overstory. Sites within the Salt River and Wyoming Ranges and in the upper Gros Ventre drainage are potentially *Abies lasiocarpa* climax. A broad band along the lower western flank of the Gros Ventre Range contains communities that appear stable. In these stable communities, which are floristically indistinguishable from the seral phases of the *Potr/Caru* c.t., *Populus tremuloides* has multiple age classes and there is no evidence of conifer invasion despite abundant seed sources nearby. These stable sites are presumably too warm for *A. lasiocarpa*, and lack the calcareous substrate necessary for successful *P. menziesii* establishment (Steele and others, see footnote 1). In other areas where *P. menziesii* is well represented in the canopy, a later seral stage is recognized as the *Potr-Psme/Caru* c.t. *Pinus contorta* and *Pinus flexilus* may be present on any of the phases as minor seral associates. On sites that are potentially conifer climax, seedling establishment is severely restricted by the thick *Calamagrostis rubescens* sod.

The *Potr/Caru* c.t. produces moderate to high amounts of undergrowth biomass, which consists almost entirely of grasses. Overstory production is highly variable, probably because of variation in both successional trends and site characteristics.

Cooper (1975) sampled several *Populus tremuloides* communities in the Targhee National Forest and in Grand Teton and Yellowstone National Parks which were dominated by *Calamagrostis rubescens*. This grass is notably absent from the Wind River Range (Steele and others, see footnote 1); (Reed 1971), but occurs frequently in eastern Idaho and northern Utah. Henderson and others (1976) reports the long persistence of *Populus tremuloides* as a seral tree in the *Pseudotsuga menziesii/C. rubescens* habitat type in northern Utah.

Populus tremuloides/Juniperus communis Community Type

(*Potr/Juco* c.t.)

This is a minor, local type which may be the result of cold air drainages. Examples of the type were found only along the lowest flank of the Wind River Range, on northerly exposures, and at elevations from 8,100 to 8,140 ft (2 469 to 2 481 m). Surrounding communities on drier sites were either the *Potr/Syor* c.t. or open *Artemisia* steppes. The type is usually below the lower timberline for successful conifer establishment. Glacial tills or boulder fields form the substrate.

A high coverage of *Juniperus communis* characterizes the type. A second layer of low shrubs includes *Pachistima myrsinites*, *Berberis repens*, and *Arctostaphylos uva-ursi*. Forbs and graminoids are not abundant.

The *Potr/Juco* c.t. consists of essentially pure stands of *Populus tremuloides*. Scattered *Pinus contorta* or *Pinus flexilis* may be present in the stand, but represent little successional change.

A *Potr/Juco* habitat type was described by Henderson and others (1977) as occurring on the north slope of the Uinta Mountains in northern Utah. The *Potr/Juco* c.t. along the Wind River Range appears to be an extension of the Uinta *Potr/Juco* habitat type.

Populus tremuloides/Berberis repens Community Type

(*Potr/Bere* c.t.)

The *Potr/Bere* c.t. is widespread throughout the Bridger-Teton National Forest. Examples were found most often scattered along the Wyoming and Wind River Ranges. It is noticeably absent from the Gros Ventre drainage. The type is normally found on gentle to moderately steep terrain on all except northerly aspects. It typically occurs in the lower portion of the *Abies lasiocarpa* zone, but sample plots ranged in elevation from 5,620 to 9,150 ft (1 713 to 2 789 m) and averaged 7,851 ft (2 393 m). These sites are characteristically cool and dry. Soil parent materials vary from coarse, poorly consolidated colluvial sandstones to glaciated tills and alluvial benches. The surrounding vegetation is usually coniferous forests which belong to the *A. lasiocarpa/Berberis repens* habitat type or, on drier sites at lower elevations, the *Pseudotsuga menziesii/B. repens* habitat described by Steele and others (see footnote 1). Nonforested communities dominated by *Artemisia* may also abut this type.

A low shrub layer dominates the undergrowth in the *Potr/Bere* c.t. *Berberis repens* usually has the highest coverage, and is used as indicator species. *Pachistima myrsinites* may be a codominant but usually is more abundant in the closely related *Potr-Abla/Bere* c.t. *Rosa woodsii*, *Shepherdia canadensis*, and *Symphoricarpos oreophilus* may also occur, but with low coverages. Occasionally this low shrub layer may be overtopped by either *Acer grandidentatum*, *Amelanchier alnifolia*, or *Prunus virginiana*. A variety of forbs and graminoids may be present under the shrub canopy, but only *Thalictrum fendleri*, *Geranium viscosissimum*, and *Achillea millifolium* have high constancy.

Populus tremuloides usually forms an even-aged overstory in this type. *Pinus flexilis* and *Pinus contorta* are usually present as seedling or sapling and share a seral status with *P. tremuloides*. In the northern part of the Gros Ventre Range and along the Snake River where calcareous deposits are present, *Pseudotsuga menziesii* may be present in the type. *Abies lasiocarpa* is usually present as seedlings and represents the potential climax overstory. As succession proceeds, this type merges into the *Potr-Abla/Bere* c.t., which differs in the amount of *A. lasiocarpa* in the overstory.

The *Potr/Bere* c.t. is a relatively poor to moderate producer of undergrowth biomass, presumably because of the dryness of these sites. This annual production is composed almost entirely of shrubs. The overstory is moderate to high in production.

Kerr and Henderson (1979) describe a *Potr/Syor-Bere* habitat type as a minor type on the Manti-LaSal National Forest. Their type is considered stable, and is characterized by a union of *Symphoricarpos oreophilus, Berberis repens, Pachistima myrsinites,* and *Rosa nutkana.* It was found at high elevations on west or southwest aspects. Reed (1971) includes *B. repens* in his stable, broadly defined *Populus tremuloides/S. oreophilus* habitat type in the Wind Rivers. The *Potr/Bere* community type of the Bridger-Teton National Forest differs from these types in being an early seral stage of the *Abies lasiocarpa/ B. repens* habitat type (Steele and others, see footnote 1) and having a shrub union which is not dominated by *S. oreophilus.* A separate *Potr/Syor* c.t. is characteristically stable and found on southwest or southeast aspects.

Populus tremuloides/Shepherdia canadensis Community Type

(*Potr/Shca* c.t.)

The *Potr/Shca* c.t. was found scattered throughout the Gros Ventre drainage at midelevations in the *Abies lasiocarpa* zone, but may also occur within the Hoback and northern portion of the Wyoming Range. This type is confined to cool and moist northerly aspects with moderately steep terrain. The sample plots ranged from 7,500 to 7,880 ft (2 286 to 2 402 m) in elevation, but the type extends much higher. Surrounding vegetation is usually mature conifer stands on cool slopes belonging to the *A. lasiocarpa/Arnica cordifolia* habitat type (Steele and others, see footnote 1), or shrub and forb meadow communities on toe slopes.

Shepherdia canadensis dominates the undergrowth in the *Potr/Shca* c.t. *Bromus ciliatus* may occur with high constancy, and forbs are usually dense, creating a second layer under the shrub canopy. *Geranium viscosissimum, Pedicularis bracteosa, Galium boreale, Thalictrum fendleri,* and *Lupinus argenteus* are often abundant. Annual production of the undergrowth is moderate.

Abies lasiocarpa and *Picea engelmannii* regenerate easily within the *Potr/Shca* c.t. Eventually, the type will probably succeed to an *A. lasiocarpa/Arnica cordifolia* climax. *Pinus flexilis* is a common seral tree. Overstory production is moderate.

Big game appear to concentrate more in the *Potr/Shca* c.t. than other *Populus* community types in the same area. *Populus tremuloides* suckers were heavily utilized, the branches highlined, and the bark of many mature stems was severely damaged by elk. In areas close to winter feed lots, elk have also highlined *Abies lasiocarpa* and *Picea engelmannii.* Moose also have hampered the invasion of *A. lasiocarpa;* the gradual increase of *Pinus flexilis* may serve to protect the *Abies* seedlings from browsing and signify a change in composition in favor of more rapid *Abies* establishment.

Populus tremuloides/Arnica cordifolia Community Type

(*Potr/Arco* c.t.)

The *Potr/Arco* c.t. is commonly found throughout the southern portion of the Wyoming and Salt River Ranges where it occupies a variety of aspects and elevations on gentle to moderately steep terrain. The sample plots ranged in elevation from 7,590 to 9,020 ft (2 313 to 2 749 m), but this type appears more prevalent in the lower portion of the *Abies lasiocarpa* zone. Surrounding vegetation may vary, depending upon the specific site characteristics. Upper elevational communities are usually surrounded by conifer stands in various stages of succession. Conifer-dominated sites on southern or eastern aspects usually belong to the *A. lasiocarpa/Arnica cordifolia* habitat type, while those on more northern slopes might fit the *A. lasiocarpa/Ribes montigenum* or *A. lasiocarpa/ Pedicularis racemosa* habitat type of Steele and others (see footnote 1). Lower elevational communities border either conifer stands or *Artemisia* steppes. The *Potr/Arco* c.t. is found on a variety of substrates, including colluvial deposits of sandstone or shale, glacial tills, and alluvium.

Arnica cordifolia dominates the sparse undergrowth. *Symphoricarpos oreophilus* is the only shrub that might be present. *Carex rossii* and *Poa nervosa* occur with a high constancy, but usually have low coverages. *Geranium viscosissimum* and *Achillea millfolium* are the only other forbs that are regular associates.

Abies lasiocarpa usually becomes established in the *Potr/Arco* c.t., and represents the climax overstory. *Pinus contorta* is present as a minor associate, usually as a result of fires. When *A. lasiocarpa* becomes increasingly important in the understory, a later seral stage is recognized as the *Potr-Abla/Arco* c.t.

The *Potr/Arco* c.t. is one of the least productive communities for undergrowth. The overstory is only moderately productive.

Populus tremuloides/Astragalus miser Community Type

(*Potr/Asmi* c.t.)

The *Potr/Asmi* c.t. is found in the northern Wind River Range and in the Gros Ventre drainage. Elevations of the sample plots range from 7,500 to 8,900 ft (2 286 to 2 713 m). The type usually occurs on south or west aspects with moderately steep slopes. Soils are usually glaciated tills. The type may be bordered by *Artemisia* steppe, or by the *Potr/Thfe* c.t. on drier slopes. Nearby conifer stands usually belong to the *Abies lasiocarpa/Arnica cordifolia* habitat type, *Astragalus miser* phase, or the *Pinus contorta/ A. cordifolia* community type (Steele and others, see footnote 1).

The *Potr/Asmi* c.t. is differentiated by the dominant forb layer of *Astragalus miser* (fig. 5). This single species either may account for almost all of the ground cover or there may be moderate amounts of *Lupinus argenteus, Thalictrum fendleri,* or *Geranium viscosissimum.* Several dry-site graminoids, such as *Leucopoa kingii, Tristeum spicatum, Festuca idahoensis,* and *Carex rossii,* may also be present, but only in small amounts. Undergrowth productivity is usually low.

Figure 5.--Populus tremuloides/Astragalus miser *community type in the Wind River Range north of the Green River.*

Pinus flexilis has a high constancy in the *Potr/Asmi* c.t., but a low average cover. Both *Abies lasiocarpa* and *Picea engelmannii* may be present as seedlings, but show little potential for rapid colonization of the site. *Populus tremuloides* had an even-aged stand structure on all of the sample plots. Overstory productivity appears moderate. This community type appears to be the result of periodic fires that maintain the *Populus* groves, coupled with environmental characteristics that retard conifer invasion. Thus it is regarded as a stable type.

The type is used extensively by both deer and elk. *Populus* stems on many sample plots had severe damage from elk chewing and scraping the bark. This damage probably occurs during winter months when the herds use these south-facing stands for cover.

Populus tremuloides/Thalictrum fendleri Community Type

(*Potr/Thfe* c.t.)

The *Potr/Thfe* c.t. can be found on the northern portion of the Wind River and Wyoming Ranges. It appears to occur only on glaciated till or on coarse sandstones with quartzite conglomerate. It occurs on a variety of slopes with southern aspects in the lower portion of the *Abies lasiocarpa* zone. Sample plots ranged in elevation from 7,420 to 9,120 ft (2 262 to 2 780 m). The *Potr/Thfe* c.t. is usually the lowest forest type in the immediate area and is often adjacent to *Artemisia* steppe. Along the Wyoming Range, the *Potr/Thfe* c.t. may abut the slightly cooler *Potr/Bere* c.t. or border conifer stands belonging to the *A. lasiocarpa/Berberis repens* or *A. lasiocarpa/Arnica cordifolia* habitat types (Steele and others, see footnote 1).

The undergrowth in the *Potr/Thfe* c.t. is characteristically dominated by low forbs (fig. 6), and at times appears sparse. *Rosa woodsii* and *Symphoricarpos oreophilus* usually occur, but only in minor amounts. Several grasses, including *Festuca idahoensis*, *Poa ampla*, *Stipa lettermannii*, and *Trisetum spicatum* have high constancy, but the canopy cover of all graminoids in a sample plot is usually less than 5 percent. Forbs are the predominant component, but only *Thalictrum fendleri* has both a high constancy and an average cover exceeding 20 percent.

Overstory in the *Potr/Thfe* c.t. consists entirely of *Populus tremuloides*. Although *Abies lasiocarpa* and *Picea engelmannii* seed sources may be nearby, seedlings of these conifers seem unable to withstand the moisture stress on these sites. *P. tremuloides* is even-aged, and many of the sample plots contained charcoal in the soil, indicating a history of fires. The relative stability of this community type is uncertain.

Big game use the *Potr/Thfe* c.t. extensively. Many of the sample plots had bark damage from browsing by elk or deer. These sites are on winter ranges and sucker utilization is very heavy.

This type has one of the lowest amounts of undergrowth production. There may be wide variation in production depending upon the previous grazing disturbances. Overstory production is moderate to high.

Figure 6.--Populus tremuloides/Thalictrum fendleri *community type in the Wind River Range north of the Green River.*

Populus tremuloides/Rudbeckia occidentalis Community Type

(*Potr/Ruoc* c.t.)

The *Potr/Ruoc* c.t. occurs along the Wyoming Range on a variety of aspects and elevations within the *Abies lasiocarpa* zone, on gentle slopes as well as on flat alluvial terraces. The sample plots ranged in elevation from 6,850 to 8,310 ft (2 088 to 2 534 m). The type appears most often on sandstone and shale substrates. Adjacent communities vary from *Potr/Lifi* c.t., *Potr/Hela* c.t., *Potr/Wyam* c.t., and the *A. lasiocarpa/Arnica cordifolia* habitat type in the southern portion of the Forest to the *Pinus contorta/Calamagrostis rubescens* community type (Steele and others, see footnote 1) and the *Artemisia* steppes along the Hoback drainage.

The *Potr/Ruoc* c.t. is a collection of several different communities that have been heavily disturbed by grazing. The undergrowth is characterized by a high coverage of either *Rudbeckia occidentalis* or *Nemophila brevifolia*. Both are indicators of overgrazing (Houston 1954). Additional undergrowth species vary, depending upon the natural flora of the site. *Achillea millefolium*, *Geranium viscosissimum*, and *Collomia linearis* have high constancy but low coverage; *Melica spectabilis* usually has both high constancy and coverage.

The *Potr/Ruoc* c.t. appears restricted to sites with moderately deep soil that have been repeatedly disturbed by cattle or sheep grazing. Fertilization with nitrogen (livestock manure) appears to prolong vigorous *Rudbeckia* growth and abundant flowering and seed set (Florez 1971). The type produces moderately high undergrowth biomass, but this is usually composed of a high percentage of *Rudbeckia occidentalis*, which may have no value for domestic stock or wildlife.

The type will usually support *Abies lasiocarpa* reproduction if grazing is not heavy. As *A. lasiocarpa* increases, the community succeeds to a *Potr-Abla/Ruoc* c.t. Moose, however, can severely restrict the growth of *A. lasiocarpa* reproduction in this type.

A *Populus tremuloides/Sambucus racemosa-Rudbeckia occidentalis* community type has been described from central Utah (Kerr and Henderson 1979) which closely resembles this *Potr/Ruoc* c.t. *Sambucus racemosa* is noticeably absent from *P. tremuloides* communities on the Bridger-Teton Forest, although it occurs on moist road cuts and on recently logged timber sale areas.

Populus tremuloides/Artemisia tridentata Community Type

(*Potr/Artr* c.t.)

The *Potr/Artr* c.t. was found at the lower timberline zone along the southern portion of the Wyoming Range and probably represents an ecotone between the adjacent *Potr/Syor* c.t. and *Artemisia* steppes. It normally occurs on south or west aspects and moderately steep terrain. The sample plots ranged in elevation from 7,820 to 7,860 ft (2 384 to 2 396 m).

The high coverage of *Artemisia tridentata* is an indicator of the type. Other shrubs with high constancy include *Symphoricarpos oreophilus* and *Berberis repens*. A wide variety of forbs and graminoids may be present, depending upon degree of disturbance. *Poa nervosa*, *Poa fendleriana*, *Stipa lettermannii*, and *Melica spectabilis* may be abundant. *Lupinus argenteus* and *Fragaria vesca* have high constancy, but low coverage. Undergrowth productivity is low to moderate.

The overstory is restricted to *Populus tremuloides*. The sites are usually too warm and dry for successful *Abies lasiocarpa* or *Pseudotsuga menziesii* invasion, although scattered *Pinus contorta* may be found as accidentals. This community type is thought to be relatively stable. Overstory production is low to moderate.

The *Potr/Artr* c.t. may be a drier phase of the more common *Potr/Syor* c.t. It differs from the *Potr/Syor* c.t. only in the presence of *Artemisia tridentata*. No other studies have described a *Potr/Artr* c.t., although Steele and others (see footnote 1) found isolated communities similar in undergrowth in southern Idaho on basaltic talus and lava tubes.

Populus tremuloides/Symphoricarpos oreophilus Community Type

(*Potr/Syor* c.t.)

The *Potr/Syor* c.t. is distributed throughout the Wyoming and Salt River Ranges. It was encountered primarily on gentle to moderately steep east and west exposures at elevations between 6,620 and 8,550 ft (2 018 and 2 606 m). The type generally occurs as a band between conifer stands and the *Artemisia* steppe or *Salix* streambanks. Nearby conifer stands usually belong to the *Abies lasiocarpa/Arnica cordifolia* habitat type (Steele and others, see footnote 1).

The abundance of *Symphoricarpos oreophilus*, usually over 20 percent canopy cover, is used as an indicator to the *Potr/Syor* c.t. Associated graminoids and forbs vary with degree of grazing disturbance. Frequently, however, *Bromus carinatus*, *Elymus glaucus*, *Melica spectabilis*, *Geranium viscosissimum*, and *Lupinus argenteus* are prominent. Undergrowth production on the seven stands sampled was moderate.

The overstory consists almost exclusively of *Populus tremuloides*. Only occasional conifers are able to establish and persist on these sites. The type is considered basically a stable *P. tremuloides* community. Overstory production in the sampled stands was low to moderate.

The *Potr/Syor* c.t. usually receives heavy grazing pressure throughout the year. Cattle use these areas during the summer months and deer and elk move down to them during the winter.

The *Potr/Syor* type was first described by Reed (1971) as a climax type in the Wind River Range. Reed's *Potr/Syor* habitat type, however, was a much more broadly defined type, consisting of the *Symphoricarpos oreophilus* union (*Berberis repens*, *Rosa woodsii*, *Amelanchier alnifolia*, *Prunus virginiana*, and *S. oreophilus*) and a wide variety of mesic-site forbs. Morgan (1969) found comparatively stable *Populus* communities containing *Symphoricarpos utahensis* in Gunnison County, Colorado, and Lewis (data on file Forest Service's Region 4) described a similar *Populus tremuloides/Symphoricarpos* habitat type in Nevada. North of the study area, Lynch (1955) described a stable *Populetum Symphoricarpetosum* association in Glacier County, Mont., that bears a strong resemblance to our *Potr/Syor* c.t. Kerr and Henderson (1979) described a seral *Potr/Syor-Bere* type in Utah.

Populus tremuloides/Wyethia amplexicaulis Community Type

(*Potr/Wyam* c.t.)

The *Potr/Wyam* c.t., a minor type along the Wyoming and Salt River Ranges, may be, at least partly, the result of overgrazing by sheep or cattle. It occurs within the middle to lower *Abies lasiocarpa* zone on gentle southeast slopes and flats. The type appears to be restricted to clayey soils that become very hard and packed when dry. Beetle (1961) indicates that the presence of *Wyethia amplexicaulis*, once established, may be an edaphic climax on generally impermeable soils.

The community type is usually open and parklike and easily identified by an almost complete cover of *Wyethia amplexicaulis* (fig. 7). Other species which might occur, but only in trace amounts, include *Lupinus* spp., *Potentilla glandulosa* or *Potentilla gracilis*, and *Symphoricarpos oreophilus*. *Abies lasiocarpa* seedlings or saplings may be present as accidentals, but show little potential for colonizing the site.

The *Potr/Wyam* c.t. was found in areas that historically received some of the heaviest grazing pressure on the entire Forest. The extent to which *Wyethia* may have invaded overgrazed sites is not known. The utilization of available moisture early in the season by *Wyethia* makes it almost impossible for the natural undergrowth to reestablish even if grazing were to be restricted. Sample plots in this type had young, even-aged canopies and lacked sufficient regeneration to maintain the stand unless subjected to another disturbance, such as fire.

The *Potr/Wyam* c.t. supports one of the least productive overstories. Although the undergrowth biomass on the sampled plots was moderate, it consisted almost entirely of the unpalatable *Wyethia amplexicaulis*.

Figure 7.--Populus tremuloides/Wyethia amplexicaulis *community type in the southern part of the Wyoming Range.*

OTHER COMMUNITIES

Although an attempt has been made in this classification to include all of the variations in aspen communities within the Bridger-Teton National Forest, several communities were encountered that do not fit the classification. These were usually unique or atypical situations for which we had insufficient data to justify community type status. In some cases, these situations may represent community types more prevalent in the neighboring regions for which an aspen classification has not yet been developed.

A single sample plot in the Wind River Range near Elkhart Park was in a pure stand of pole-size *Populus tremuloides*. The undergrowth was dominated by a mixture of *Vaccinium scoparium* and *Rubus parviflorus*. This stand was on a steep boulder field surrounded by even-aged *Pinus contorta* resulting from a recent fire. Presumably, *P. tremuloides* was able to colonize the boulder field because of remnant individuals in a moist meadow below the boulder field. *Vaccinium scoparium* as undergrowth to *P. tremuloides* has not been reported previously in the Intermountain Region.

Two additional sample plots in the Wind River Range were unclassified. One was at the outlet of a small lake where periodic damming by beaver resulted in a high water table. The lush undergrowth is a mixture of *Glyceria striata*, *Carex vesicaria*, *Calamagrostis canadensis*, and *Eleocharis palustris*. The other sample plot appeared similar to the *Potr/Thfe* c.t.; the undergrowth, however, differs in the absence of *Thalictrum fendleri* and in the presence of *Arctostaphylos uva-ursi*.

Several situations exist where the natural vegetation has been completely altered by recent disturbance. A young (28-year-old) stand of *Populus tremuloides* resulting from a recent fire in the South LaBarge Creek drainage had been repeatedly grazed by cattle throughout the development of the stand. The undergrowth is completely dominated by *Lupinus argenteus*. Unusually heavy grazing removed most of the undergrowth in two sample plots in the Wyoming Range. These communities would belong to the *Potr/Arco* c.t. under normal conditions, but now are virtually devoid of an herb or shrub layer.

A final community, not fitting the classification, was sampled in Grand Teton National Park. This community most closely resembles the *Potr/Lifi* c.t.; the undergrowth, however, consisted of *Elymus glaucus* and *Aconitum columbianum*.

CONCLUSIONS

Populus tremuloides appears to have a wider ecological amplitude than the associated conifers in the same area. This is exemplified by the variety of associated species contributing to the definition of 26 community types. Elevation for our 186 sample plots ranged from 5,620 to 9,321 ft (1 713 to 2 841 m). *Populus tremuloides* comprises a major portion of the lower timberline zone communities and is also found scattered throughout the upper timberline zone. The communities highest in elevation are usually found on south- or southeast-facing slopes, with a mean elevation of 7,867 ft (2 398 m). Lower communities are usually found on more northern aspects, with a mean elevation of 7,352 ft (2 241 m). *Populus tremuloides* communities occur most frequently on southern aspects at middle elevations.

Two hundred seventy vascular species were encountered in the *P. tremuloides* communities on the Bridger-Teton Forest. A surprisingly large number of these species occur as regular members of coniferous forest communities. Others are not found under a closed conifer canopy, but are more closely associated with open meadows or *Artemisia* steppes. There is a large difference in site requirements among the individual undergrowth species. Indicator species such as *Equisetum arvense* and *Ranunculus alismaefolius* have high fidelity, occurring in only 2 percent of the total sample plots, but with coverages as high as 90 percent. Other species such as *Geranium viscosissimum* and *Lupinus argenteus* have less rigid requirements, being found in 81 percent and 58 percent of all plots, respectfully.

The variability in undergrowth is a reflection of the variability in successional trends as well as in site characteristics. Of the 26 community types described by this study, 17 have the potential for developing into nine different climax communities dominated by conifers. In addition, nine community types may remain stable *Populus tremuloides* communities. These trends are summarized in table 3.

The natural units of vegetation described as community types in this study have several potential values for the resource manager. They serve as a means of communicating ideas pertaining to sites with similar environments and vegetation. These sites would be expected to respond to similar management actions. The community types serve as a means of accumulating field observations and research results. When coupled with the habitat type classification, realistic management alternatives for all resources may become clearer.

Finally, the community type classification is not a substitute for existing soil surveys, timber surveys, wildlife surveys, or range surveys. It does, however, serve as a natural complement to these studies in the development of more intensive land use plans and successful management practices.

Table 3.--Probable successional trends relating ***Populus tremuloides*** **community types (c.t.) to either stable *P. tremuloides* communities or climax conifer community types (c.c.t.) as described by Steele and others (see footnote 1)**

Potr/Raal c.t. →	Questionable stability	
Potr/Eqar c.t. →	*Picea/Eqar* c.c.t.	
Potr/Hela c.t. →	Questionable stability	
Potr/Prvi c.t. →	*Psme/Bere* c.c.t.	
Potr-Abla/Prvi c.t. →	*Abla/Bere* c.c.t.	
Potr/Lifi c.t. →	*Potr-Abla/Lifi* c.t. →	*Abla/Arco* c.c.t.
	→	*Abla/Rimo* c.c.t.
Potr-Abla/Lifi c.t. →	*Abla/Arco* c.c.t.	
→	*Abla/Rimo* c.c.t.	
Potr-Abla/Pera c.t. →	*Abla/Pera* c.c.t.	
Potr/Spbe c.t. →	*Potr-Psme/Spbe* c.t. →	*Psme/Spbe* c.c.t.
	→	*Psme/Syal* c.c.t.
Potr-Psme/Spbe c.t. →	*Psme/Spbe* c.c.t.	
→	*Psme/Syal* c.c.t.	
Potr/Caru c.t. →	Stable	
→	*Abla/Caru* c.c.t.	
→	*Potr-Psme/Caru* c.t. →	*Psme/Caru* c.c.t.
Potr-Psme/Caru c.t. →	*Psme/Caru* c.c.t.	
Potr/Juco c.t. →	Questionable stability	
Potr/Bere c.t. →	*Potr-Abla/Bere* c.t. →	*Abla/Bere* c.c.t.
Potr-Abla/Bere c.t. →	*Abla/Bere* c.c.t.	
Potr/Shca c.t. →	*Potr-Abla/Shca* c.t. →	*Abla/Arco* c.c.t.
Potr-Abla/Shca c.t. →	*Abla/Arco* c.c.t.	
Potr/Arco c.t. →	*Potr-Abla/Arco* c.t. →	*Abla/Arco* c.c.t.
Potr-Abla/Arco c.t. →	*Abla/Arco* c.c.t.	
Potr/Ruoc c.t. →	*Potr-Abla/Ruoc* c.t. →	uncertain
Potr-Abla/Ruoc c.t. →	uncertain	
Potr/Asmi c.t. →	Questionable stability	
Potr/Thfe c.t. →	Questionable stability	
Potr/Artr c.t. →	Stable	
Potr/Syor c.t. →	Stable	
Potr/Wyam c.t. →	Questionable stability	

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APPENDIX A -- CONSTANCY AND CANOPY COVER

Appendix A1. Constancy and average canopy cover (the latter in parenthesis) of important plants in aspen community types within the Bridger-Teton National Forest. (The code for constancy values is at the bottom of the table; canopy cover is the average percent for those stands in which the species was found, except "**" denotes a trace value.)

Community Type:	POTR-ABLA/PRVI	POTR-ABLA/LIFI	POTR-ABLA/PERA	POTR-ABLA/BERE	POTR-ABLA/SHCA	POTR-ABLA/ARCO	POTR-ABLA/RUOC	POTR-PSME/SPBE	POTR-PSME/CARU	POTR/RAAL	[illegible]	POTR/HELA	POTR/PRVI
No. of stands:	1	[illegible]	2	7	6	[illegible]	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6
TREES													
Populus tremuloides <1 dm. d.b.h.	10(40)	10(21)	10(42)	7(27)	8(15)	10(32)	10(**)	5(2)	10(16)	10(25)	10(11)	10(22)	6(10)
Populus tremuloides 1-3 dm. d.b.h.	10(70)	10(61)	10(35)	10(47)	10(58)	10(45)	10(55)	10(73)	10(42)	10(53)	10(50)	10(47)	10(69)
Populus tremuloides >3 dm. d.b.h.	-(0)	2(15)	-(0)	3(10)	-(0)	-(0)	10(38)	-(0)	3(3)	10(18)	5(10)	10(37)	-(0)
Abies lasiocarpa	10(15)	10(19)	10(20)	9(23)	10(21)	10(52)	10(15)	-(0)	3(**)	10(20)	5(3)	6(5)	-(0)
Picea engelmannii	-(0)	-(0)	5(1)	4(11)	2(35)	-(0)	10(6)	-(0)	-(0)	-(0)	5(3)	2(1)	-(0)
Pseudotsuga mensiezii	-(0)	2(2)	-(0)	3(7)	-(0)	-(0)	-(0)	10(19)	10(21)	-(0)	-(0)	-(0)	[illegible]
Pinus contorta	-(0)	-(0)	-(0)	1(**)	3(1)	7(6)	-(0)	-(0)	3(**)	-(0)	10(8)	4(9)	[illegible]
Pinus flexilus	-(0)	4(**)	-(0)	6(3)	5(1)	-(0)	-(0)	-(0)	3(**)	-(0)	5(**)	-(0)	-(0)
SHRUBS													
Acer grandidentatum	10(6)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	5(**)	-(0)	-(0)	-(0)	-(0)	3(33)
Amelanchier alnifolia	10(10)	2(1)	-(0)	3(1)	5(1)	3(**)	-(0)	10(8)	3(4)	-(0)	-(0)	-(0)	10(14)
Arctostaphylos uva-ursi	-(0)	-(0)	-(0)	1(**)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Artemisia tridentata	-(0)	-(0)	-(0)	1(10)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Berberis repens	10(3)	2(1)	-(0)	10(12)	8(3)	-(0)	5(**)	10(4)	3(1)	-(0)	5(**)	-(0)	8(22)
Ceanothus velutinus	-(0)	-(0)	5(1)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Juniperus communis	-(0)	-(0)	5(**)	4(1)	2(2)	-(0)	5(**)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Lonicera involucrata	-(0)	-(0)	-(0)	-(0)	5(2)	-(0)	-(0)	-(0)	-(0)	3(**)	5(**)	2(1)	-(0)
Pachistima myrsinites	10(15)	2(**)	10(1)	7(9)	8(4)	3(**)	-(0)	5(1)	-(0)	-(0)	-(0)	-(0)	-(0)
Physocarpus malvaceus	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	5(70)	-(0)	-(0)	-(0)	-(0)	-(0)
Potentilla fruticosa	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Prunus virginiana	10(60)	-(0)	-(0)	-(0)	2(1)	-(0)	-(0)	5(**)	3(2)	-(0)	-(0)	-(0)	10(32)
Ribes montigenum	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	3(2)	-(0)	-(0)	-(0)
Rosa woodsii	10(40)	4(**)	-(0)	9(1)	7(5)	3(**)	-(0)	10(1)	7(2)	-(0)	-(0)	-(0)	10(14)
Shepherdia canadensis	-(0)	6(1)	10(2)	6(14)	10(27)	3(**)	-(0)	5(1)	-(0)	-(0)	5(1)	-(0)	2(1)
Sorbus scopulina	10(10)	-(0)	-(0)	-(0)	3(2)	-(0)	-(0)	5(10)	-(0)	-(0)	-(0)	-(0)	-(0)
Spiraea betulifolia	-(0)	-(0)	-(0)	-(0)	2(2)	-(0)	-(0)	10(43)	-(0)	-(0)	-(0)	-(0)	-(0)
Symphoricarpos albus	-(0)	-(0)	-(0)	1(4)	-(0)	-(0)	-(0)	5(3)	-(0)	-(0)	-(0)	-(0)	-(0)
Symphoricarpos oreophilis	10(4)	8(1)	10(2)	9(12)	8(2)	3(3)	5(**)	5(2)	7(10)	-(0)	-(0)	2(**)	8(27)
GRAMINOIDS													
Agropyron caninum	-(0)	4(**)	-(0)	4(**)	-(0)	-(0)	-(0)	-(0)	3(1)	-(0)	-(0)	-(0)	2(**)
Bromus carinatus	-(0)	4(3)	-(0)	-(0)	-(0)	-(0)	5(3)	-(0)	-(0)	3(**)	-(0)	4(10)	-(0)
Bromus ciliatus	-(0)	-(0)	-(0)	4(1)	3(3)	-(0)	-(0)	-(0)	3(3)	3(**)	5(**)	-(0)	5(1)
Calamagrostis canadensis	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	5(40)	2(1)	-(0)
Calamagrostis rubescens	10(25)	2(**)	-(0)	3(5)	5(3)	-(0)	-(0)	5(15)	10(37)	-(0)	5(**)	-(0)	8(36)
Carex aquatilis	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	3(20)	-(0)	2(15)	-(0)
Carex geyerii	-(0)	-(0)	-(0)	3(1)	2(5)	-(0)	-(0)	-(0)	-(0)	-(0)	5(**)	-(0)	-(0)
Carex hoodii	-(0)	-(0)	5(**)	3(**)	-(0)	-(0)	5(1)	-(0)	3(**)	-(0)	-(0)	4(1)	2(**)
Carex microptera	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	7(40)	5(1)	-(0)	-(0)
Carex rostrata	-(0)	-(0)	5(1)	4(**)	2(**)	10(7)	5(**)	-(0)	-(0)	-(0)	5(**)	-(0)	-(0)
Elymus glaucus	10(1)	8(4)	-(0)	1(1)	8(1)	-(0)	10(10)	5(**)	10(3)	-(0)	10(32)	6(5)	8(3)
Festuca idahoensis	-(0)	-(0)	-(0)	1(1)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	2(1)
Leucopoa kingii	-(0)	-(0)	-(0)	1(**)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Melica spectabilis	-(0)	6(2)	-(0)	1(**)	-(0)	3(7)	10(10)	-(0)	7(1)	7(**)	-(0)	10(4)	2(1)
Phleum pratense	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	5(**)	-(0)	3(**)	3(**)	-(0)	4(1)	2(3)
Poa ampla	-(0)	2(**)	-(0)	1(**)	-(0)	-(0)	-(0)	-(0)	3(1)	-(0)	-(0)	4(2)	-(0)
Poa fendleriana	-(0)	-(0)	-(0)	1(**)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Poa nervosa	-(0)	2(**)	5(**)	6(1)	-(0)	7(20)	-(0)	-(0)	3(1)	-(0)	5(**)	8(2)	3(2)
Stipa lettermani	-(0)	-(0)	-(0)	1(1)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	3(2)
Trisetum spicatum	-(0)	-(0)	5(**)	6(1)	2(**)	7(1)	-(0)	-(0)	3(**)	-(0)	5(**)	-(0)	-(0)

Appendix [illegible] (continued)

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Achillea millefolium	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Arnica cordifolia	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Aster [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Aster [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Aster foliaceus	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Aster [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Balsamorhiza sagittata	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Campanula rotundifolia	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Castilleja miniata	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] lanceolata	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Clematis [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Collomia linearis	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Delphinium nuttallianum	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Disporum trachycarpum	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Epilobium angustifolium	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Equisetum arvense	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Erigeron peregrinus	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Erigeron speciosus	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Fragaria vesca	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Geranium [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Hackelia [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Hedysarum boreale	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Helianthella [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Heracleum lanatum	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Hydrophyllum [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ligusticum [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Lupinus argenteus	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Mertensia ciliata	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Nemophila [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Osmorhiza chilensis	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Osmorhiza [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Pedicularis [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Pedicularis racemosa	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Perideridia gairdneri	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Potentilla [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Potentilla gracilis	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ranunculus alismaefolius	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Rudbeckia occidentalis	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Senecio crassulus	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Senecio serra	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Senecio streptanthifolius	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Senecio triangularis	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Smilacina stellata	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Solidago multiradiata	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Stellaria jamesiana	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Taraxacum officinale	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Thalictrum fendleri	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Trifolium longipes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Valeriana occidentalis	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Viola adunca	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Viola nuttallii	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Wyethia amplexicaulis	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Appendix A2. Constancy and average canopy cover (the latter in parenthesis) of important plants in aspen community types within the Bridger-Teton National Forest. (The code for constancy values is at the bottom of the table; canopy cover is the average percent for those stands in which the species was found, except "**" denotes a trace value.)

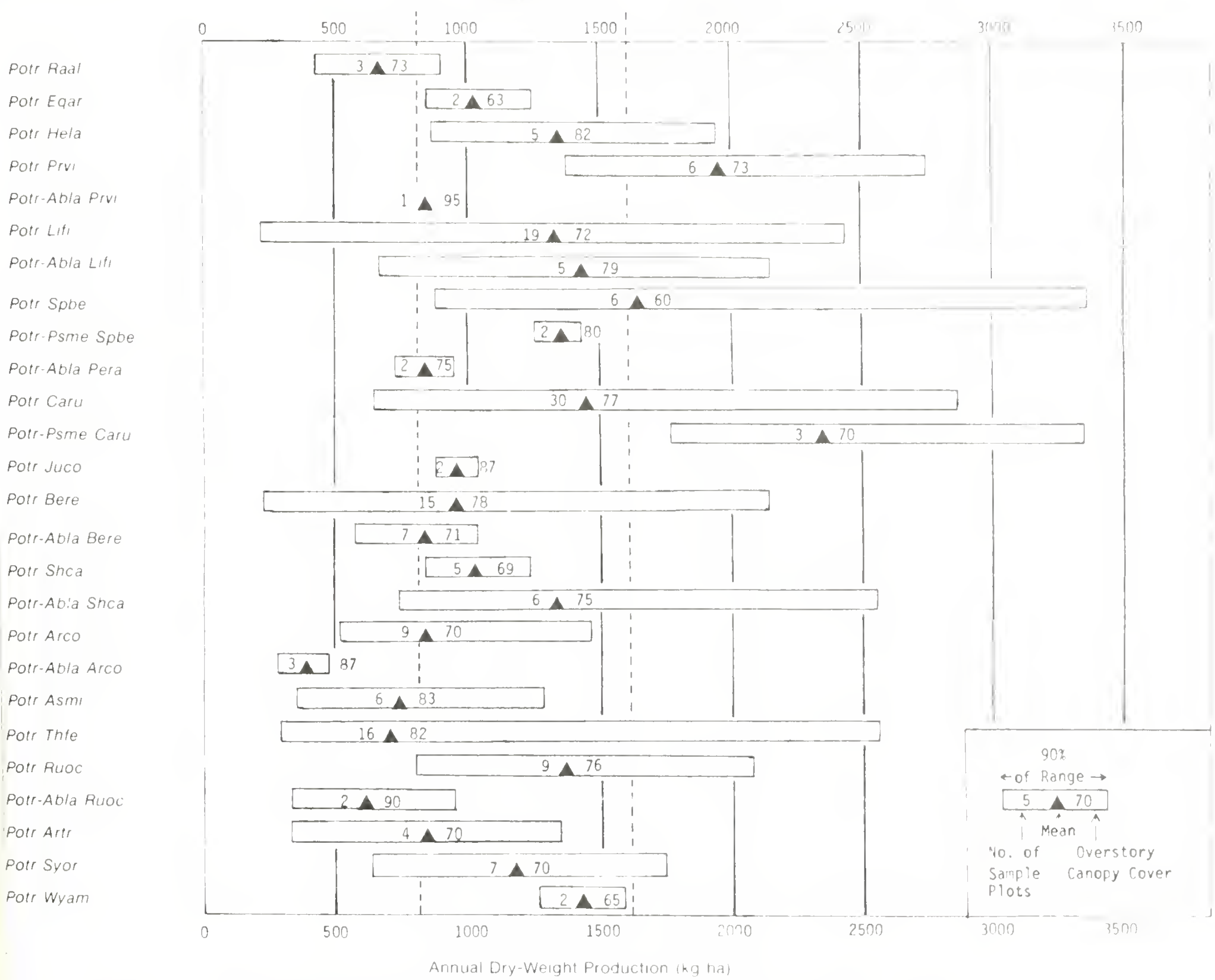
Community Type:	POTR/ LIFI	POTR/ SPBE	POTR/ CARU	POTR/ JUCO	POTR/ BERE	POTR/ SHCA	POTR/ ARCO	POTR/ ASMI	POTR/ THFE	POTR/ RUOC	POTR/ ARTR	POTR/ SYOR	POTR/ WYAM
No. of stands:	19	6	30	2	15	5	9	6	16	9	4	7	2
TREES													
Populus tremuloides <1 dm. d.b.h.	10(14)	10(17)	10(29)	10(60)	10(33)	10(20)	10(32)	10(24)	9(13)	10(26)	10(40)	10(26)	10(5)
Populus tremuloides 1-3 dm. d.b.h.	10(56)	8(58)	10(56)	10(25)	9(56)	10(56)	10(51)	10(65)	10(68)	10(59)	10(36)	10(60)	10(68)
Populus tremuloides >3 dm. d.b.h.	5(24)	-(0)	3(21)	-(0)	1(13)	4(3)	1(50)	3(10)	1(38)	2(13)	-(0)	3(13)	-(0)
Abies lasiocarpa	4(6)	2(**)	4(1)	-(0)	3(4)	10(**)	8(6)	3(**)	3(2)	8(3)	3(**)	7(**)	5(**)
Picea engelmannii	2(**)	-(0)	1(**)	-(0)	1(1)	10(3)	-(0)	2(**)	1(**)	1(1)	-(0)	-(0)	-(0)
Pseudotsuga mensiezii	1(**)	10(5)	2(4)	-(0)	3(1)	-(0)	1(7)	-(0)	-(0)	-(0)	-(0)	-(0)	5(**)
Pinus contorta	1(1)	2(**)	2(2)	5(8)	3(5)	2(2)	6(8)	-(0)	-(0)	2(2)	5(5)	1(**)	-(0)
Pinus flexilus	3(5)	-(0)	5(1)	10(6)	5(2)	8(1)	4(1)	8(2)	4(1)	1(**)	3(1)	1(**)	-(0)
SHRUBS													
Acer grandidentatum	-(0)	7(1)	-(0)	-(0)	1(45)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Amelanchier alnifolia	1(**)	8(17)	5(3)	-(0)	5(5)	-(0)	1(2)	-(0)	1(1)	-(0)	5(3)	4(1)	-(0)
Arctostaphylos uva-ursi	-(0)	-(0)	1(2)	5(45)	1(13)	2(**)	1(**)	-(0)	1(3)	-(0)	-(0)	1(1)	-(0)
Artemisia tridentata	1(**)	-(0)	+(1)	-(0)	1(1)	-(0)	2(1)	-(0)	1(**)	2(**)	10(18)	4(1)	5(1)
Berberis repens	1(3)	7(2)	5(10)	10(40)	10(29)	2(1)	2(1)	3(4)	2(1)	-(0)	8(5)	3(1)	-(0)
Ceanothus velutinus	-(0)	2(**)	+(15)	-(0)	1(**)	-(0)	1(2)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Juniperus communis	1(2)	2(**)	1(1)	10(45)	1(**)	-(0)	-(0)	-(0)	-(0)	-(0)	5(1)	1(3)	-(0)
Lonicera involucrata	-(0)	-(0)	1(1)	-(0)	-(0)	2(1)	1(**)	2(**)	1(**)	-(0)	-(0)	-(0)	-(0)
Pachistima myrsinites	1(**)	5(1)	2(19)	5(30)	4(2)	-(0)	1(3)	-(0)	1(**)	-(0)	3(**)	3(10)	-(0)
Physocarpus malvaceus	-(0)	3(**)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Potentilla fruticosa	-(0)	-(0)	+(**)	-(0)	1(1)	4(6)	-(0)	-(0)	3(2)	-(0)	5(3)	-(0)	-(0)
Prunus virginiana	1(**)	7(4)	3(2)	-(0)	3(2)	-(0)	1(**)	-(0)	1(**)	-(0)	8(4)	3(4)	-(0)
Ribes montigenum	1(**)	-(0)	-(0)	-(0)	-(0)	-(0)	1(3)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Rosa woodsii	2(**)	8(5)	8(8)	5(1)	7(3)	10(25)	1(70)	5(14)	8(1)	2(1)	10(1)	7(5)	-(0)
Shepherdia canadensis	3(4)	-(0)	2(3)	10(20)	6(7)	10(37)	4(2)	5(1)	4(2)	2(1)	3(2)	1(1)	5(**)
Sorbus scopulina	-(0)	3(3)	-(0)	-(0)	1(1)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Spiraea betulifolia	-(0)	10(46)	-(0)	-(0)	1(**)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Symphoricarpos albus	-(0)	3(7)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Symphoricarpos oreophilis	6(1)	5(11)	6(8)	10(3)	5(8)	8(6)	7(15)	7(3)	7(4)	7(7)	8(15)	10(32)	10(**)
GRAMINOIDS													
Agropyron caninum	5(2)	-(0)	4(**)	5(**)	3(**)	6(1)	3(1)	2(**)	7(**)	6(2)	-(0)	3(2)	5(**)
Bromus carinatus	7(3)	-(0)	4(1)	5(2)	3(3)	-(0)	3(4)	5(**)	4(**)	9(13)	8(7)	7(13)	-(0)
Bromus ciliatus	3(12)	-(0)	5(6)	-(0)	3(4)	8(24)	2(1)	2(**)	4(2)	-(0)	-(0)	3(**)	5(**)
Calamagrostis canadensis	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	1(**)	-(0)	-(0)	-(0)
Calamagrostis rubescens	2(11)	10(14)	9(48)	-(0)	3(2)	-(0)	-(0)	-(0)	3(2)	2(1)	-(0)	1(6)	-(0)
Carex aquatilis	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Carex geyerii	1(**)	-(0)	3(45)	5(**)	4(7)	-(0)	-(0)	2(**)	-(0)	1(**)	-(0)	-(0)	-(0)
Carex hoodii	3(1)	-(0)	1(**)	-(0)	2(1)	2(1)	2(1)	-(0)	3(1)	4(**)	3(**)	4(1)	-(0)
Carex microptera	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)	-(0)
Carex rostrata	1(**)	-(0)	1(**)	-(0)	5(**)	2(**)	6(1)	3(**)	1(1)	-(0)	3(**)	6(1)	10(**)
Elymus glaucus	7(9)	8(1)	6(5)	5(**)	5(4)	-(0)	2(**)	2(1)	4(1)	6(2)	5(3)	10(11)	5(**)
Festuca idahoensis	-(0)	-(0)	1(1)	5(**)	2(**)	-(0)	2(1)	2(2)	4(1)	3(**)	8(7)	1(2)	5(4)
Leucopoa kingii	-(0)	-(0)	+(**)	-(0)	1(1)	-(0)	-(1)	5(6)	1(3)	-(0)	5(1)	-(0)	-(0)
Melica spectabilis	5(2)	-(0)	2(1)	-(0)	4(1)	-(0)	3(3)	2(**)	1(2)	9(14)	8(16)	7(14)	5(1)
Phleum pratense	1(**)	3(**)	2(1)	-(0)	3(4)	-(0)	1(**)	2(**)	1(**)	6(1)	-(0)	3(3)	10(**)
Poa ampla	4(2)	-(0)	2(2)	-(0)	2(1)	2(**)	2(1)	5(1)	6(1)	3(14)	5(5)	3(5)	5(**)
Poa fendleriana	-(0)	-(0)	-(0)	5(1)	-(0)	4(**)	1(3)	-(0)	-(0)	-(0)	8(10)	-(0)	-(0)
Poa nervosa	3(4)	3(3)	2(10)	10(1)	4(6)	4(**)	7(2)	8(**)	5(2)	9(6)	5(6)	6(14)	5(**)
Stipa lettermani	1(**)	-(0)	3(1)	-(0)	3(3)	4(1)	2(1)	7(1)	8(1)	-(0)	3(5)	4(1)	5(1)
Trisetum spicatum	3(2)	-(0)	1(1)	5(**)	2(1)	4(1)	6(1)	5(1)	5(**)	2(1)	3(1)	-(0)	-(0)

APPENDIX B -- PRODUCTIVITY

Appendix B1. Mean productivity by community type. (Means are shown with 95 percent confidence limits where n ≥ 5, or one standard deviation where n < 5, fo undergrowth and overstory production. Overstory production is mean annual increment.)

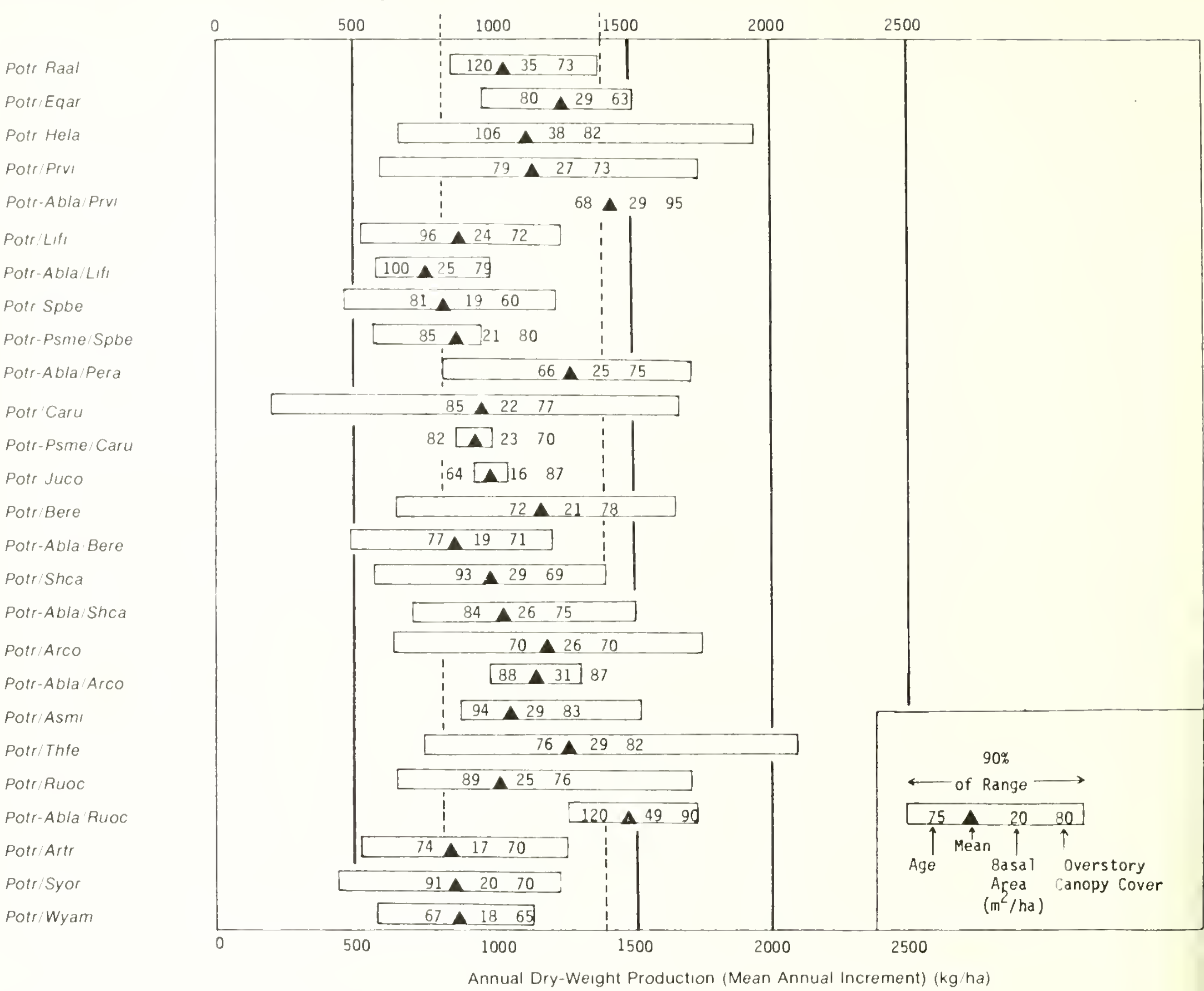
Community type	Number of plots	Undergrowth productivity	Overstory			
			Age	Basal area	Canopy cover	Productivity
		kg/ha		*m^2/ha*		*kg/ha*
Potr/Raal	3	683(338)	120	35	73	1064(320)
Potr/Eqar	2	1051(310)	80	29	63	1245(418)
Potr/Hela	5	1333±759	106	38±20	82±14	1121±693
Potr/Prvi	6	1973±543	79	27±16	73±12	1159±537
Potr-Abla/Prvi	1	856(?)	68	29	95	1438(?)
Potr/Lifi	19	1324±365	96	24±3	72±6	880±121
Potr-Abla/Lifi	5	1420±724	100	25±7	79±10	784±237
Potr/Spbe	6	1676±1318	81	19±6	60±18	805±385
Potr-Psme/Spbe	2	1339(92)	85	21	80	864(449)
Potr-Abla/Pera	2	845(174)	66	25	75	1284(776)
Potr/Caru	30	1454±253	85	22±3	77±5	938±140
Potr-Psme/Caru	3	2346(972)	82	23	70	927(68)
Potr/Juco	2	963(106)	64	16	87	975(95)
Potr/Bere	15	967±372	72	21±6	78±6	1150±240
Potr-Abla/Bere	7	822±180	77	19±10	71±10	853±282
Potr/Shca	5	1032±235	93	29±10	69±11	991±504
Potr-Abla/Shca	6	1357±798	84	26±10	75±17	1039±329
Potr/Arco	9	848±379	70	26±9	70±11	1191±305
Potr-Abla/Arco	3	370(104)	88	31	87	1116(149)
Potr/Asmi	6	755±385	94	29±8	83±12	1079±331
Potr/Thfe	16	702±325	76	29±6	82±6	1288±237
Potr/Ruoc	9	1380±397	89	25±7	76±16	1005±350
Potr-Abla/Ruoc	2	642(518)	120	49	90	1478(398)
Potr/Artr	4	841(581)	74	17	70	845(347)
Potr/Syor	7	1187±355	91	20±5	70±10	853±281
Potr/Wyam	2	1438(62)	67	18	65	858(377)

Appendix B2



Appendix B2. Estimated undergrowth productivity by community types.

Appendix B3



Appendix B3. Estimated overstory productivity by community types.

Youngblood, A. P., and W. F. Mueggler
1981. Aspen community types on the Bridger Teton National Forest in Western Wyoming. USDA For. Serv. Res. Pap. INT 272, 34 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401

A community type classification is presented for aspen-dominated communities on the Bridger-Teton National Forest. A diagnostic key that utilizes indicator plant species is provided for field identification of 26 community types. Tables are provided for detailed comparison of vegetation composition. Environment, relationship to surrounding vegetation, successional status, and productivity are discussed.

KEYWORDS: aspen forests, Wyoming, vegetation classification, community types

The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

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United States
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Forest Service

**Intermountain
Forest and Range
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Research Paper
INT-273

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Biomass of Singleleaf Pinyon and Utah Juniper

**Elwood L. Miller, Richard O. Meeuwig, and
Jerry D. Budy**

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RESEARCH SUMMARY

Relationships between tree measurements and biomass of singleleaf pinyon (*Pinus monophylla*) and Utah juniper (*Juniperus osteosperma*) were investigated on 109 trees on 19 study sites in Nevada and eastern California. The resulting equations and tables provide a means for estimating the total aboveground biomass as well as the weights for the various size fractions by species. The tables can also be used to estimate the cordwood and slash resulting in a typical fuelwood harvesting operation.

The entire aboveground biomass was separated into four size classes and weighed in the field. Cross-sectional disks and samples of twigs, foliage, and deadwood were used to determine the moisture contents of the various size fractions. The relationships between tree measurements and ovendry weights of the various size fractions were evaluated utilizing stepwise multiple regression techniques. Of the 13 tree measurements evaluated, stem diameter and average crown diameter were the most highly correlated with the ovendry weights.

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INTRODUCTION

The pinyon-juniper (p-j) woodland forest of the western United States has a long history of use largely because of the scarcity of timber in this region. For centuries this woodland forest has provided people with nuts, fuelwood, fenceposts, and poles (Fogg 1966). However, after the turn of the century the importance of the p-j decreased markedly mainly because of the availability of fossil fuels, the decline in rural population, and the decrease in mining. Although much of the research during the last three decades was initiated to curtail or convert the p-j (Box and others 1966), recent interest has focused on the ecology, management, and potential use of this forest resource (Aldon and Loring 1977; Springfield 1976; Gifford and Busby 1975; Barger and Ffolliott 1972). Two extensive p-j bibliographies were compiled by West and others (1973) and by Aldon and Springfield (1973).

The increased interest in p-j reveals the need for reliable mensurational data. Although volume tables exist, they are usually based on a small number of field measurements often from a local area. During the late 1930's and early 1940's a number of workers developed volume tables based on various tree variables. Howell (1937) found that crown width and stump diameter best estimated volumes for one-eed juniper in Arizona. Stump diameter and maximum crown width were used to construct fuelwood volume tables for one-seed and Rocky Mountain junipers (Howell nd Lexen 1939). Howell (1941) reported that differences n volume for trees of similar stump diameter and crown width were due to wide variations in tree form. Bradshaw nd Reveal (1943) developed tree classifications for ingleleaf pinyon and Utah juniper based on four maturity lasses. However, they still found wide variation in form of rees in the same class. Blackburn (1967) developed six ge classes for both pinyon and juniper based on growth ng counts, height, basal diameter, and outward ppearances. Reveal (1944) prepared volume tables for ngleleaf pinyon and Utah juniper based on diameter at reast height (d.b.h.), tree height, and average crown ameter measurements.

Growth measurements on Utah juniper in Arizona were made using tree height and stump diameter (Herman 1953). Using the same trees, Myers (1962) later found no relation between stump diameter and 20-year growth in height, diameter, and volume.

Aerial volume tables for pinyon-juniper stands were developed using total height, average crown diameter, and percent crown cover of the stand (Moessner 1962). Mason and Hutchings (1967) estimated foliage yields of Utah juniper based on crown diameter measurements. Storey (1969) found that tree weights of singleleaf pinyon and Utah juniper were closely correlated with maximum crown diameter and average crown diameter.

Although volume is the standard unit of measurement in forestry, it is not satisfactory for noncommercial woodland species such as pinyon and juniper, which lack a "merchantable bole." In addition, various products have been utilized from tree components other than the bole. Biomass, or weight, as a unit of measurement appears more reasonable in estimating the total quantity of usable wood products available in the p-j woodland. Also, the feasibility of whole-tree harvesting indicates a need for the aboveground biomass data.

In the southern United States, biomass tables have been developed for loblolly pine (Taras and Clark 1975), shortleaf pine (Clark and Taras 1976), and longleaf pine (Taras and Clark 1977). Crown biomass studies have been conducted on lodgepole pine (Gary 1976) and on 11 species of Rocky Mountain conifers (Brown 1978). H. E. Young (1976a) summarizes work from 62 forest biomass studies. Numerous biomass studies are reported by the Working Party on the Mensuration of the Forest Biomass (IUFRO) in three volumes (Young 1976b, 1973, 1971). Storey (1969) conducted the only study of tree weights in the p-j woodland. Recently, a line-intersect method to inventory cordwood in the p-j woodland was reported (Meeuwig and others 1978). Clendenen (1979) developed volume tables for p-j on the Carson National Forest in northern New Mexico.

The study reported here was initiated largely because of the lack of a sufficient unit of measurement for making decisions on the potential use of p-j woodland resources. Because of the growth habit of p-j and its various potential wood products, biomass was selected as the unit of measurement to be evaluated and determined in this study.

Objectives of the study were to:

1. Develop prediction equations that use measureable, independent tree variables to estimate aboveground biomass as related to resource potentials and quantity of fuel.
2. Obtain data for analysis of growth relations and site quality of pinyon-juniper in Nevada.

METHODS

Study Locations

Study locations were selected from stands that facilitated access and tied in with other studies in the p-j. Although a majority of the study sites were in western Nevada, an east-west transect of sites was established across the central portion of the state. Analysis showed no significant difference between the western sites and the east-west transect sites. Thus, the study locations appear to be fairly representative of typical p-j woodlands found in Nevada. The geographic distribution, specific locations, and physiographic features of the 19 study sites are in appendix A.

Sample points were established at each study site. Points that showed evidence of recent fire, cutting, chaining, or other disturbance were avoided. Once a sample point was established at a site, the nearest tree of each species in each diameter class was sampled. The five diameter classes based on diameter at the root collar were:

(1) <4 inches (<10 cm)
(2) 4-8 inches (10-20 cm)
(3) 8-12 inches (20-30 cm)
(4) 12-16 inches (30-40 cm)
(5) >16 inches (>40 cm).

This selection method provides approximately equal coverage of all size classes in the stand.

Field Techniques

For each sample tree selected, various crown variables were estimated and recorded. Before felling, the lower branches and most of the larger upper branches were cut flush to the main stem and placed on weighing tarps by size classes. After felling, the entire above-stump portion of the tree including all previously cut branches were separated into four classes and weighed using a load cell attached to a boom extended from the rear of a pickup. The four size classes weighed separately were:

(1) >3 inches (>7.6 cm) diameter outside bark (d.o.b.)
(2) 1-3 inches (2.5-7.6 cm) d.o.b.
(3) <1 inch (<2.5 cm) d.o.b.
(4) deadwood--all diameters.

Although all deadwood was weighed together, occular estimates of the percent in each of the size fractions was recorded. All tree weights of the above size classes were recorded to the nearest 1 pound using a digital meter.

The proportions of foliage, twigs less than 0.25 inches (0.64 cm) and branches 0.25 to 1 inch (0.64 to 2.5 cm) were determined by subsampling approximately 10 percent of <1 inch (<2.5 cm) size class fraction (fig. 1). Cross-sectional disks were taken along the main stem(s) at stump height, at 4-ft intervals, and at points where the d.o.b. measured 6 inches (15 cm), 3 inches (7.6 cm), and 1 inch (2.5 cm). Disks (2.5 cm and 7.6 cm) were also taken from randomly selected branches greater than 3 inches (7.6 cm) d.o.b. beyond the butt swell, usually about 5 cm from the cut end. These disks, along with samples of twigs, foliage, and deadwood, were weighed in the field using spring scales of varying capacities and sealed in plastic bags for laboratory analysis.

Tree Measurements

The growth form of p-j trees is such that some tree measurements, especially stem diameters, were quite difficult to obtain before the destructive sampling process began. Thus, the tree measurements listed below are in the order obtained during the sampling process and do not imply any relative rank of importance.

Measurements before any limbing or felling:

(1) Crown class (dominant, codominant, intermediate, or suppressed)
(2) Foliage class (dense, medium, or sparse)
(3) Crown form (rounded, oblong, triangular, tapered, or irregular)
(4) Crown projection (on ground)

Before felling:

(5) Number of stems (greater than 3 inches [7.6 cm] d.o.b.)
    -at root collar
    -at stump height
    -at breast height
(6) Number of forks (greater than 3 inches [7.6 cm] d.o.b.)
(7) Stem diameters (d.o.b.)
    -diameter at root collar (d.r.c.)
    -diameter at stump height (d.s.h.) (12 inches [30 cm])
    -diameter at breast height (d.b.h.)

After felling:

(8) Total tree height (includes stump)
(9) Maximum crown diameter (across the stump)
(10) Minimum crown diameter (across the stump)
(11) Tree age (at stump height).

The individual tree measurements are tabulated by species in appendix B.

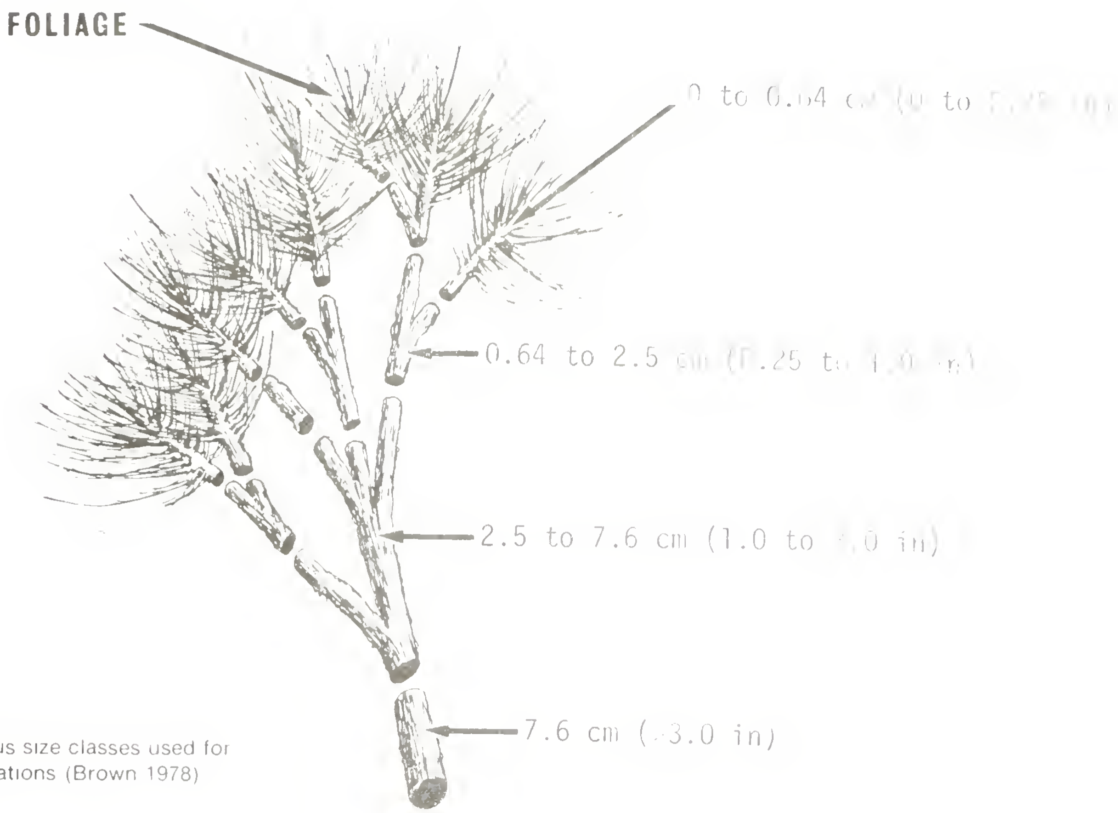

Figure 1.--The various size classes used for biomass determinations (Brown 1978)

Laboratory Analysis

The tree disks, along with the samples of twigs, foliage, and deadwood, were used to determine the moisture contents of the various size fractions. The disks were also used to determine the specific gravity of the wood. On all disks greater than 1 inch (2.5 cm), the bark was removed in the laboratory, dried, and weighed separately. The samples were ovendried to a constant weight at 95° C, and moisture contents were computed on a green-weight basis. Percentage of bark was determined by a dry-weight basis from the disks greater than 1 inch (2.5 cm). The moisture content values were utilized to convert the green weights of the size fractions determined in the field to ovendry weights.

The specific gravity of the wood was determined from the green volume and the ovendry weights of the disks.

RESULTS

Total Tree Biomass

The results include aboveground biomass measurements for 109 trees, 76 pinyon and 33 juniper. The individual tree weights are given in appendix C. The means of the tree variables and the average biomass are shown in table 1 by diameter classes. For a given diameter class, the pinyon were taller, had a greater crown spread, had less taper in the main stem(s), and weighed more than the juniper. The largest pinyon sampled had a green weight of 11,146 lb (5 066 kg) and the largest juniper, 3,421 lb (1 555 kg).

The proportions of the total biomass in the various size fractions are shown in table 2. The component proportions were also computed on a green-weight basis, but the percentages in each size fraction differed only slightly (1 to 2 percent) from the dry-weight basis calculations, and thus are not reported here. The proportion of total biomass in wood and bark greater than 3 inches (7.6 cm) is greater in pinyon than in juniper. In both species the proportion of foliage decreases as tree size increases; also, juniper has greater proportion of foliage than pinyon (table 3). Although the proportion of deadwood increases as tree size increases, the proportion of wood and bark greater than 7.6 cm also increases. This indicates that these species, or at least the trees sampled in this study, do not reach an overmature or decadent stage as commonly reported for the two species. The largest and oldest pinyon sampled had over 70 percent of its total biomass in wood and bark greater than 7.6 cm. The diameter growth of this pinyon has been essentially constant for more than three centuries (Meeuwig and Budy 1979). The tendency of these species to increase in the proportion of tree weight in wood and bark greater than 7.6 cm may be a characteristic of woodland trees because studies on southern conifers indicate that the proportions of tree weight in wood or foliage remain relatively constant as tree size increases (Taras and Clark 1977; Clark and Taras 1976). The most important aspect regarding the distribution of biomass is the amount of slash, that is, all the biomass less than 7.6 cm. Conventional cordwood harvesting of these species leaves approximately 50 percent of the biomass of even the larger trees. If the resources are to be utilized to their fullest and not create greater management problems, the application of total tree harvesting appears advantageous.

The equations and weight tables presented in this report are on an ovendry basis. The green weight of the total tree or the various size fractions can be estimated using the moisture contents given in table 4. Moisture content was calculated on a green-weight basis; thus, to obtain a green weight simply divide the ovendry weight by 1 minus the moisture content expressed as a decimal.

$$\text{Green weight} = \frac{\text{Ovendry weight}}{1 - \text{moisture content}}$$

Table 1.--**The tree variable means and the average biomass for each diameter class**

Species	**Diameter class**	**Sample trees**	**Tree variables (*x*)**									**Average biomass**	
			Height	**d.r.c.**	**d.s.h.**	**d.b.h.**	**Crown Max**	**Crown Min**	**Crown Average**	**Forks**	**Age**	**Green**	**Dry**
	cm	*No.*	*m*	*cm*			*m*			*No.*	*Yr*	*kg*	
Pinyon	<10	4	2.0	6.0	4.9	2.1	1.4	1.0	1.2	0	56	4.3	2.3
	10-20	19	4.2	15.9	14.6	9.8	2.7	2.2	2.5	0	79	66.8	35.1
	20-30	17	6.1	24.7	23.5	19.0	4.4	3.6	4.0	2	97	247.1	135.5
	30-40	17	7.1	36.3	34.5	28.7	5.6	4.4	5.0	12	126	583.0	333.4
	>40	19	9.0	55.2	53.1	47.5	8.0	6.3	7.2	35	164	1627.2	966.0
Juniper	10-20	7	4.2	17.2	15.3	8.3	2.9	2.1	2.5	0	91	52.9	28.4
	20-30	8	5.1	25.9	22.3	14.3	3.7	3.1	3.4	1	98	135.1	73.4
	30-40	7	5.0	34.0	28.8	16.9	4.5	3.6	4.1	4	124	226.9	121.3
	>40	11	6.7	58.2	48.3	32.2	6.7	5.4	6.1	13	147	666.3	368.7

Table 2.--**The distribution of aboveground biomass (dry weight) in size fractions**

Species	**Diameter class**	**Sample trees**	**Average biomass**	**Size fractions (cm)**					
				>7.6	**2.5 to 7.6**	**0.64 to 2.5**	**<0.64**	**Foliage**	**Deadwood**
	cm	*No.*	*kg*	*Percent*					
Pinyon	<10	4	2.3	0	23	26	16	29	5
	10-20	19	35.1	28	15	11	13	27	6
	20-30	17	135.5	34	18	10	12	19	7
	30-40	17	333.4	42	17	8	8	14	11
	>40	19	966.0	52	13	6	6	11	12
Juniper	10-20	7	28.4	24	15	11	8	40	2
	20-30	8	73.4	28	18	10	8	33	3
	30-40	7	121.3	23	23	12	6	30	6
	>40	11	368.7	36	19	9	5	24	7

Table 3.--**The distribution of aboveground biomass (dry weight) in tree components**

Species	**Diameter class**	**Sample trees**	**Average biomass**	**Tree component proportions**			
				Wood	**Bark**	**Deadwood**[1]	**Foliage**
	cm	*No.*	*kg*	*Percent*			
Pinyon	<10	4	2.3	47	18	5	29
	10-20	19	35.1	51	16	6	27
	20-30	17	135.5	57	17	7	19
	30-40	17	333.4	58	17	11	14
	>40	19	966.0	62	15	12	11
Juniper	10-20	7	28.4	48	10	2	40
	20-30	8	73.4	53	11	3	33
	30-40	7	121.3	53	11	6	30
	>40	11	368.7	59	10	7	24

[1] Deadwood component not separated into wood and bark fractions.

Table 4 --**The average moisture content of the total tree and of the various size fractions**

Species	Diameter class	Sample trees	Total tree	Size fractions (cm)				Foliage	Deadwood
				> 7.6	2.5 to 7.6	0.64 to 2.5	< 0.64		
	cm	*No*	*Percent green weight*						
Pinyon	< 10	4	45	--	45	50	47	46	12
	10-20	19	47	44	47	52	51	50	12
	20-30	17	45	43	45	49	50	50	15
	30-40	17	43	44	42	47	50	50	13
	> 40	19	42	43	41	47	51	51	11
Juniper	10-20	7	47	50	51	53	42	42	10
	20-30	8	46	48	48	49	43	43	12
	30-40	7	46	47	49	49	45	45	12
	> 40	11	45	49	49	49	43	43	12

Regression Analysis

The relationships between tree variables and ovendry weights were evaluated by screening all possible combinations of variables and weights using forward and reverse stepwise multiple regression techniques. Since all the relationships were nonlinear, logarithmic transformations (base e) were used throughout the analysis. The improvement in the standard error of the estimate and the sequential and partial F-test critera were used to select the number of tree variables to be included in the final prediction equations (Draper and Smith 1966). For most weight categories, the final equations have two tree variables. The addition of more variables did not significantly improve the prediction equations and also would not lend itself to the construction of weight tables.

Although the use of logarithmic equations for predicting weights is acceptable, the bias encountered when the logarithmic estimates are converted back to original units has been questioned. Baskerville (1972) suggested the use of a correction factor for this downward bias. However, Magwick and Satoo (1975) pointed out that the bias using logarithmic equations is of minor importance compared with the variation among samples. Although Brown (1978) applied correction factors for the logarithmic transformation bias to most of his crown weight equations, he omitted the correction factor in some cases because it contributed more bias than it eliminated. In this study, the bias encountered was low and the use of a correction factor introduced greater bias. Thus, a correction factor was not applied to the logarithmic estimates.

In order to express the precision of the predictive equations, coefficient of determination (R^2), standard error of the estimate, percent mean error, and the percent bias are reported for each equation. For predictive purposes, most investigators presently use some measure of the actual deviation between the predicted and observed weights (Brown 1978; Faurot 1977; Whittaker and Woodwell 1968). The percent mean error is an indication of the average variation of the sample. Faurot (1977) states that expressing the deviation in percentage overcomes the inherent problem of heterogeneous variance. The percent mean error is analogous to the standard deviation of the regression and is also similar to the estimate of the relative error reported by Whittaker and Woodwell (1968). Percent mean error is obtained as follows (Faurot 1977)

$$[\sum_{i=1}^{n}(|Y_i - Y_i|100/Y_i)\quad n-k-1]^2$$

Percent bias is obtained as follows (Faurot 1977):

$$100(\Sigma Y_i - \Sigma Y_i)/\Sigma Y_i$$

where

Y_i = observed value

Y_i = arithmetic estimated value

n = number of observations

k = number of independent variables.

Equations

The prediction equations for the various size fractions are presented in table 5 for pinyon and in table 6 for juniper. All equations are logarithmic (base e) and follow the model:

$$LnW = f(LnH,\ LnDSH \text{ or } LnDBH,\ LnC,\ LnD{\cdot}LnC,\ LnS)$$

where

W = weight, kilograms

H = height, meters

DSH = diameter at stump height (30 cm), centimeters

DBH = diameter at breast height, centimeters

C = average crown diameter, meters

S = number of stems at breast height

An interaction variable, **LnD•LnC**, was introduced in the regression analysis and proved to be beneficial to some of the prediction equations. For the pinyon equations, **D** is the **DSH** and for the juniper equations, **D** is the **DBH**. The advantage of using the interaction variable is that it increases the precision of the equations while still lending itself to the construction of weight tables using two independent variables. The equations listed in tables 5 and 6 have the deadwood component included in the various size fractions. The deadwood component was weighed separately in the field because of its lower moisture content, and then its ovendry weight added to the appropriate size fraction. Although 76 pinyons were weighed, the four trees in the < 10 cm diameter class were eventually deleted from the regression analysis. The prediction equations were much improved by deleting the four small saplings. Equations are being developed for seedlings and saplings in the <10 cm diameter class, and will be reported elsewhere.

Of the various tree measurements, the average crown diameter was the most significant variable for both species. Although the stem diameter measurements were also significant, the stump height diameter was more useful in the pinyon equations and the breast height diameter was more useful in the juniper equations. Height had no predictive value in the juniper equations, but it was significant in the pinyon equations for the total biomass and the biomass greater than 7.6 cm.

Thus, in order to use the equations presented in this paper, three variables are required for pinyon: crown diameter, stump diameter, and tree height. Only two variables are required for juniper: crown diameter and d.b.h. However, for multiple stem junipers, it is advised to correct the greater than 7.6 cm biomass for the number of stems. For single stem junipers, no correction is needed.

Weight Tables

Equations from tables 5 and 6 were used to construct weight tables. Predicted ovendry weights of the greater than 7.6 cm (3 inch) and the less than 7.6 cm biomass are presented in tables 7-10 by stem diameter and average crown diameter or height classes. The predicted total aboveground weight for pinyon can be obtained by adding the weights in tables 7 and 8. For juniper, the total weight is presented in table 11.

Note that the prediction equation for the juniper weight of the greater than 7.6 cm biomass contains a correction factor for the number of stems at d.b.h. This correction factor ranges from only 1-2 kg for most junipers with up to 20 multiple stems, and thus is important mainly for the smaller trees.

The tables and equations presented in this report were developed from trees sampled within Nevada and thus should be validated in new areas before using. Extrapolation beyond the data range or to species other than singleleaf pinyon and Utah juniper is not recommended without rescaling the variables to fit the population. Trees with similar bole and crown diameters may vary considerably in weight because of differences in crown size, crown form, and density of foliage.

Table 5.--**Prediction equations for estimating ovendry weight of the aboveground biomass of singleleaf pinyon trees greater than 10 cm at the root collar (basis: 72 trees)**

Tree component	Equation[1]	R^2	Standard error of estimate	Percent mean error	Percent bias
Total	$LnW = -2.025 + 1.399\,(LnDSH) + 0.671\,(LnH) + 0.922\,(LnC)$	0.987	0.156	15.9	4.0
>2.5 cm	$= -4.280 + 1.762\,(LnDSH) + 1.146\,(LnH) + 0.653\,(LnC)$	.988	.173	17.0	5.3
>7.6 cm	$= -6.024 + 2.159\,(LnDSH) + 1.663\,(LnH)$	.988	.184	18.6	2.4
<7.6 cm	$= -3.203 + 1.761\,(LnDSH) + 3.280\,(LnC) - 0.554\,(LnDSH \cdot LnC)$	.973	.194	19.5	-1.0
2.5 to 7.6 cm	$= -6.843 + 2.460\,(LnDSH) + 4.013\,(LnC) - 0.742\,(LnDSH \cdot LnC)$	.959	.293	30.3	-2.4
0.64 to 2.5 cm	$= -6.128 + 2.211\,(LnDSH) + 3.685\,(LnC) - 0.727\,(LnDSH \cdot LnC)$	.935	.312	34.5	-3.5
< 0.64 cm	$= -4.078 + 1.556\,(LnDSH) + 3.293\,(LnC) - 0.571\,(LnDSH \cdot LnC)$	.918	.304	34.2	-2.5
Foliage	$= -2.434 + 1.082\,(LnDSH) + 2.814\,(LnC) - 0.378\,(LnDSH \cdot LnC)$	.912	.305	33.2	-2.4

[1] Where

W= weight, kilograms
DSH= diameter at stump height (30 cm), centimeters
H= height, meters
C= average crown diameter, meters
Ln= natural logarithm, base e.

Table 6.--**Prediction equations for estimating ovendry weight of the aboveground biomass of Utah juniper trees greater than 10 cm at the root collar (basis: 33 trees)**

Tree component	Equation[1]	R^2	Standard error of estimate	Percent mean error	Percent bias
Total	$LnW = 0.296 + 0.845\,(LnDBH) + 1.444\,(LnC)$	0.963	0.210	20.0	-0.6
>2.5 cm	$= -1.232 + 1.113\,(LnDBH) + 1.466\,(LnC)$	.966	.232	23.8	-0.5
>7.6 cm	$= -1.423 + 1.241\,(LnDBH) + 0.347\,(LnDBH \bullet LnC) - 0.274\,(LnS)$	.968	.243	24.4	-0.2
<7.6 cm	$= -0.951 + 1.118\,(LnDBH) + 2.703\,(LnC) - 0.394\,(LnDBH \bullet LnC)$	.950	.232	22.3	-1.6
2.5 to 7.6 cm	$= -3.467 + 1.293\,(LnDBH) + 3.693\,(LnC) - 0.552\,(LnDBH \bullet LnC)$	.937	.314	34.7	-1.8
0.64 to 2.5 cm	$= -3.182 + 1.185\,(LnDBH) + 3.072\,(LnC) - 0.451\,(LnDBH \bullet LnC)$	.908	.348	42.5	-4.2
< 0.64 cm	$= -3.388 + 1.251\,(LnDBH) + 3.071\,(LnC) - 0.553\,(LnDBH \bullet LnC)$	.921	.271	26.0	-3.4
Foliage	$= 0.047 + 0.616\,(LnDBH) + 1.219\,(LnC)$	.915	.261	26.9	1.0

[1] Where

W = weight, kilograms
DBH = diameter at breast height, centimeters
C = average crown diameter, meters
S = number of stems at d.b.h.
Ln = natural logarithm, base e

Table 7.--**Predicted ovendry weights (kg) for the greater than 3 inch (7.6 cm) biomass of singleaf pinyon**

D.s.h.	Tree height (m)														D.s.h.
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
cm	*kg*														*Inches*
10		1	2												4
15		3	5	8	12	16									6
20		5	10	16	23	31	40								8
25		8	16	25	37	50	64	80							10
30		12	23	38	54	74	95	119	144						12
35		17	32	52	76	103	133	166	202	240					14
40			43	70	101	137	177	221	269	320	375				16
45			56	90	130	177	228	285	347	413	484				18
50			70	113	164	222	287	358	435	519	608				20
55			86	139	201	272	352	440	535	637	747	863	986	1115	22
60				168	243	329	425	530	645	769	901	1041	1189	1345	24
65				199	289	391	505	631	767	914	1071	1238	1414	1599	26
70					339	459	593	740	900	1072	1257	1452	1659	1877	28
75					393	532	688	859	1045	1245	1458	1686	1926	2178	30
80						612	791	987	1200	1431	1677	1938	2213	2504	32
85						697	901	1125	1369	1631	1911	2208	2523	2853	34
90							1020	1273	1548	1845	2162	2499	2854	3229	36
95							1145	1431	1740	2074	2430	2808	3208	3629	38
100							1280	1598	1944	2316	2714	3137	3583	4053	40
105							1422	1776	2160	2514	3016	3485	3981	4504	42
110							1572	1963	2388	2846	3334	3854	4403	4980	44
	3	7	10	13	16	20	23	26	30	33	36	39	43	46	
	Tree height (ft)														

$LnW = -6.024 + 2.159\,(LnDSH) + 1.663\,(LnH)$
Standard error (SE) = 0.184
Mean error (E) = 18.6 percent
Average bias (B) = 2.4 percent
R^2 = 0.998

Table 8.--**Predicted ovendry weights (kg) for the less than 3 inch (7.6 cm) biomass for singleaf pinyon**

D.s.h.	Average crown diameter (m) 1	2	3	4	5	6	7	8	9	10	11	12	13	D.s.h.
cm							*kg*							*Inches*
10		9	21											4
15		16	34	56	84	116								6
20		24	47	75	108	145	186							8
25		33	61	94	131	172	217	264						10
30		43	75	112	153	198	245	296	348					12
35		53	90	131	175	223	273	325	379	435				14
40			105	149	197	247	299	352	407	464	522			16
45			120	168	218	270	324	378	434	491	549			18
50			135	187	239	293	348	403	460	517	575			20
55			151	205	260	315	371	428	484	542	599			22
60				224	280	337	394	451	508	565	622	679		24
65				242	300	358	416	473	530	587	644	700		26
70						379	438	495	552	609	665	721	776	28
75						400	459	516	573	630	685	740	795	30
80						420	479	537	594	650	705	759	812	32
85						440	500	557	614	669	723	777	829	34
90						460	519	577	633	688	741	794	846	36
95						480	539	596	652	706	759	811	861	38
100						499	558	615	670	724	776	827	876	40
105						518	577	634	688	741	793	842	891	42
110						537	596	652	706	758	809	858	905	44
Average crown diameter (ft)	3	7	10	13	16	20	23	26	30	33	36	39	43	

$\mathrm{Ln}W = -3.203 + 1.761\ (\mathrm{Ln}DSH) + 3.280\ (\mathrm{Ln}C) - 0.554\ (\mathrm{Ln}DSH \bullet \mathrm{Ln}C)$

Standard error (SE) = 0.194
Mean error (E) = 19.5 percent
Average bias (B) = -1.0 percent
R^2 = 0.973

Table 9.--**Predicted ovendry weights (kg) for the greater than 3 inch (7.6 cm) biomass for Utah juniper**

D.b.h.	Average crown diameter (m) 1	2	3	4	5	6	7	8	9	10	11	D.b.h.
cm						*kg*						*Inches*
5		3	3									2
10		7	10	13	15							4
15		13	19	26	32	37	43	49				6
20		20	31	42	53	64	75	86	97			8
25		28	45	62	79	97	115	134	152			10
30			60	84	110	136	163	191	219	248		12
35			77	110	145	181	219	258	299	340	383	14
40			96	138	184	232	283	336	391	447	505	16
45				169	227	289	355	423	494	568	645	18
50						352	434	520	610	705	802	20
Average crown diameter (ft)	3	7	10	13	16	20	23	26	30	33	36	

$\mathrm{Ln}W = -1.423 + 1.241\ (\mathrm{Ln}DBH) + 0.347\ (\mathrm{Ln}DBH \bullet \mathrm{Ln}C) - 0.274\ (\mathrm{Ln}S)$[1]

Standard error (SE) = 0.243
Mean error (E) = 24.4 percent
Average bias (B) = -0.2 percent
R^2 = 0.968

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[1] For trees with multiple stems, multiply the weight by $S^{-0.274}$

Table 10.--**Predicted ovendry weights (kg) for the less than 3 inch (7.6 cm) biomass for Utah juniper**

D.b.h.	1	2	3	4	5	6	7	8	9	10	11	D.b.h.
	Average crown diameter (m)											
cm						*kg*						*Inches*
5		10	23									2
10		18	36	61	91							4
15		25	48	77	111	150	193	240				6
20		32	59	91	128	168	213	261	312			8
25		38	68	103	142	184	230	279	330			10
30			77	115	155	199	246	295	346	400		12
35			86	125	167	212	259	308	360	413	467	14
40			94	135	178	224	272	321	372	424	478	16
45				144	189	235	283	333	383	435	488	18
50						246	294	343	393	444	497	20
	3	7	10	13	16	20	23	26	30	33	36	
	Average crown diameter (ft)											

LnW = -0.951 + 1.118 (Ln*DBH*) + 2.703 (LnC) - 0.394 (Ln*DBH* • LnC)

Standard error (SE) 0.232

Mean error (E) = 22.3 percent

Average bias = -1.6 percent

R^2 = 0.950

Table 11.--**Predicted ovendry weights (kg) of total aboveground biomass for Utah juniper**

D.b.h.	1	2	3	4	5	6	7	8	9	10	11	D.b.h.
	Average crown diameter (m)											
cm						*kg*						*Inches*
5		14	26									2
10		26	46	70	96							4
15		36	65	98	135	176	220	267				6
20		46	83	125	173	225	281	340	404			8
25		56	100	151	209	271	339	411	487			10
30			116	176	243	316	395	479	568	662		12
35			133	201	277	361	450	546	647	754	865	14
40			148	225	310	404	504	611	725	844	968	16
45				248	343	446	557	675	801	932	1070	18
50						487	609	738	875	1019	1170	20
	3	7	10	13	16	20	23	26	30	33	36	
	Average crown diameter (ft)											

LnW = 0.296 + 0.845 (Ln*DBH*) + 1.444 (LnC)

Standard error (SE) = 0.210

Mean Error (E) = 20.0 percent

Average bias (B) = -0.6 percent

R^2 = 0.963

CONCLUSIONS

The results of this study indicate that the aboveground biomass of pinyon and juniper is closely correlated with average crown diameter for both species, and stem diameter at stump height for pinyon and diameter at breast height for juniper. These findings agree in part with those reported by Storey (1969). Although his study evaluated each tree variable separately, our analysis indicated that the precision of the estimates was improved by using multiple regression techniques.

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APPENDIX A

Figure 2.--Geographic distribution of study plots. This map shows the pinyon-juniper woodlands in the Great Basin and pinpoints the location of 19 study sites. (Derived from ERTS-I photography, Beeson 1974.)

Table 12 --**Plot location and physiographic features**

Plot	Trees	Mountain range	Location			Elevation	Plot aspect	Slope	Topographic position
			T	R	Sec.				
						(ft)		*Percent*	
1	1-4	Pine Nut	15N	22E	11	7250	S	9	Middle 1/3 of slope
2	5-8	Pine Nut	15N	22E	2	7200	SW	12	Lower 1/3 of slope
3	9-16	Pine Nut	13N	22E	34	6800	E	12	Lower 1/3 of slope
4	17-20	Bald Mountain	8N	25E	34	7000	SW	8	Lower 1/3 of slope
5	21-24	Wellington Hills	8N	24E	15	7200	E	2	Plateau
6	25-28	Wellington Hills	9N	23E	21	5900	N	18	Stream bottom
7	29-36	Toiyabe	19N	44E	22	6850	E	15	Upper 1/3 of slope
8	37-42	Toquima	16N	46E	20	7200	NE	7	Middle 1/3 of slope
9	43-49	Shoshone	13N	39E	23	7400	SE	5	Ridgetop
10	50-56	Paradise	12N	37E	13	7000	N	15	Lower 1/3 of slope
11	57-63	Monitor	15N	49E	8	7700	N	22	Lower 1/3 of slope
12	64-70	White Pine	12N	59E	23	6900	NW	10	Lower 1/3 of slope
13	71-78	Ruby	25N	56E	14	6800	SW	5	Ridgetop
14	84-92	Sweetwater	7N	25E	31	7550	SE	15	Plateau
15	93-99	Sweetwater	7N	25E	29	7200	E	5	Middle 1/3 of slope
16	100-105	Sweetwater	7N	25E	29	6900	NE	20	Lower 1/3 of slope
17	106-107	Pine Nut	14N	22E	12	6300	SE	5	Lower 1/3 of slope
18	108-111	Pine Nut	15N	22E	2	7100	S	5	Lower 1/3 of slope
19	112-114	Pine Nut	15N	22E	20	6100	E	3	Plateau

APPENDIX B

Table 13.--**Pinyon tree measurements**

Diameter class	Tree no.	Tree ht.	Diameter			Crown diameter			Forks	Class			Crown	Stems
			RC	SH	BH	Max	Min	Ave.	no.	Age	Crown	Foliage	form	RC-SH-BH
(cm)		(m)	(cm)			(m)				(yr)				
<10	85	2.1	8.0	6.0	2.7	1.4	1.2	1.3	0	64	4	3	5	
	87	2.4	6.0	5.5	3.2	1.6	1.0	1.3	0	48	4	3	5	
	97	2.1	7.0	5.8	2.0	1.6	1.4	1.5	0	57	4	3	5	
	105	1.4	2.8	2.2	0.4	0.8	0.6	0.7	0	56	4	1	5	
10-20	1	2.5	13.5	12.7	4.8	2.5	2.3	2.4	0	60	3	5	5	
	5	3.0	17.3	15.2	7.1	2.8	2.3	2.6	1	56	3	7	1	
	9	3.8	11.4	10.2	8.4	2.2	1.5	1.9	0	63	3	3	4	
	17	3.6	15.5	16.0	9.4	2.7	2.1	2.4	0	69	3	5	5	
	23	3.8	19.6	14.5	10.4	3.0	2.7	2.9	0	73	3	3	4	
	27	7.4	16.0	15.2	14.0	3.4	2.8	3.1	0	82	3	1	5	
	32	5.2	18.3	18.5	15.0	3.4	2.5	3.0	0	63	3	3	4	
	41	4.8	18.8	16.3	13.2	3.3	2.8	3.0	0	53	3	7	3	
	46	5.2	18.5	18.3	14.7	3.1	2.7	2.9	0	96	3	3	5	
	51	6.1	18.8	15.2	12.7	2.1	1.5	1.8	0	140	3	3	5	
	60	4.1	16.3	16.0	12.2	3.1	2.6	2.9	0	90	3	3	4	
	66	5.5	18.5	18.0	14.5	3.4	1.5	2.5	1	114	3	3	5	
	77	4.3	15.2	14.5	9.9	2.7	2.4	2.6	0	88	4	3	5	
	86	4.2	12.9	12.2	9.1	2.1	1.9	2.0	0	75	3	3	4	
	93	4.2	15.2	13.8	10.2	2.7	1.7	2.2	0	60	3	5	5	
	95	3.4	13.7	13.7	7.1	2.0	1.9	2.0	0	74	4	3	5	
	98	3.2	16.0	13.2	4.6	2.1	1.7	1.9	0	81	4	5	5	
	100	3.6	11.0	9.1	3.5	2.5	1.6	2.0	0	115	4	1	5	
	109	2.6	16.0	14.7	6.0	2.5	2.3	2.4	1	42	3	7	2	1-1-2
20-30	2	5.9	24.1	23.4	20.3	4.0	3.1	3.6	3	89	2	1	5	
	7	3.4	20.6	19.1	9.9	3.4	2.8	3.1	2	58	3	7	5	
	10	6.0	24.6	24.9	19.8	4.1	3.6	3.9	0	75	2	3	4	
	18	4.0	23.6	22.1	12.7	3.8	3.6	3.7	0	85	3	5	5	
	21	6.1	25.7	24.4	20.3	5.2	4.2	4.7	7	100	3	3	5	
	25	7.9	26.9	25.4	21.8	4.9	4.3	4.6	0	71	2	3	4	
	34	5.8	21.6	21.8	16.3	4.5	4.0	4.3	0	109	2	3	4	
	39	5.0	22.9	18.8	14.2	4.7	3.9	4.3	4	56	3	9	3	
	45	5.6	20.6	19.8	17.3	5.1	3.7	4.4	0	105	3	3	5	
	52	9.7	27.7	26.7	22.6	4.1	2.7	3.4	2	134	2	1	5	
	62	7.2	30.3	29.7	23.9	5.6	5.1	5.3	1	118	1	5	4	
	64	5.6	25.9	24.4	20.8	4.0	3.6	3.8	3	149	2	5	3	
	71	6.4	25.1	24.1	19.6	4.8	4.1	4.5	0	83	2	7	4	
	84	6.2	23.5	22.3	18.7	3.5	2.7	3.1	1	112	3	3	5	
	94	7.2	27.3	25.3	24.4	5.5	3.2	4.4	3	75	2	3	5	
	101	7.8	21.0	19.0	16.7	3.1	2.2	2.7	1	154	3	1	5	
	110	4.2	28.4	29.0	23.8	4.2	4.0	4.1	9	78	2	5	1	1-1-10
30-40	3	5.6	36.8	36.3	25.1	7.1	6.3	6.7	16	120	2	5	1	
	8	4.6	39.1	32.0	15.2	4.6	4.5	4.5	9	60	2	5	2	1-2-2
	13	8.5	35.1	31.5	29.5	4.4	2.3	3.3	7	131	2	1	5	
	20	5.8	31.7	31.7	26.9	5.7	5.0	5.4	10	129	3	3	5	
	22	6.2	38.1	38.4	31.0	7.3	5.9	6.6	25	164	2	5	5	
	36	8.5	34.5	34.0	30.0	6.2	4.6	5.4	16	147	1	5	5	
	38	8.4	39.9	36.3	30.0	6.7	5.4	6.0	15	105	2	3	1	
	44	7.0	37.8	36.3	32.0	5.7	4.7	5.2	17	153	2	3	1	
	53	9.5	38.4	37.1	32.5	7.3	4.2	5.8	17	148	2	3	5	
	63	7.1	35.8	36.3	31.8	5.4	4.5	4.9	13	213	2	3	5	
	67	6.9	37.6	36.3	33.6	5.9	4.4	5.1	10	185	1	1	5	1-1-2
	73	8.3	39.9	35.8	32.3	5.8	4.9	5.3	15	128	1	5	5	
	89	6.4	35.3	34.6	28.1	4.5	3.4	3.9	6	109	2	3	5	

Table 13 --con

Diameter class	Tree no.	Tree ht.	Diameter			Crown diameter			Forks no.	Age	Class		Crown form	Stems
			RC	SH	BH	Max	Min	Ave.			Crown	Foliage		RC-SH-BH
(cm)		(m)	(cm)			(m)				(yr)				
	90	7.9	34.0	31.5	27.5	4.7	3.6	4.2	4	78	2	5	4	
	96	6.9	35.6	34.5	34.0	5.4	5.0	5.2	15	79	2	7	4	
	103	9.2	35.0	31.0	26.0	3.5	3.1	3.3	2	146	3	1	5	
	108	4.2	32.8	32.0	22.1	4.1	3.7	3.9	4	80	1	5	2	1-1-2
40+	4	8.2	43.7	40.6	35.6	6.9	6.3	6.6	19	117	1	5	2	
	6	5.2	42.9	43.4	30.5	5.6	5.2	5.4	18	80	1	5	1	
	14	9.9	51.1	46.2	49.0	8.4	6.7	7.6	32	165	1	5	1	
	19	9.1	50.5	48.5	44.2	7.7	5.2	6.4	29	158	1	3	5	
	24	8.8	47.8	45.7	52.3	9.1	7.6	8.4	32	148	1	3	5	
	26	8.5	46.0	41.9	35.6	8.7	7.7	8.2	19	69	1	3	5	
	29	9.8	44.2	45.8	52.3	6.6	5.0	5.8	20	118	1	3	5	
	37	8.4	40.9	37.1	33.5	6.2	5.4	5.8	18	102	1	5	4	
	43	8.4	54.6	52.1	41.9	9.1	7.5	8.4	30	180	1	3	5	
	56	14.0	70.9	68.3	61.7	9.8	6.6	8.2	41	189	1	3	5	
	65	8.4	54.6	52.1	41.1	7.7	7.0	7.4	41	242	1	3	5	
	75	8.8	60.7	60.2	44.7	8.8	6.5	7.6	41	189	1	4	5	
	88	7.5	41.6	39.9	33.1	5.6	3.9	4.7	15	128	1	3	1	
	91	10.1	110.5	104.1	115.6	12.9	11.4	12.2	132	368	1	1	5	
	92	10.4	80.8	72.4	54.6	11.2	7.9	9.6	61	259	1	3	5	
	99	9.6	58.4	59.2	57.9	9.3	6.6	8.0	49	195	1	3	5	1-1-3
	102	10.2	44.3	40.5	36.7	5.8	3.2	4.5	19	168	2	1	5	
	104	9.8	56.0	59.0	47.0	7.0	5.5	6.2	36	158	1	3	5	
	111	5.2	48.4	51.0	35.1	6.0	5.3	5.6	18	80	2	7	1	1-1-2

APPENDIX C

Table 14.--**Juniper tree measurements**

Diameter class	Tree no.	Tree ht.	Diameter			Crown diameter			Forks no.	Age	Class		Crown form	Stems RC-SH-BH
			RC	SH	BH	Max	Min	Ave.			Crown	Foliage		
(cm)		*(m)*	*(cm)*			*(m)*				*(yr)*				
10-20	15	4.0	17.8	15.5	7.6	1.9	1.8	1.8	0	54	3	5	4	
	35	6.1	19.6	18.0	10.7	3.9	2.4	3.2	1	120	3	1	5	
	47	3.9	17.3	17.8	10.7	3.3	2.2	2.7	0	107	4	3	5	
	50	4.8	14.5	12.4	8.1	3.4	2.2	2.8	0	88	3	3	5	
	59	4.8	19.8	14.7	9.7	2.5	1.9	2.2	0	91	3	5	4	
	68	2.7	11.4	11.2	4.1	2.5	1.8	2.1	0	107	3	3	5	
	72	3.4	20.1	17.5	7.1	2.5	2.3	2.4	0	71	3	5	3	
20-30	11	6.4	27.9	23.9	18.3	4.1	3.8	3.9	0	89	3	3	5	
	16	4.8	21.8	18.3	13.0	2.2	1.9	2.0	0	59	3	5	4	1-2-2
	28	5.6	20.8	20.6	12.2	3.7	3.5	3.6	1	72	3	5	5	
	30	4.1	25.4	19.8	14.5	2.8	2.6	2.7	0	85	3	5	3	
	42	4.3	20.6	19.8	12.2	4.0	3.3	3.7	0	92	3	5	5	
	54	5.2	30.2	23.6	16.3	4.2	3.3	3.8	2	116	3	3	3	
	58	6.2	27.4	22.6	17.5	3.6	2.8	3.2	2	120	3	1	5	
	74	4.2	33.3	29.7	10.2	5.0	3.8	4.4	3	149	3	3	5	
30-40	33	6.0	32.8	28.2	16.0	4.1	3.2	3.7	2	122	3	5	3	
	49	6.7	35.6	26.7	20.3	5.6	3.8	4.8	6	144	2	1	5	
	61	4.6	31.0	22.6	17.0	4.5	3.8	4.2	1	118	3	3	5	
	70	3.6	32.0	31.0	12.2	4.1	3.2	3.7	0	195	3	5	1	1-1-4
	78	4.8	36.6	33.5	23.1	6.5	5.6	6.0	11	159	3	6	5	
	112	5.2	37.5	27.0	17.8	4.1	3.6	3.8	4	69	2	5	2	1-4-5
	113	4.2	32.2	32.5	12.0	2.8	2.1	2.4	4	64	3	3	5	1-5-6
40+	12	9.4	60.2	45.7	35.1	6.4	4.6	5.5	10	115	1	3	5	
	31	6.2	49.0	34.0	22.6	4.4	3.9	4.1	10	121	2	3	5	
	40	6.2	42.9	33.0	24.4	7.4	5.7	6.6	6	88	1	7	1	1-2-2
	48	4.1	43.4	32.5	14.0	5.1	4.8	4.9	10	156	4	5	1	
	55	6.6	48.8	37.1	28.4	5.4	4.6	5.0	8	122	1	5	4	1-2-2
	57	7.0	96.5	66.8	50.5	10.2	8.6	9.4	28	301	1	3	5	1-2-2
	69	5.2	50.5	50.5	36.1	8.5	6.9	7.7	21	249	2	5	1	1-1-5
	76	5.9	50.5	48.8	40.9	7.9	6.0	7.0	11	187	1	3	1	1-1-6
	106	8.0	50.0	41.1	29.8	5.7	4.0	4.8	9	79	1	5	1	
	107	7.8	55.3	58.2	29.6	6.7	4.6	5.6	9	78	2	7	1	1-1-5
	114	7.5	92.5	83.3	42.8	6.4	6.0	6.2	19	120	1	3	5	1-11-16

Table 15 **Pinyon tree weights**

Diameter class	Tree no.	Green Weight							Dry Weight						
		> 3	1-3	¼-1	< ¼	F	D	Total	> 3	1-3	¼-1	< ¼	F	D	Total
(cm)		(kg)													
< 10	85	0.0	1.7	1.1	1.1	2.1	0.15	6.1	0.0	0.99	0.47	0.59	[illegible]	0.13	3.3
	87	0.0	1.8	.78	.83	1.5	.07	5.0	0.0	.95	.38	.45	.82	.06	2.7
	97	0.0	1.5	.96	.96	1.9	.21	5.5	0.0	.82	.44	.52	1.0	.19	3.0
	105	0.0	0.0	.32	.08	.15	.02	.57	0.0	0.0	.20	.04	.07	.02	.33
10-20	1	5.0	6.8	7.8	7.2	14.9	0.5	42.2	2.5	3.2	3.5	3.5	[illegible]	0.4	20.2
	5	10.6	19.1	7.6	16.5	27.6	.9	82.3	5.7	10.6	3.9	7.9	13.2	.8	42.1
	9	8.5	2.3	3.0	4.5	9.6	.9	28.9	4.4	1.1	1.0	2.2	4.7	.7	14.2
	17	16.3	5.9	5.9	9.8	20.2	1.8	59.9	9.7	3.2	2.6	4.9	10.2	1.6	32.1
	23	16.7	11.3	5.3	8.6	17.0	1.8	60.7	8.7	5.7	2.3	4.2	8.4	1.6	31.0
	27	45.8	9.1	11.9	9.8	21.3	.9	98.9	24.1	4.5	5.2	5.1	11.0	.8	50.7
	32	40.1	18.2	14.6	18.4	40.0	.9	132.2	20.5	8.8	6.6	8.6	18.6	.8	63.9
	41	25.8	14.1	23.2	20.8	45.4	1.4	130.6	14.0	7.1	10.6	9.9	21.6	1.1	64.4
	46	36.1	14.1	8.4	11.2	21.2	5.9	96.9	21.1	8.3	4.3	5.5	10.3	5.5	54.9
	51	28.3	5.5	4.4	6.2	15.3	4.5	64.6	18.5	3.2	2.4	3.3	7.8	4.2	39.3
	60	19.7	11.3	13.1	10.6	23.5	5.9	84.1	11.2	6.2	7.4	5.1	11.3	5.3	46.6
	66	39.2	15.4	15.9	6.6	16.9	4.5	98.6	22.1	7.7	7.2	3.0	7.6	4.1	51.6
	77	16.8	7.3	3.2	19.6	31.0	2.7	80.7	9.0	3.8	1.6	9.7	15.4	2.5	42.0
	86	12.0	5.0	4.4	6.1	14.4	.8	42.8	6.6	2.4	2.2	3.2	7.7	.7	23.0
	93	13.9	9.5	3.5	6.5	7.2	3.2	43.8	7.5	5.1	2.0	3.3	3.7	2.9	24.3
	95	7.1	5.4	4.2	4.2	8.4	1.4	30.7	4.1	3.0	2.0	2.2	4.5	1.2	17.0
	98	7.7	5.9	4.3	4.3	8.7	3.2	34.1	4.7	3.6	2.0	2.3	4.6	2.9	20.0
	100	2.4	3.4	1.9	1.6	4.1	1.4	14.8	1.7	2.2	1.0	.8	2.0	1.3	8.9
	109	5.0	6.3	8.6	4.4	17.4	.8	42.6	2.7	3.2	3.7	2.1	8.2	.7	20.6
20-30	2	85.1	40.9	25.4	30.1	43.0	6.8	231.3	44.4	20.8	10.7	15.2	21.7	5.3	118.0
	7	16.7	35.4	17.7	22.6	30.9	2.3	125.6	9.0	19.4	8.3	10.9	14.9	1.8	64.2
	10	78.7	27.2	23.3	30.8	58.0	22.2	240.2	42.4	13.3	10.2	15.9	30.0	18.0	129.9
	18	35.8	27.2	19.1	31.6	47.3	6.4	167.4	20.5	14.7	8.9	16.3	24.5	5.5	90.5
	21	91.7	62.3	17.4	34.4	55.2	15.4	276.4	57.2	39.8	10.2	17.8	28.5	13.1	166.7
	25	134.1	72.1	34.5	44.1	73.8	11.3	369.9	72.4	38.1	23.3	21.3	35.7	10.4	201.3
	34	56.2	33.1	22.9	24.0	46.5	5.4	188.2	29.6	17.5	10.0	11.0	21.4	5.0	94.7
	39	36.3	50.0	37.5	41.5	66.1	2.3	233.7	18.3	25.4	16.5	20.9	33.3	2.0	116.4
	45	56.0	28.6	21.1	24.9	38.7	10.0	179.4	32.8	17.8	11.0	11.6	18.0	9.4	100.8
	52	155.1	24.1	15.1	15.3	29.0	52.2	290.8	96.5	14.1	8.3	7.3	13.9	43.6	183.7
	62	137.1	94.8	42.8	50.6	88.0	21.3	434.7	76.6	54.7	24.1	24.4	42.4	18.7	240.9
	64	71.4	32.7	22.1	27.6	41.1	15.9	210.7	39.7	19.0	12.5	13.6	20.2	14.6	119.5
	71	92.3	60.8	41.1	45.9	73.2	5.4	318.7	50.6	33.7	20.3	23.1	36.9	5.0	169.5
	84	74.7	22.7	12.0	16.9	16.5	7.7	150.5	40.5	11.5	6.0	9.3	9.1	6.0	82.4
	94	113.2	59.0	27.0	39.9	66.5	9.1	314.6	58.6	33.7	14.0	20.7	34.6	8.2	169.8
	101	69.5	15.0	13.3	7.0	12.8	9.6	127.2	44.3	9.0	6.8	3.5	6.4	8.6	78.5
	110	67.1	74.9	45.7	49.0	94.5	9.5	340.6	46.0	35.5	19.8	23.0	44.4	7.9	176.6
30-40	3	224.8	172.2	49.0	64.3	93.1	42.6	646.0	122.6	100.0	25.7	32.0	46.3	35.9	362.4
	8	77.1	100.4	49.0	54.4	89.8	10.9	381.6	40.6	54.9	22.4	28.9	47.8	9.1	203.8
	13	258.5	29.6	20.6	16.6	43.1	78.9	447.3	155.8	18.7	10.7	8.1	21.1	65.9	280.4
	20	157.7	64.6	32.2	36.1	80.9	29.5	401.0	97.6	41.2	18.4	17.0	38.1	25.2	237.4
	22	347.3	138.7	56.8	56.3	94.6	89.8	783.5	200.2	84.6	31.6	28.4	47.8	75.2	467.8
	36	293.3	110.3	81.6	54.7	108.7	47.2	695.7	170.7	67.9	47.5	25.5	50.7	40.7	403.1
	38	347.0	175.9	97.5	48.5	156.1	55.3	880.3	195.3	104.3	53.0	23.9	76.9	48.2	501.7
	44	272.0	150.5	55.9	83.3	119.8	47.2	728.7	163.4	94.6	33.6	39.5	56.7	41.8	429.6
	53	471.3	162.1	55.3	70.6	97.2	95.2	951.8	272.9	98.3	32.0	34.2	47.1	79.0	563.6
	63	256.5	84.5	43.3	45.6	84.3	31.3	545.5	137.7	46.6	21.7	21.9	40.4	28.7	296.9
	67	247.5	83.5	71.1	47.6	79.5	70.3	600.0	141.9	48.2	35.5	22.1	36.9	62.1	346.9
	73	339.0	90.4	42.6	69.0	96.9	35.4	673.4	180.0	50.3	20.3	33.8	47.5	31.3	363.3
	89	177.9	64.5	42.3	32.5	47.7	25.4	390.2	96.1	38.7	23.6	18.1	26.6	21.6	224.7
	90	199.5	59.9	45.9	42.8	80.9	15.4	444.5	102.8	32.6	24.1	22.6	42.7	13.6	238.3
	96	277.8	131.6	69.8	57.5	148.5	35.8	721.1	149.5	72.0	36.6	30.4	78.5	32.3	399.4
	103	190.1	18.6	14.0	17.2	29.6	37.2	306.7	115.8	10.8	7.4	8.8	15.1	34.0	191.9
	108	85.1	62.6	37.9	44.7	75.2	7.7	313.3	42.5	31.5	17.6	21.4	36.0	7.0	156.0

Table 15.--con

Diameter class	Tree no.	Green Weight							Dry Weight						
		> 3	1-3	¼-1	< ¼	F	D	Total	> 3	1-3	¼-1	< ¼	F	D	Total
(cm)		*(kg)*													
40+	4	471.9	260.7	96.1	153.6	192.5	49.0	1223.8	205.8	144.4	44.7	72.2	90.5	41.0	598.7
	6	221.8	163.1	50.7	93.9	202.0	24.9	756.4	117.3	89.6	24.2	28.8	61.9	21.1	343.0
	14	1128.1	178.2	73.8	78.9	210.1	268.5	1937.7	641.1	115.7	40.2	38.9	103.6	224.4	1163.9
	19	782.7	200.0	70.1	96.4	256.2	105.2	1510.7	460.7	121.0	38.6	46.6	123.7	92.8	883.3
	24	884.9	247.7	102.2	99.0	179.4	87.1	1600.2	475.9	143.9	53.9	50.4	91.4	75.5	891.1
	26	440.7	232.6	114.2	118.7	207.1	24.9	1138.2	236.5	131.6	59.6	61.2	106.9	23.0	618.8
	29	653.2	146.3	62.2	93.4	140.1	101.2	1196.4	363.7	80.4	31.2	46.7	70.0	98.1	690.3
	37	346.5	103.8	93.7	91.7	159.8	73.0	868.5	200.0	65.2	55.0	46.2	80.6	63.2	510.1
	43	852.0	175.7	137.5	112.5	223.6	165.6	1666.9	492.1	105.0	79.8	51.7	102.7	150.1	981.4
	56	1685.9	227.9	117.6	130.5	177.4	314.3	2653.6	1086.2	139.7	63.9	68.0	92.4	295.2	1745.4
	65	622.1	187.5	101.9	75.9	125.1	80.3	1192.8	371.2	100.8	50.0	36.6	60.3	72.4	691.3
	75	1092.3	231.1	159.6	117.8	226.0	92.1	1918.9	595.7	121.2	80.5	58.5	112.3	80.5	1048.8
	88	366.2	73.2	31.8	44.7	78.2	46.3	640.4	197.6	45.1	17.4	24.3	42.5	40.5	367.3
	91	3725.4	365.0	126.3	137.1	260.0	452.7	5066.5	2220.0	243.6	78.3	72.0	136.4	386.9	3137.2
	92	1560.0	236.5	132.3	123.7	277.0	236.8	2566.2	994.7	146.2	75.6	62.6	140.2	216.7	1636.1
	99	1152.2	152.1	70.1	63.8	235.3	234.1	1907.6	719.6	92.1	38.8	32.2	119.0	210.5	1212.4
	102	484.1	73.6	46.0	24.8	57.6	91.2	777.2	305.7	43.5	24.7	12.3	28.6	80.8	495.6
	104	932.4	138.5	70.1	77.1	145.8	158.3	1522.2	571.0	85.0	40.9	38.5	72.8	138.5	946.6
	111	306.9	142.0	68.0	77.5	149.3	29.5	773.2	158.7	71.3	31.3	35.6	68.7	26.9	392.5

Table 16.--**Juniper tree weights**

Diameter class	Tree no.	Green Weight							Dry Weight						
		> 3	1-3	¼-1	< ¼	F	D	Total	>3	1-3	¼-1	< ¼	F	D	Total
(cm)		(kg)													
10-20	15	11.9	3.6	6.6	2.5	12.3	0.0	37.0	5.4	1.6	2.5	1.4	7.0	0.0	18.0
	35	31.3	22.3	9.1	5.9	28.1	3.6	100.3	15.2	10.9	4.5	3.6	17.1	3.2	54.5
	47	17.1	10.0	6.7	4.0	27.4	1.4	66.6	8.9	4.9	3.3	2.3	16.0	1.2	36.7
	50	9.8	5.9	8.0	3.8	15.4	.9	43.8	4.9	2.9	4.0	2.2	8.9	.8	23.7
	59	12.6	7.7	4.8	2.9	14.5	.9	43.4	7.3	3.9	2.3	1.6	8.0	.8	23.8
	68	3.8	4.5	1.9	1.6	10.2	0.0	22.0	1.9	2.3	.9	.9	5.8	0.0	11.7
	72	12.2	11.3	8.3	4.3	21.4	0.0	57.5	5.8	5.4	41.	2.6	12.7	0.0	30.6
20-30	11	60.2	33.1	6.7	16.6	54.3	3.6	174.5	34.1	17.3	3.5	9.4	30.8	3.2	98.4
	16	24.7	6.8	5.1	5.5	20.8	0.0	63.0	11.7	3.4	3.0	3.2	12.4	0.0	33.7
	28	33.6	39.9	16.3	12.5	43.3	.4	146.1	15.3	18.9	7.8	7.4	25.6	.3	75.5
	30	21.3	15.9	13.0	5.9	25.6	.9	82.6	12.1	8.6	6.3	3.4	14.6	.8	45.8
	42	28.2	26.8	22.5	9.4	48.4	.4	135.7	13.4	12.6	10.6	5.3	27.4	.4	69.8
	54	46.1	42.2	20.3	11.0	68.9	6.8	195.4	22.0	22.9	10.2	5.5	34.6	6.0	101.3
	58	54.0	18.2	10.4	6.5	39.3	3.6	132.0	29.0	9.1	4.6	3.6	21.5	3.3	71.1
	74	38.7	31.8	20.4	9.1	45.7	5.4	151.3	22.2	19.2	11.8	5.5	27.5	5.1	91.4
30-40	33	81.6	60.4	23.3	13.7	60.9	6.4	246.3	39.4	29.5	11.7	7.5	33.6	5.0	126.8
	49	113.6	74.5	25.6	12.6	118.7	17.7	362.7	56.8	37.6	12.9	7.2	67.9	15.0	197.5
	61	54.3	30.0	15.4	8.0	45.1	10.4	163.2	31.6	16.9	8.6	4.5	25.0	9.0	95.6
	70	16.0	31.4	16.7	6.4	27.3	4.5	102.3	9.3	17.3	8.7	3.4	14.4	4.1	57.2
	78	115.4	90.9	68.5	21.5	94.6	10.0	400.8	60.6	43.4	33.6	12.5	55.2	9.0	214.4
	112	42.5	66.7	33.7	10.0	74.2	2.7	229.9	19.1	30.9	16.0	5.2	38.7	2.4	112.3
	113	8.7	17.7	11.8	6.8	34.5	3.2	82.8	4.9	9.5	6.2	3.6	18.4	3.0	45.5
40+	12	267.0	118.1	38.2	20.4	114.7	15.0	573.4	131.8	61.6	20.1	12.0	67.5	11.5	304.5
	31	133.0	80.0	46.1	15.6	100.2	25.4	400.4	70.6	43.1	25.0	8.9	56.8	23.0	227.4
	40	131.9	125.4	61.5	38.6	129.0	8.1	494.5	60.0	58.0	28.6	22.6	75.4	6.4	251.0
	48	81.3	101.7	52.1	17.6	125.3	31.8	409.8	39.3	49.7	27.3	10.3	73.2	26.0	225.9
	55	164.4	96.3	55.8	20.1	123.2	9.1	468.9	79.0	49.1	27.3	11.5	70.8	8.2	245.9
	57	860.1	167.1	71.5	39.5	273.2	143.3	1554.7	523.5	99.2	40.3	21.0	145.5	126.8	956.3
	69	294.4	137.1	61.7	31.5	132.7	63.0	720.4	173.7	75.7	32.2	18.6	78.5	57.0	435.8
	76	342.5	120.8	68.9	27.9	166.4	37.2	763.6	186.2	65.5	37.0	16.2	96.7	34.7	436.2
	106	227.8	109.8	49.2	11.7	113.3	7.7	519.5	101.2	51.2	23.6	6.7	64.8	7.1	254.7
	107	223.9	123.9	92.0	26.0	136.0	7.7	609.5	108.4	54.9	41.5	15.0	78.6	7.0	305.5
	114	315.7	174.4	75.9	32.5	195.1	21.3	814.9	154.3	82.9	36.2	17.1	102.4	19.2	412.0

Miller, E. L., R. O. Meeuwig, and J. D. Budy.
1981. Biomass of singleleaf pinyon and Utah juniper. USDA For. Serv. Res. Pap. INT-273, 18 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Biomass determinations in singleleaf pinyon (*Pinus monophylla*) - Utah juniper (*Juniperus osteosperma*) stands in Nevada indicate that stem diameter and average crown diameter are the tree measurements most highly correlated with ovendry weights. The equations and tables developed provide a means for estimating the total aboveground biomass as well as the weights for the various size fractions by species. The tables can also be used to estimate the cordwood and slash resulting from fuelwood harvesting operations.

KEYWORDS: biomass, weight, Utah juniper (*Juniperus osteosperma*) singleleaf pinyon (*Pinus monophylla*), prediction equations, weight tables

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The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

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**Intermountain
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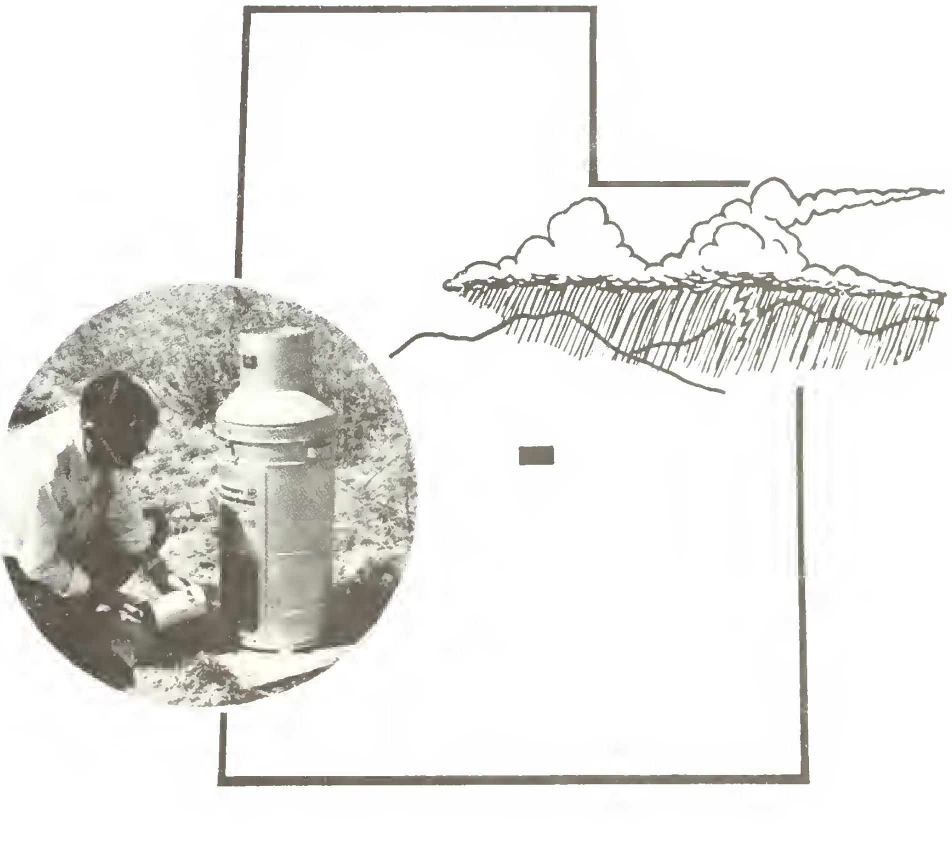
Precipitation Characteristics of Summer Storms at Straight Canyon Barometer Watershed, Utah

Joel E. Fletcher, A. Leon Huber, Eugene E. Farmer, Keith R. McLaughlin, John Rector, and Larry J. Schmidt



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RESEARCH SUMMARY

This paper presents results of data analyses for 10 precipitation intensity stations at Straight Canyon barometer watershed in central Utah located at elevations between 7,250 ft (2 210 m) and 10,400 ft (3 170 m) m.s.l. All data were collected between 1967 and 1974 during the months of May to October, with all records complete for July, August, and September.

The following analyses were made: (1) record consistency, (2) definition of local precipitation zones, (3) intensity-duration-frequency characteristics, (4) 24-hour precipitation depths, (5) monthly depths and numbers of storms, (6) storm occurrence by time of day, (7) storm occurrence by storm duration, (8) annual maximum erodent values for Straight Canyon gages, Davis County experimental watershed, and Great Basin experimental area. The precipitation zone between 7,000-8,000 ft (2 134 - 2 438 m) m.s.l. is expected to receive the highest rainfall intensities. Rainfall intensity decreases with elevation. The zones receiving the greatest rainfall receive the lowest intensities. The major portion of storms occur between the hours of 11:00 a.m. and 3:00 p.m. Eighty percent of the storm have durations shorter than 2.8 hours, with the highest elevations having the shortest durations. Erodent values are inversely proportional to the elevation and penetration past the uplift barrier. The use of erodent values is described.

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Precipitation Characteristics of Summer Storms at Straight Canyon Barometer Watershed, Utah

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INTRODUCTION

Precipitation records in high mountain areas are scanty. In Utah and the balance of Western United States nearly all of the rainfall intensity gages are located at elevations below 6,000 ft (1 829 m) m.s.l. Even in the valleys most of the recording rain gage records have not been reduced except by hours.

The papers of Farmer and Fletcher (1971, 1972a, 1972b), Chang (1969), and Croft and Marston (1950) have been given considerable insight into the characteristics of high mountain, short-burst rainfall events. Miller and others (1973) improved the isohyetal maps of the Western United States and included regressions for determining short duration expectancies from those for 6 hours for returns between 2 years and 100 years.

Personnel of the Utah Water Research Laboratory and Intermountain Forest and Range Experiment Station (1976) developed annual isoerodent maps of the United States including the Mountain States, in order to extend the universal soil loss equation to all areas of the country. As a consequence of the availability of these maps, the use of isoerodent values for runoff peak forecasting was tested and the annual isoerodent values were found to be the most pertinent precipitation parameter for forecasting runoff peaks from ungaged watersheds (Fletcher and others 1976).

This paper presents an extension of Farmer and Fletcher (1971) to include 10 precipitation gages of the Straight Canyon barometer watershed area and the isoerodent values for the Straight Canyon area, the Davis County area, and the Great Basin experimental area.

All precipitation gages were operated during June through September and four were operated from April through October. Gages were at elevations ranging from 7,235 ft (2 205 m) m.s.l. for the Orange Olsen site to 10,400 ft (3 170 m) m.s.l. for the Skyline site. The gages were sufficiently close to one another that single storms were frequently recorded on more than one precipitation gage.

The Straight Canyon barometer watershed is located 12 miles W.N.W. of Orangeville, Utah, immediately adjacent to the Great Basin experimental watershed. It lies up the left fork of Cottonwood Creek and occupies an area of about 145 square miles. Elevation ranges between 6,852 ft (2 088 m) and 11,300 ft (3 444 m) m.s.l. The description given by Farmer and Fletcher (1971) of the Great Basin experimental area is also applicable to the Straight Canyon barometer watershed.

Total annual rainfall ranges from 16.10 inches (40.89 cm) at Lower Joes Valley to slightly over 40 inches (102 cm) on the three peaks (U.S. Weather Bureau 1967). Approximately 44 percent of the precipitation falls during the period May to September.

Summer precipitation contributes little water to the annual stream flow volume, but it is important to the production of mountain vegetation that is vital to soil stability (Packer 1951; Orr 1957; Packer 1963; and Croft and Bailey 1964), however, vegetal cover is only one factor that affects the hydrologic performance of a watershed. Storm characteristics also have a major effect on the processes of soil erosion and flood production, especially when the land becomes barren of vegetal cover due to fire, road construction, overgrazing, or urban development.

A storm was defined for this study as a period of precipitation, uninterrupted for a period exceeding 1 hour, delivering at least 0.10 inch (2.5 mm) of water. Most of these storms were convective thunderstorms and frontal thunderstorms aided through orographic lifting. Summer convective cells, often associated with lightning, usually approach from the south or southwest, which is the direction of the prevailing wind of that season. Some of the storms that delivered the greatest intensity of rainfall were probably of a type that has been termed orographic-convective. The primary source of summer moisture aloft comes from the Pacific Ocean (Hales 1972, 1973). A small proportion of the total storms comes from large frontal systems.

Summer convective storms delivering very high-intensity rainfall have been the source of destructive debris floods. Summer debris floods emanating from the Wasatch Range were particularly destructive (Bailey and others 1934; Bailey and other 1947). These summer-flood flows took lives, destroyed property, and disrupted communities.

METHODS

Machine methods were used to digitize the original analog rainfall records. Compilation of the digitized records was done by computer. The final computer output for every storm consisted of both accumulated precipitation depth and rainfall intensity for the following 12 time durations: 2, 5, 10, 15, 20, and 30 minutes and 1, 2, 4, 6, 12, and 24 hours. The computer output also included the total precipitation depth for every month as well as a yearly summary of maximum depth and intensity.

Record Consistency

All of the records were checked for consistency by double-mass plotting (Searcy and Hardison 1960). This technique was applied to the combined depth records only for July and August because all of the gages were in operation during these months.

Frequency Analysis

A detailed annual series frequency analysis of rainfall intensity was made for every station. A separate analysis was made for each of the 12 time durations. The formula developed by Weibull was used to obtain plotting positions (Chow 1964):

$$T = \frac{n+1}{m}$$

where

T = recurrence interval, years
n = number of years of record
m = order number of the items arranged in descending order.

This formula has been found to be theoretically suitable for plotting annual maximum series on extremal distribution paper (Chow 1953).

Table 1.—Listing of precipitation intensity stations, Straight Canyon barometer watershed

Station	Location, fig. 1	Precipitation zone number	Period of record	No. of years	Elevation
					Feet
Horn Mountain	1	1	1967 - 1974	8	9,275
Bubs Meadow	2	1	1967 - 1974	8	8,150
Wagon Road Ridge	3	2	1967 - 1974	8	10,100
Seely Guard Station	4	1	1967 - 1974	8	8,990
Swasey Ridge	5	2	1967 - 1974	8	10,030
Skyline	6	1	1967 - 1974	8	10,400
Lower Black Canyon	7	3	1967 - 1974	8	7,765
Central Weather Station	8	1	1967 - 1974	8	9,020
Orange Olsen	9	1	1967 - 1974	8	7,235
Scad Valley	10	1	1967 - 1974	8	9,160

Table 2.—Average properties of the precipitation zones of Straight Canyon barometer watershed

Precipitation zone	Average elevation	Average I_{10}/I_2	Average penetration	Average R	Average R_{10}/R_2	Vegetation type
	Feet		*Miles*			
1	8,890	1.98	29.1	12.5	3.8	Conifer-aspen
2	10,065	3.11	26.7	13.9	8.1	Grass
3	7,765	2.98	27.7	16.7	4.1	Grass-sage

Precipitation Zones

Peck and Brown (1962) divided Utah into 20 precipitation regions. They found that a large amount of the variation between regions in the May-September precipitation was accounted for by elevation. All of our data are point data. Consequently, we had to define criteria for dividing the study areas into homogeneous zones in order to make areal application of these point data.

The three criteria used were: (1) station elevation; (2) the values from the station intensity-duration-frequency curve; and (3) the station I_{10}/I_2 ratio for all durations between 2 and 30 minutes (fig. 1, tables 1 and 2). The latter is a dimensionless ratio that expresses the average slope of the short-duration rainfall intensity curves between 2 and 10 years. This ratio was computed by dividing the summation of intensities having durations of 2, 5, 10, 15, 20, and 30 minutes for the 10-year recurrence interval by the comparable summation for a recurrence interval of 2 years. Any region that is homogeneous with respect to its rainstorm characteristics should have frequency curves of about equal slope or steepness. Consequently, the I_{10}/I_2 ratio is useful statistic for comparing the slopes of frequency curves as a basis for judging homogeneity of precipitation zones.

24-Hour Precipitation Depth

The intensities for the 24-hour duration were converted to precipitation depths for recurrence intervals of 10, 25, and 50 years. Twenty-four hours was the longest duration examined in this study.

Average Monthly Depth and Number of Storms

Analyses for the average monthly depth of precipitation and the average number of storms per month are complete only for June-September. At the highest elevation stations, the data for May and October were insufficient to compute a reliable monthly average

Storm Occurrence by Hour

Storm occurrence by hour was analyzed by compiling the number of storms starting in any hour of the day expressed as a percent of the total storms. These data were plotted as a mass curve for each zone

Storm Penetration

Storm penetration is a measure of the distance a storm travels downwind from the first uplift barrier, in this case the Wasatch and Pavant Mountain Ranges. The greater the penetration, the less precipitation falls at a given elevation.

Erodent, R, Values

The erodent values for each precipitation station were calculated from the unit intensity and volume by the relationship:

$$EI = \sum_{0}^{yr} \left(\frac{916 + 331 \log I}{100} \times P \right) \times I_{30}$$

where

EI = rainfall erosivity index for 1 year or other period

I = rainfall intensity for a short unit of time

P = volume of precipitation in the same unit of time

I_{30} = the annual maximum, or other period as for EI, 30-minute rainfall intensity

R = the mean annual EI value as derived from a frequency plot of annual EI values. (See Wischmeier and Smith 1958.)

Figure 1 —Map of Straight Canyon barometer watershed Utah showing zones and gages

Storm Duration

The duration of all storms at all precipitation gages was divided into 0.25-hour units and the frequency in each group recorded and expressed as a percentage of the total number of storm events. These percentages were plotted against the unit of duration in which each occurred.

RESULTS

Consistency Test

The records were not adjusted. None of the mass curves plotted as smooth straight lines and isolated points fluctuated both above and below the trend line. Even so, the breaks in the lines didn't persist for a period as long as 5 years. The breaks in the lines were considered to be no greater than might reasonably be expected for thunderstorm data obtained from mountainous areas. Furthermore, none of the differences between the first and second half of the records were significant so the records could be said to be consistent.

Precipitation Zones

Within the study area the precipitation zones are related to the vegetal patterns (table 2), as was noted by Farmer and Fletcher (1971), even though the contrasts in vegetal types are not as great at Straight Canyon as on the Davis County or Ephraim watersheds.

Intensity-Duration-Frequency Characteristics

The curves in figures 2, 3, and 4 are for recurrence intervals of 2 to 50 years and storm durations between 2 minutes and 24 hours. All return period intensity values for 10 years and longer were determined by linear interpolation. As such, these must be used with caution. Also, the recurrence interval is the average interval during which an intensity of a given duration will recur as an annual seasonal maximum.

Snow may have occurred during any month of the year at the higher elevations, and thus was probably caught in all of the higher elevation gages. There is little doubt, however, that values for periods shorter than 2 hours and recurrence intervals longer than 10 years are from rainfall events.

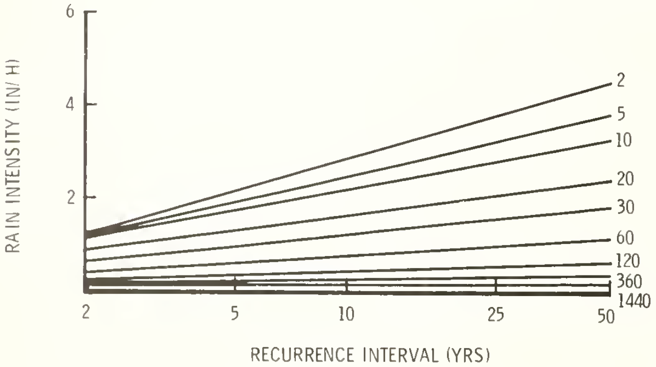

Figure 2.—Rainfall intensity-duration-frequency curves for Straight Canyon barometer watershed, Utah, zone 1.

The rainfall intensities in each precipitation zone are appreciably different from those in any other zone. For example, for a duration of 2 minutes and 2-year recurrence, the intensity is 1.20 in (30 mm)/h for zone 1, 0.30 in (8 mm)/h for zone 2, and 1.65 in (4.2 mm)/h for zone 3. At a 50-year recurrence, the 2-minute intensities become 4.52 in (118 mm), 7.65 in (194 mm), and 13.50 in (343 mm)/h, respectively. The 50-year/2-year ratios for a 2-minute duration become 3.77 in (96 mm), 25.5 in (648 mm), and 8.18 in (208 mm)/h for zones 1, 2, and 3, respectively.

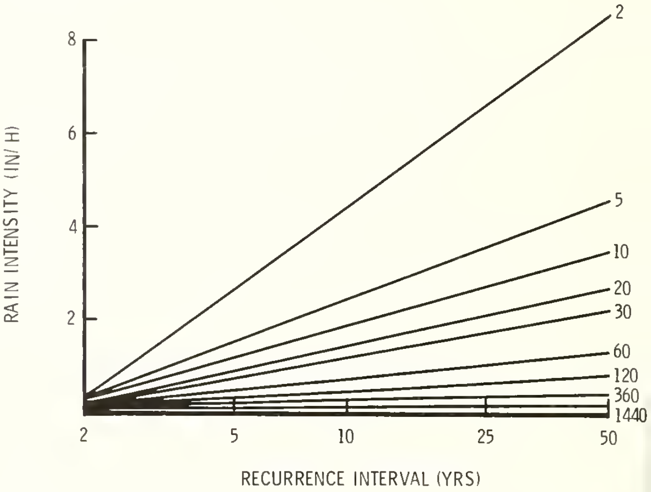

Figure 3.—Rainfall intensity-duration-frequency curves for Straight Canyon barometer watershed, Utah, zone 2.

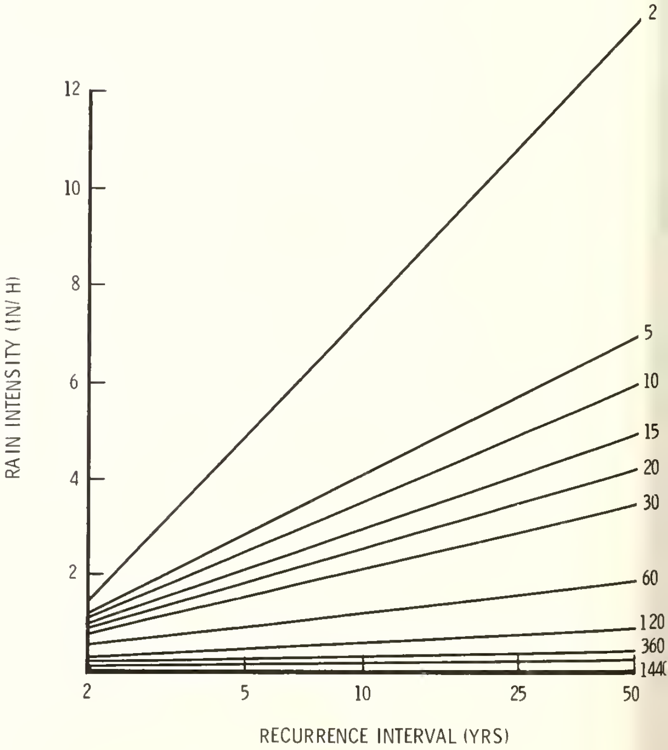

Figure 4.—Rainfall intensity-duration-frequency relationship curves for Straight Canyon barometer watershed, Utah, zone 3.

24-hour Precipitation Depth

Only 4 percent of the storms at the Straight Canyon barometer watershed have durations longer than 7 hours. However, the longer duration storms are of interest in the design of contour trenches and road drainage devices. Storms of long duration rarely produce floods in this area.

The 24-hour volumes were tabulated for the three zones for recurrences of 10, 25, and 50 years and are presented in table 3. As would be expected, considering the penetration distance from the mountain front the 14-hour precipitation volumes are smaller than the volumes for either Davis County or Ephraim experimental areas.

Average Monthly Depth and Number of Storms

The monthly precipitation depths were determined from gage catch. We hoped that these data could assist in clarifying the mountain-valley precipitation relationships when used in conjunction with intensity-duration-frequency characteristics.

Monthly precipitation fluctuates widely between zones and between years. Any month during the period May-October may be completely dry at one or more precipitation stations. Also, any month may exceed the average threefold to sevenfold.

The average number of storms during each month and within each zone varies widely as does the monthly volumes of precipitation (table 4). These values resemble those for the Great Basin experimental area (Farmer and Fletcher 1971). The expected relation between a valley station, Castle Dale, was of a relatively low order. Furthermore, the most intense rains occurred in zone 3 while the greatest monthly volume fell in zone 2. This distribution confirms the significant correlation between elevation and monthly rainfall volume. Figure 5 illustrates the seasonal precipitation volumes for the three zones and Castle Dale, which is in the valley just below Straight Canyon barometer watershed. Indications with these incomplete data confirm the September dry season mentioned by Price and Evans (1937) for the Great Basin experimental area, but certainly there is no dry spot in June although the summer season does appear to be bimodal. Our analysis shows a low precipitation volume for July and September at Straight Canyon barometer watershed as well as at Ephraim experimental area and Davis County experimental watershed.

Table 3.—Expected annual seasonal maximum 24-hour precipitation depths (inches) by precipitation zones and recurrence intervals

Zone	Recurrence interval (years) 10	25	50
		Straight Canyon barometer watershed	
1	1.50	1.83	2.08
2	1.48	1.79	2.03
3	1.37	1.70	1.97
		Davis County experimental watershed	
1	2.21	2.54	2.74
2	2.04	2.38	2.45
3	1.44	1.87	2.11
4	1.54	1.87	1.97
		Great Basin experimental area	
1	1.15	1.30	1.34
2	1.49	2.16	2.47
3	1.70	2.16	2.33
4	1.39	1.66	1.70

Table 4.—Precipitation depth (inches) and number of storms by month and zone, Straight Canyon barometer watershed

Month	Zone 1 Depth	Zone 1 Number	Zone 2 Depth	Zone 2 Number	Zone 3 Depth	Zone 3 Number
July	1.17	5.4	1.46	5.2	1.10	6.1
August	1.25	7.9	1.57	10.3	1.18	8.0
September	0.81	3.1	0.74	3.9	0.70	2.3

The summer precipitation burst is considered to be a reflection of the summer Gulf of California monsoonal storms as well as orographic convection. The monsoonal storms generally peak during August but may occur in the period June through October.

Storm Occurrence by Hour

On the average, storms occur on the Straight Canyon barometer watershed most frequently between 1100 and 1300 hours. Figure 6 shows the percentage of storms occurring during each period of the 24-hour day. Note that few storms occur between 2100 and 900 hours. This observation agrees with the distributions found on the Great Basin experimental area (Farmer and Fletcher 1971). Both these curves differ significantly from the curves for Davis County.

The concentration of the storms in the afternoon is expected because convection must trigger the monsoonal storms as well as orographic convective storms.

Storm Penetration

The storm penetration distances in miles downwind from the Wasatch-Pavant fronts for each gage on the Straight Canyon barometer watershed are shown in table 2. A good, simple correlation with a log-log transform exists between the miles of penetration and 10-year, 10-minute precipitation intensity. The correlation coefficient, $r^2 = 0.59$, is significant at the 1 percent probability. When all gages are included in the relationship, the gages on the windward slopes dominate the relationship and the correlation reverses to become significantly negative at the 5 percent probability level.

Within Straight Canyon the 10-year, 10-minute rainfall intensity increases from 1.55 in (39 mm) to 2.85 in (72 mm) per hour as penetration increases from 20 to 30 miles. On the other hand when all three locations are in the regression, the 10-year, 10-minute precipitation intensity decreases from 3.00 in (76 mm) per hour at 0.7 miles to 2.30 in (58 mm) per hour at 30 miles.

Erodent Values, R

The mean annual EI values for the three locations may be seen in tables 2 and 5 for each of the precipitation zones. Since R values are determined from log probability plots of the annual EI values, it is important to know not only the R or mean annual (2-year) EI value but the slope of the line that was used in the rainfall frequency depth curves. The ratio of the 10-year EI value to the 2-year (R_{10}/R_2) gives this slope. Then an EI value for any frequency greater than the mean annual value (R_2) can be determined.

For periods of time shorter than 1 year the curves as a percentage of the mean annual R value are of use. Figure 7 shows the monthly percentage of the annual R value that occurs from the beginning of the season to each date to the end of the season for each of the three precipitation zones of the Straight Canyon barometer watershed. Figure 8 shows the same data for the Great Basin experimental area zones and figure 9 shows the same data for the Davis County experimental watershed zones.

Use of R Values

Wischmeier and Smith (1958) presented a method for utilizing the R value as a parameter for estimating mean annual erosion east of the Rocky Mountains. Utah State University and Intermountain Forest and Range Experiment Station (1976) extended the procedure to

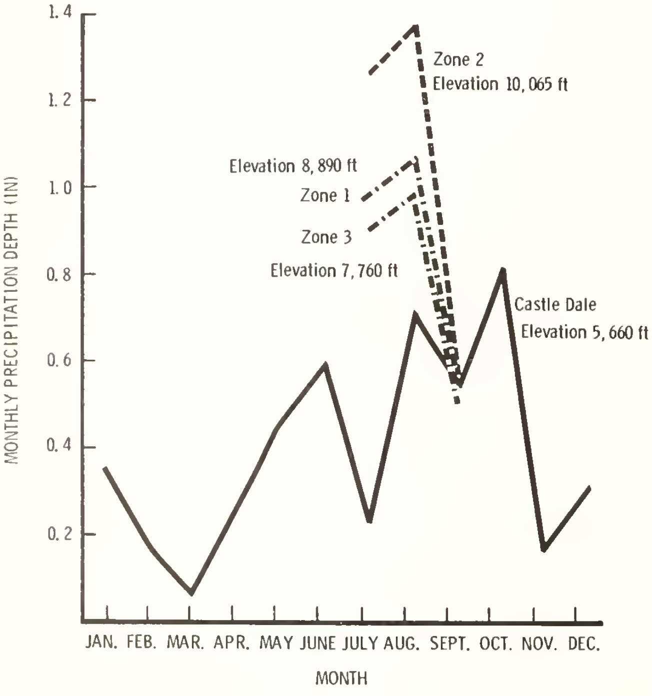

Figure 5.—The mean monthly precipitation depths for Straight Canyon barometer watershed zones 1, 2, and 3 and Castle Dale, Utah.

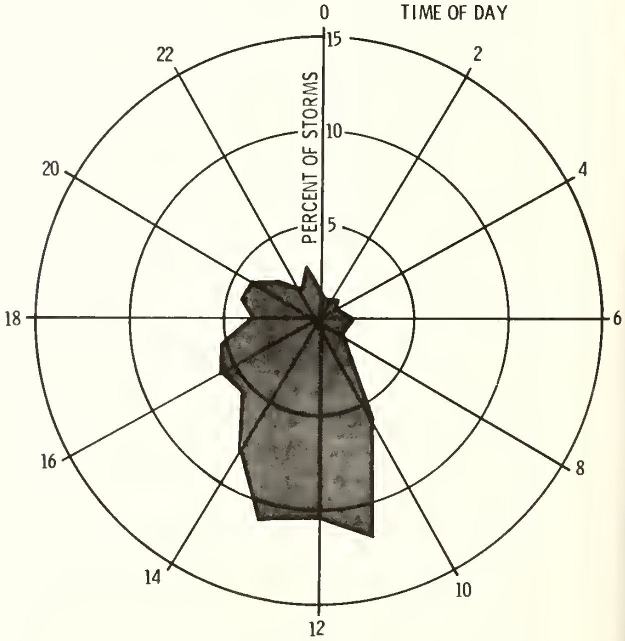

Figure 6.—The frequency distribution of storms by hour of the day at Straight Canyon barometer watershed, Utah.

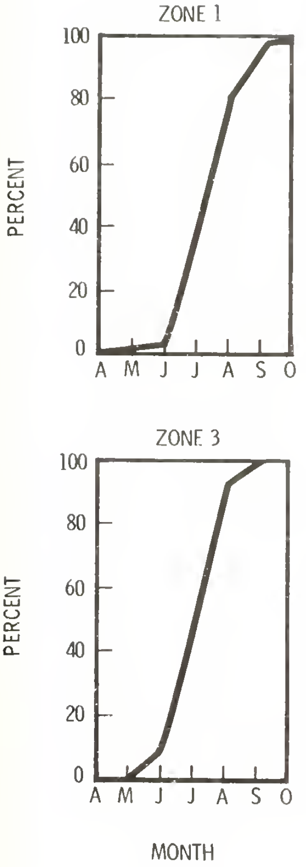

Figure 7.—The monthly erodent or rainfall erosivity values as a percentage of R for zones 1, 2, and 3 of Straight Canyon barometer watershed, Utah.

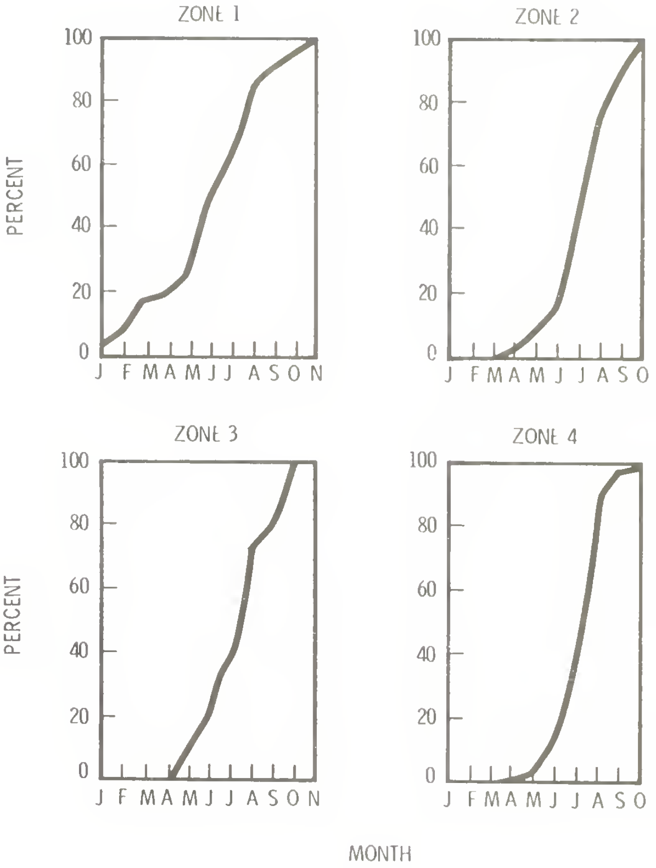

Figure 8.—The monthly erosivity values as a percentage of R for zones 1, 2, 3, and 4 for the Great Basin Experimental Area, Utah.

Table 5.—R values by precipitation zone for Davis County experimental watershed and Great Basin experimental area

Zone	Vegetation	R	R_{10}/R_2	I_{10}/I_2	Mean elevation
					Feet
		Davis County experimental watershed			
1	Oak brush	15.5	5.7	1.87	4,350
2	Aspen-fir	19.4	4.2	1.94	6,930
3	Spruce-fir	14.5	4.6	2.30	8,380
4	Spruce-fir	9.6	5.4	2.49	8,760
		Great Basin experimental area			
1	Pinyon-juniper	24.8	9.0	2.35	5,550
2	Oak brush	11.1	3.9	3.16	7,650
3	Aspen-fir	20.0	5.2	1.73	8,850
4	Spruce-fir	16.6	3.4	2.25	9,850

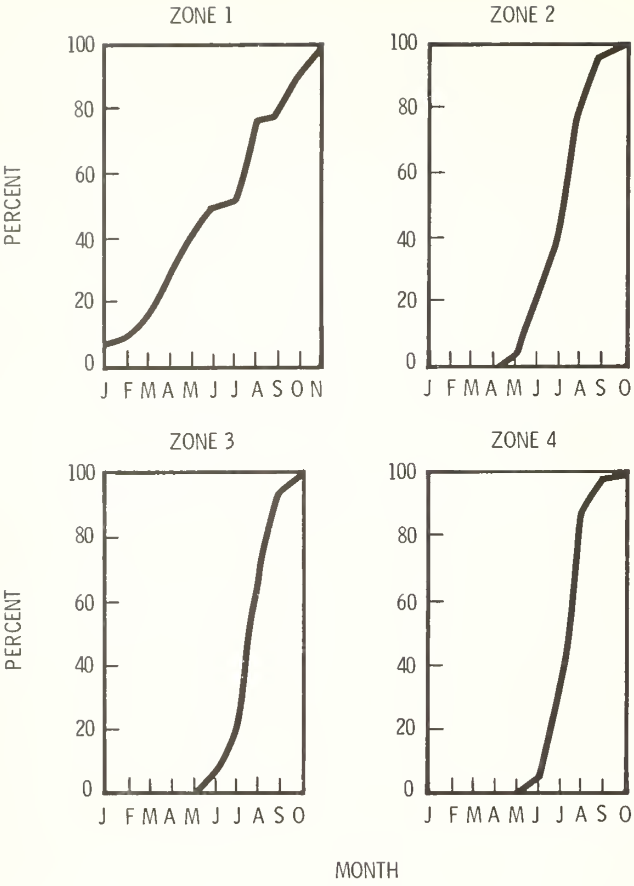

Figure 9.—The monthly values as a percentage of R for zones l, 2, 3, and 4 of Davis County experimental watershed, Utah.

the balance of the United States. Briefly, the method the mean annual erosion per acre, A, is equal to the product of R; an erodibility factor, K; a slope length factor, L; a slope steepness factor, S; and a cover practice parameter, CP.

The latter group also substituted VM for CP as more appropriate to nonfarm areas. The VM symbolizes vegetation management. All other treatments could be reduced to changing the values of slope or slope length, for example contour ditches, terraces, etc.

In the universal soil loss equation the values of L are in terms of the ratio of soil lost from a slope length of 72.6 feet (22 m) and the values of S are in terms of the ratio of the soil lost from a slope steepness of 9 percent gradient.

Example. A small homogeneous (soil, cover, and slope) area rectangular in shape has a slope length of 73 feet (22.3 m) and a gradient of 9 percent. There is 1 ton per acre (2.25 t/ha) of litter on the surface of the soil whose erodibility is 0.50. Is this sufficient protection to have less than 4 tons per acre (9 t/ha) of erosion if a 10-year event should occur? The R value is 31 and the R_{10}/R_2 is 8. Figure 10 shows the tons per acre (t/ha) of litter as related to the RKLS value that the mulch can withstand without failure or appreciable erosion.

Solution. Enter figure 10 with 1 ton/acre (2.25 t/ha) and read RKLS = 74. This is the RKLS the litter can safeguard if the VM value is 1.0.

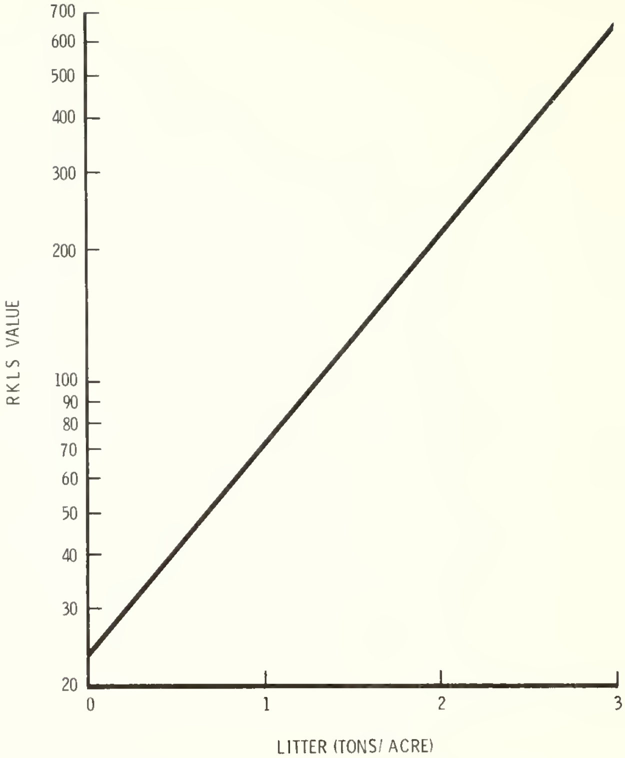

Figure 10.—The relationship between RKLS and the tons per acre of litter.

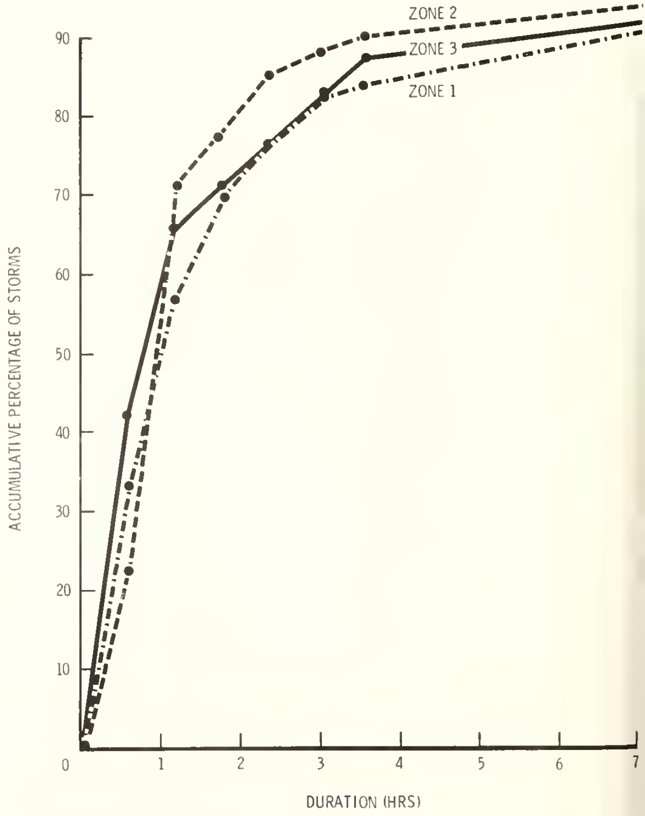

Figure 11.—The mass frequency distribution of storm duration in hours for zones 1, 2, and 3 of Straight Canyon barometer watershed, Utah.

The 10-year RKLS of the site may be determined as follows:

R = 31 × 8 = 248
K = 0.50
LS = 1
RKLS = 248 × 0.50 × 1.0 = 124

124 > 74; therefore this amount of litter will not protect the site if the litter is the only protection the site has. If in addition to the 1 ton per acre (2.25 t/ha) of litter, there is a 10 percent ground cover of grass and a 50 percent canopy of tall weeds, this would make the VM factor equal to 0.19, figure 11. The site RKLS would reduce VM to 0.19 × 124 = 23.6, thus fully protecting the site from the 10-year R.

R values have other uses. For example, suppose we needed the 10-year runoff peak from a 1-square-mile watershed whose difference in elevation between the top and bottom of the watershed was 1,000 ft (305 m) and the R value at the watershed center was 30, the equation developed by Fletcher and others (1977) could be used as follows:

$$\hat{q}_{10} = 1.28015\ A^{0.56172}\ R^{0.94356}\ (DH)^{0.16887}$$

The desired 10-year peak flow would then be

$$\hat{q}_{10} = 1.28015\ (1)^{0.56172}\ (30)^{0.94356}\ (1000)^{0.16887}$$
$$= 101.8\ ft^3/S\ (2886\ liters/sec).$$

Storm Occurrence by Storm Duration

The percentage of short durations is appreciably higher on the Straight Canyon zones than either at the Davis County experimental watersheds or the Ephraim experimental area. Figure 11 shows the cumulative frequency distribution of storm durations. The correla-ion between elevation and duration can be seen in the mean values for each zone where zone 1 mean eleva-on 9,045 ft (2 757 m) has 33 percent of the storms horter than 36 minutes, zone 2 mean elevation 10,065 (3 068 m) has 22 percent of the storms shorter than 36 minutes, and zone 3 elevation 7,765 ft (2 367 m) has 41 ercent of the storms shorter than 36 minutes. Inciden-ally, only one storm at one location lasted up to 15 ours.

STORM DURATION The duration distribution of the ,228 storm events on the Straight Canyon barometer atershed are shown in figure 12. The longest duration ecorded for any storm was 15 hours, with 90 percent of he storms having durations shorter than 5 hours and pproximately half of the storms having durations horter than 1 hour.

STORM DEPTHS The largest single storm depth as 1.50 in (38 mm). Figure 13 shows the frequency districution of the 1,228 storm depths. Note that more han 65 percent of the storms have depths smaller than 0.15 in (3.8 mm). The depth distribution of storms at Straight Canyon essentially fits a log normal distribu-on as evidenced by the straight line in figure 13.

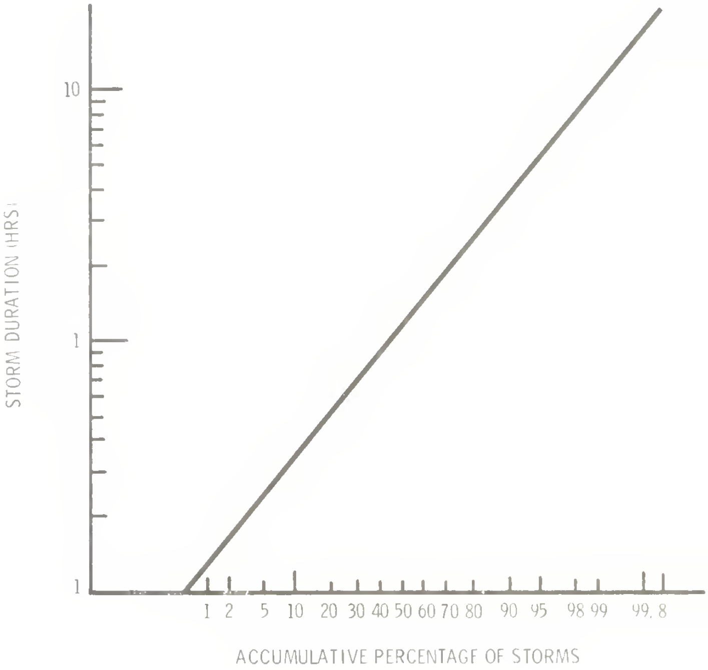

Figure 12.—The frequency distribution of durations of 1,228 storms on the Straight Canyon barometer watershed, Utah

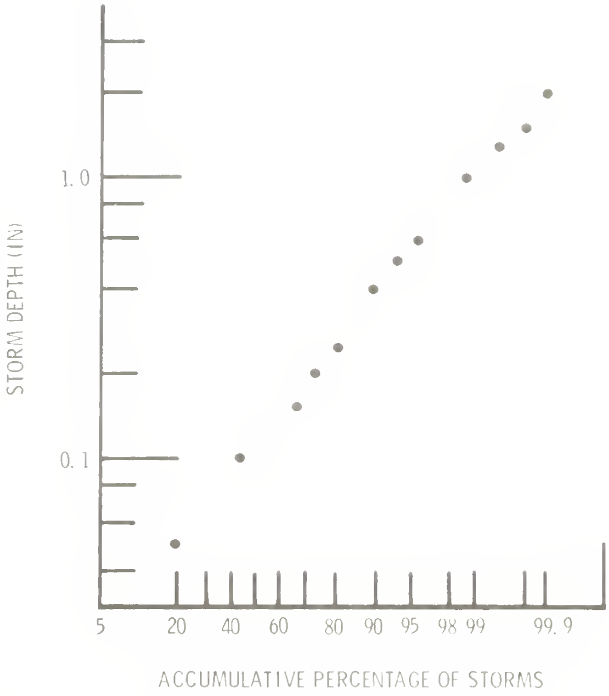

Figure 13.—The frequency distribution of storm depths for 1,228 storms on Straight Canyon barometer watershed, Utah

DISCUSSION

In general, the mountain-valley intensity relationships stated by Brancato (1942) hold true for these data. He stated:

> With regard to variation of thunderstorm rainfall with elevation . . . over a long period of time a station located at a lower elevation is likely to experience the most intense thunderstorm.

Dorroh (1946) also substantiates this hypothesis.

Plant cover destruction resulting in active flood and sediment source areas has occurred prevalently on high-elevation herbaceous sites that lie above the aspen-fir type, and was due primarily to summer grazing overuse by livestock. Our data show that the rainfall intensities expected to occur on such sites are quite substantial.

Some of the rainfall intensities that can be expected to occur probably will be greater than the infiltration capacities of some sites, particularly those in poor hydrologic condition. Hence, overland flow is almost a certainty. Fortunately, management practices on mountain watersheds can drastically alter runoff volumes, flood peaks, and erosion. This has been amply and convincingly demonstrated on the Davis County experimental watershed (Bailey and others 1934; Bailey and others 1947). On both study areas in the middle 1930's, severe mudrock floods were generated by storm events with a recurrence interval of only 15 years. Since that time, both vegetal and mechanical rehabilitation measures have resulted in the satisfactory disposition of storm rains of equal or greater magnitude.

The greatest annual rainfall intensities can be expected at the lowest elevation on the Straight Canyon barometer watershed. This is different than on the Ephraim side of the mountain but similar values were obtained at Oaks climate station, which is the same elevation band as zone 3 on Straight Canyon.

Depth-duration curves suggest that the longer the storm, the greater the runoff. Osborn (1964) has pointed out that the use of depth-duration data can result in misleading runoff values. He reported that, in the semiarid Southwest rangeland, major runoff events are often the result of short-lived, high-intensity convective storms. Osborn's conclusion is generally applicable to our study areas. Major amounts of summer runoff will usually come from storms of medium duration, namely 2 to 6 hours, with short periods of high-intensity rainfall bursts.

The slope of the depth duration curves of Straight Canyon all lie within the range of values found on the Great Basin experimental area.

Elevation significantly affects 10-minute, 10-year precipitation intensity at Straight Canyon and Great Basin but not on the Davis County area. Precipitation intensity decreases more than an inch per hour as elevation increases 5,000 ft (1 524 m).

A better relationship exists between the 10-minute, 10-year precipitation and the miles of penetration from the Wasatch-Pavant front. This relationship has a coefficient of variation of about 60 percent on the Straight Canyon area, decreasing to 50 percent on the Great Basin area and becoming nonsignificant on the Davis County area.

Although the mountain-valley intensity relationships tended to follow Brancato's (1942) thesis that the lower lying stations receive the most intense rainfall, our data do not support his contention concerning the amount of rainfall. He stated:

> Three to four times as many thunderstorms occurred on the middle and upper windward slopes of the mountains as on the relatively flat and lower portions of the basin. However, contrary to published and popular accounts, the thunderstorms produced the greatest amount of precipitation at the lower elevations and not on the mountain slopes. The most favorable conditions for the production of heavy rain is the presence of an air mass with a sufficient amount of available energy and the greatest possible amount of moisture. Orographic lifting is very effective as a mechanism to release the latent energy in an air mass, but as the air is lifted over progressively higher terrain, the total amount of available precipitable water above any given area becomes progressively smaller.

Two assumptions upon which Brancato bases his thesis might be questioned. One is the assumption that the amount of precipitable water in an airmass becomes significantly less as it is forced over a single mountain crest. It is not likely that the total precipitable water changes very much on adjacent precipitation zones. Significant diminution of precipitable water requires the passage of an airmass over substantial sections of terrain. Another questionable assumption is that orographic lifting is the dominant mechanism triggering storms. Orographic effects may well contribute to summer shower activity, but the local daytime slope heating and induced upslope breezes are probably more important. Cold fronts and upper troughs may also contribute to some of the storms, especially early and late in the season. These may act in conjunction with daytime surface heating and orographic lifting.

The relation between elevation and number of storms is similar to that between elevation and average monthly rainfall depth. The ratio between the number of storm occurrences at the highest zones and at the lowest zones varies between 1.0 and 1.2.

The Straight Canyon 60-minute rainfall intensities are more like those given by Farmer and Fletcher (1971) for southern Utah than central Utah. Other observations regarding area of application are similar.

On the basis of the zonal R values, both erosion and runoff peaks should be about 1.3 times as great in zone 3 as in zone 1.

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Straight Canyon barometer watershed was divided into three similar precipitation intensity zones. The 50-year precipitation intensity (2-minute duration) increased from about 4 in (102 mm) per hour on zone 1, to about 13 in (330 mm) per hour on zone 3. Daily precipitation depths were revised, with zone 3 receiving 91.97 in (50 mm) and zone 1, 2.08 in (53 mm). Rainfall erosivity (R) increased from 12.5 hundreds of foot-tons per acre-inch (3.375 hundreds of t/ha-cm) in zone 1, to 16.7 hundreds of foot-tons per acre-inch (4.51 hundreds of t/ha-cm) in zone 3.

KEYWORDS: mountain precipitation, rainfall intensity, rainfall erosivity, rainfall time, rainfall duration

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**Intermountain
Forest and Range
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Research Paper
INT-275

May 1981

Effects of Prescribed Fire on Soil Nitrogen Levels in a Cutover Douglas-fir/Western Larch Forest

**Martin F. Jurgensen, Alan E. Harvey,
and Michael J. Larsen**

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RESEARCH SUMMARY

The effects of a prescribed broadcast fire on soil nitrogen (N) levels and related soil properties were determined following the clearcutting of a 250-year-old Douglas-fir/western larch stand in northwestern Montana. Soil N losses from burning amounted to slightly over 90 lb/acre (100 kg/ha), all from the surface organic layers. This was 6 percent of the total N originally present in the surface 12 inches (30 cm) of soil. In contrast, soil ammonium concentration increased within 2 days following the fire. Rapid nitrification also occurred after a 3-week lag period. The higher nitrate levels were associated with increased populations of nitrifying bacteria. Both soil ammonium and nitrate concentrations returned to preburn levels by the end of the following summer.

Soil acidity was decreased after the burn and had not yet returned to original levels in the organic horizons 4 years later. Organic matter content of the mineral soil was not affected by the fire.

No long-term depletion of soil N reserves would result from this prescribed fire. Plant reestablishment on the site benefited by increased soil N availability.

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INTRODUCTION

The relationship of fire to soil nutrient cycling and availability has been the subject of intensive study for many years. Numerous reviews cover this and other facets of fire effects on soil (such as Viro 1974, Raison 1979, Wells and others 1979). Of the many essential plant nutrients, nitrogen (N) is the most affected by burning because nearly all N in forest soils is present in the organic form. Volatilization of soil and plant N occurs during a fire, with the actual amounts lost dependent on fire intensity (Knight 1966). In most soils, N-containing rocks and minerals are lacking to replace fire-related N losses. Nitrogen additions to the soil come from: (1) small amounts of N present in precipitation and dust; (2) conversion or "fixation" of atmospheric N_2 gas into usable forms by soil and root-inhabiting microorganisms; or (3) application of mineral or organic fertilizers.

In contrast to total N changes, soil N availability may be improved following a fire, with increases in N mineralization rates frequently reported (Wells and others 1979). The growth of postfire regeneration may be favored by such higher levels of soil ammonium (NH_4) or nitrate (NO_3), but these greater amounts of available N would also be susceptible to leaching losses, especially as NO_3.

When evaluating the potential environmental impact of various harvesting treatments on site quality, some reduction of soil N levels from burning may be acceptable as compared to the N losses that may occur by use of mechanical site preparation equipment (Wells and others 1979). In order to determine the suitability of fire as a postharvest site treatment, information must be obtained on how fire affects the soil N status. This paper reports the results of a prescribed broadcast fire on soil N levels and other soil properties following the clearcutting of a mature Douglas-fir/western larch forest in western Montana.

STUDY AREA AND TREATMENT

This study was conducted on the Coram Experimental Forest, approximately 10 miles (16 km) south of Glacier National Park in western Montana, as part of a comprehensive residue utilization research program. The experimental site was an undisturbed 250-year-old forest typical of the Douglas-fir/western larch timber type. Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmannii*) were the dominant tree species in the study area. The vegetation represents an *Abies lasiocarpa/Clintonia* habitat type (Pfister and others 1977).

Elevation of the study plots was nearly 4,538 ft (1 375 m). The plots were located on a steep (55 to 60 percent) east-facing slope. The soils were quite stony (>50 percent) and derived from weathered argillite and impure limestone material. Soil fine materials (<0.08 inch, or <2 mm) were silt loam in texture (Klages and others 1976).

The area used in this study was a 7.5-acre (3-ha) clearcut harvested in the fall of 1974 and broadcast burned in early September 1975. As part of the residue utilization study, all live and dead material (standing and down) of 8.0 ft (2.5-m) length, 3-inch (7.6-cm) diameter, and at least one third sound was removed prior to burning. The fuels on the site were relatively moist at the time of burning, which resulted in a generally low intensity fire. This was shown by a duff depth reduction of only 25 percent from the original 2.7-inch (6.8-cm) thick surface organic layer. A more detailed description of the burn conditions and fuel volumes have been given by Artley and others (1978) and Benson and Schlieter (1980). An adjacent uncut stand was used as a control.

METHODS

Sampling

We took 30 soil cores (4 x 12 inches, or 10 x 30 cm) randomly throughout the cut area 1 day prior to burning, 2 days following the burn, and 6 weeks after the burn for determination of: total and available N, organic matter content, acidity (pH), populations of nitrifying bacteria, and the occurrence of water repellent layers. In addition, we took 10 cores periodically from September 1975 to October 1976, both in the burned area and the adjacent control stand, to more closely monitor changes in available N levels and soil acidity. The bimonthly samplings in December, February, and April were limited to six cores at midplot due to deep snow on the site.

Each soil core was separated in the field into the following fractions: (1) surface litter (0_1 horizon), (2) humus (0_2 horizon); (3) decayed wood in the soil (referred to here as the 0_3 layer); (4) surface 0-2 inches (0-5 cm) of mineral soil; and (5) remaining mineral soil to a total core depth of 12 inches (30 cm). Approximate soil volumes occupied by each fraction were determined by measuring its depth in the undisturbed core. The occurrence of water repellency in the mineral soil was determined using the water-drop-penetration test on the soil surface and at each 2-inch (5-cm) soil depth (Adams and others 1970).

Soil Analysis

In the laboratory each soil fraction was shaken for [illegible] minutes in a standard 0.08 inch (2 mm) soil sieve. The decayed wood and humus aggregates were gently crumbled before sieving. Material less than 0.08 inch (2 mm) was retained for chemical analysis. Determinations of NH_4 and NO_3 content, acidity, and autotrophic nitrifying bacteria populations were performed on undried soil within 24 hours after collection.

Ammonium content of each soil fraction was measured in a 2N KCl extract by a specific-ion electrode (Banwart and others 1972). Nitrate content was determined on a distilled water leachate by specific-ion electrode, according to Bremner and others (1968). Acidity was measured electrometrically using a 1:2 mineral soil to water ratio, or a 1:5 organic matter to water ratio. Nitrifying bacteria numbers (*Nitrosomonas*) were estimated in the 0_1 and 0-2 inches (0-5 cm) of mineral soil fractions using the Most-Probable-Number Technique (Alexander and Clark 1965).

Soil for total N and organic content analyses was dried in a forced-draft oven at 140° F (60° C). Total N values were determined by macro-Kjeldahl techniques with salicylic acid added to include NO_3 ((Bremner 1965). Organic matter content was estimated by weight loss-on-ignition (Ball 1964).

Statistical Analysis

Data on nitrogen concentrations and populations of autotrophic nitrifying bacteria were analyzed to detect significant differences among horizons before and after the prescribed broadcast fire. One-way and two-way analysis of variance was used to analyze these data.

RESULTS

Total Nitrogen

Since N is oxidized and/or volatilized as a result of fire, considerable changes would be expected in soil N content after the prescribed burn. Losses of N occurred only in the soil organic layers (table 1). The organic fractions are extremely important to the N economy of this site, containing over 53 percent of the total N in the surface 12 inches (30 cm) of soil prior to burning. Even after the fire, 49 percent of the N was still present in the organic layers. We did not find a significant decrease in the total N concentration of the surface litter layer (0_1) after the fire. We attributed this somewhat surprising result to the variable and spotty nature of the burn. However, the largest N losses occurred in the 0_1 layer, which was caused by a 60 percent reduction in average horizon thickness. The depth of the humus horizon (0_2) decreased by nearly 30 percent, but the N concentration of the remaining material increased significantly. Consequently, only neligible amounts of N were lost from this layer. No significant differences were found in the decayed wood (0_3) or in the mineral soil. In total, slightly over 100 kg/ha or 6 percent of the N present in the surface 12 inches (30 cm) of soil was lost as a result of the prescribed fire. However, this value does not include any N losses from the burning of larger woody slash.

Table 1.--Nitrogen content of soil organic layers as affected by prescribed fire

Soil layer	Before burn % N	Before burn Lb N/acre	Before burn kg N/ha	Two days after burn % N	Two days after burn Lb N/acre	Two days after burn kg N/ha
Litter (0_1)	1.19	114	128	0.87NS	36	40
Humus (0_2)	0.71	302	339	.91*	297	333
Decayed wood (0_3)	.46	421	472	.69NS	410	460
Mineral						
0 - 5 cm	.12	205	230	.12NS	205	230
5 - 22 cm	.08	543	609	.08NS	543	609
All layers	--	1,586	1 778	--	1,492	1 672

NS = no significant difference $p > 0.05$.

* = significant difference $0.01 < p < 0.05$.

Available Nitrogen

In contrast to total N contents, NH_4 and NO_3 concentrations increased as a result of the fire. The levels of available N present in the humus layer for 13 months after burning are shown in figure 1. Similar changes in NH_4 and NO_3 concentrations were recorded for the soil mineral layers, but the actual values were much lower than those found in the organic fractions. A large increase in NH_4 levels was evident immediately after burning. No postfire change was detected in NO_3 values until nearly 3 weeks later when rapid nitrification began. This rise in NO_3 concentration was followed by an equally rapid decline over the next week. Leaching of NO_3 due to 2.5 inches (6.3 cm) of rain during that period probably caused this loss. In fact, the 6 weeks following the fire were especially wet, with the area receiving 5.4 inches (13.5 cm) of rain. After this decline, NO_3 concentrations again increased substantially. We found that the higher soil NO_3 level after burning was associated with a significant population increase of autotrophic nitrifying bacteria, both in the organic layers and mineral soil (table 2).

By the middle of October, the NH_4 concentrations began to decline and showed a steady decrease during the winter and spring months until preburn levels were reached by the end of the next summer (fig. 1). Nitrate concentrations generally followed a similar pattern, but a spring nitrification peak was evident on the burned site. Such an increase in the nitrification rate may also have occurred in the control soil but could have been obscured by plant N uptake.

When the NH_4 and NO_3 results were converted to total amounts of available N present in the surface 12 inches (30 cm) of soil (table 3), the pronounced effect of fire on surface organic horizons was again evident. Available N levels in these layers increased by fourfold within 2 days after the fire, followed by a gradual decrease during the next 13 months. The mineral soil showed a similar trend but attained the highest available N values later in the fall, presumably due to leaching of NH_4 and NO_3 from the organic horizons.

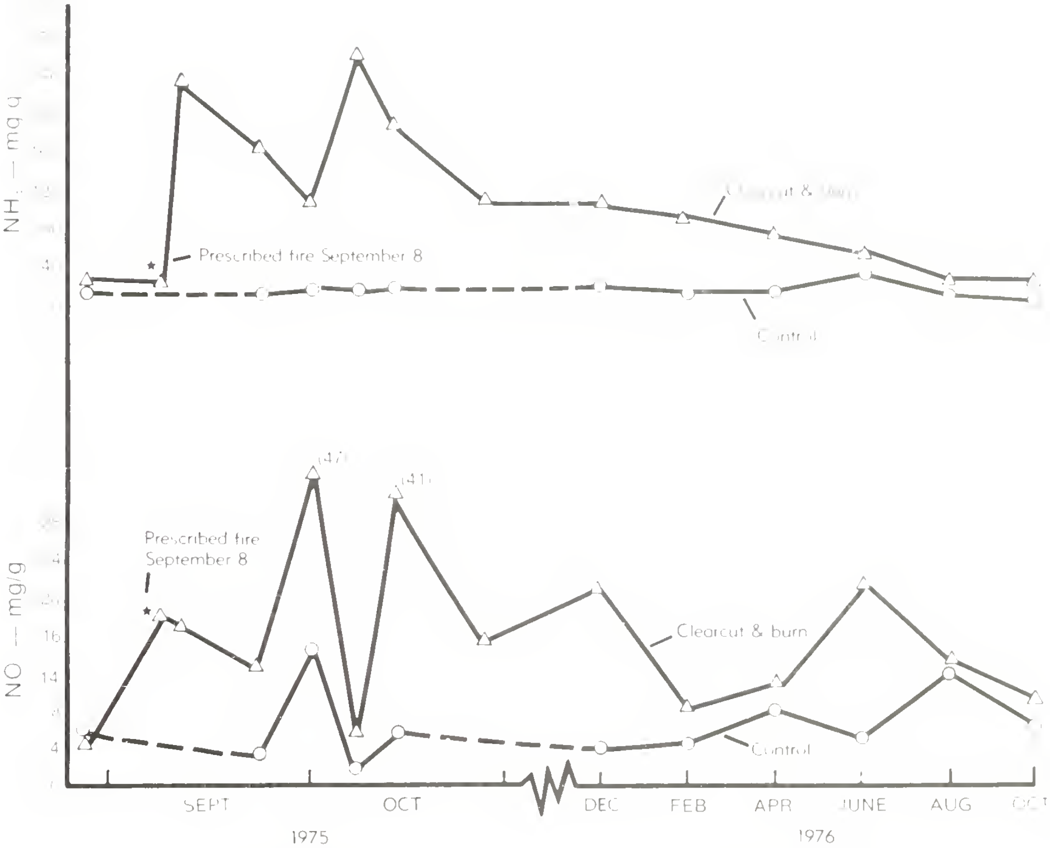

Figure 1.--Available nitrogen levels in the humus layer (0_2) after a prescribed fire in a clearcut Douglas-fir/western larch stand

Table 2.--Soil populations of autotrophic nitrifying bacteria (*Nitrosomonas*) before and after a prescribed fire

Soil layer	Bacteria/g of dry soil	
	Before burn	Six weeks after burn
Humus (0_2)	800	3 280*
Mineral (0 - 5 cm)	240	960*

* = significant difference $0.01 < p < 0.05$

Table 3.--Available soil nitrogen (NH_4 and NO_3) content as affected by prescribed fire

Soil layer	Before fire	After fire			
		2 days	6 weeks	9 months	13 months
	--------------	------Lb acre(kg ha)---	------	-----	--
$0_1 + 0_2$	1.9 (2.1)	9.0 (10.1)	4.4 (4.9)	1.6 (1.8)	0.7 (0.8)
Decayed wood (0_3)	1.8 (2.0)	6.5 (7.3)	6.2 (6.9)	5.2 (5.8)	2.1 (2.3)
Mineral					
0 - 5 cm	1.2 (1.3)	2.9 (3.3)	5.1 (5.7)	2.1 (2.4)	.7 (.8)
5 - 22 cm	3.7 (4.2)	4.8 (5.4)	7.0 (7.9)	5.2 (5.8)	2.4 (2.7)
All layers	8.6 (9.6)	23.3 (26.1)	22.7 (25.4)	14.1 (15.8)	5.9 (6.6)

Other Soil Properties

The effects of the prescribed fire on other soil properties were also monitored. Soil acidity decreased over one pH unit in the 0_2 layer following the burn (fig. 2). We also found decreased soil acidity in the mineral horizons but to a lesser degree. At the end of the next growing season the pH of the 0_2 horizon in the burned soil was still higher than in the adjacent uncut stand. A sampling of the area 4 years after the burn showed that the pH of the 0_2 had not yet returned to preburn status. In contrast, soil acidity in the mineral horizons on the burned site decreased to original values by the following fall.

There was no apparent effect of the fire on organic matter content of the surface mineral layer, which averaged 4.2 percent before and after the fire. Fire did not cause any appreciable development of water repellent layers in the mineral soil. Prior to the fire the surface of only one of the 30 mineral cores showed evidence of water-repellent properties. After the burn nine of the cores gave a positive water repellency test but only on the soil surface. This development was temporary, since at the end of 6 weeks no water repellency was found.

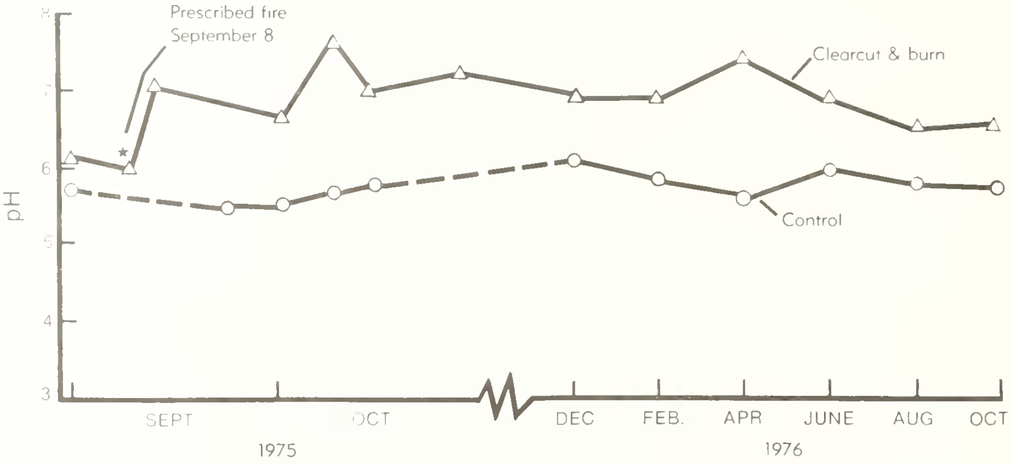

Figure 2.--Effects of a prescribed fire on pH in the humus layer (0_2) of a clearcut Douglas-fir/western larch stand.

DISCUSSION

Investigations concerned with the effects of fire on soil N status have often been contradictory. Some have reported losses of soil N, while others have indicated either no change, or in a few cases, N gains after a fire (Wells and others 1979). Many of these contradictions undoubtedly come from differences inherent in study design, sampling technique, and analytical methods. Others come from actual site differences as reflected in the type, amount, and condition of forest fuel present.

The intensity and duration of a fire are important variables that affect N losses (Knight 1966). The moist fuel conditions on the Coram site prior to the fire resulted in a generally "cool burn" (Artley and others 1978). Such a fire would account for the rather small N losses from the forest floor and the lack of organic matter change in the mineral soil. These results contrast with those of DeByle (1976), who found a significant reduction of organic matter in the surface mineral layer and N losses exceeding 180 lb/acre (200 kg/ha) following a prescribed fire on a similar clearcut Douglas-fir/western larch site. In this instance, the fire was more intense and fuel consumption more complete than occurred at the Coram site. The relatively high proportion of N present in the surface organic matter as compared to the mineral soil makes this timber type highly susceptible to N losses during a fire. Similar soil conditions exist in ponderosa pine stands in the Southwest (Campbell and others 1977; Welch and Klemmedson 1975).

As noted earlier, N would be added to burned sites by inputs from precipitation and biological N-fixation by soil microorganisms. The N gains from both these sources over a stand rotation of 100 to 150 years on the Coram site would more than replenish the N losses due to this fire, as well as the N removed in the timber harvest (Jurgensen and others 1979; Stark 1979). Consequently, no long-term site depletion of soil N is expected to result from the effects of the prescribed burn.

Increases in the concentration and total amounts of available soil N were found after burning. Similar fire-related gains in NH_4 and/or NO_3 content have also been reported for other conifer sites in the Northern Rocky Mountain Region (Hooker and Tisdale 1974; Orme and Leege 1976; Skujins[1]). Higher NH_4 levels result from an immediate release of N when the organic matter is burned followed by a partial mineralization of remaining organic N by the soil microflora (Mroz and others 1980). Microbial activity is stimulated by the release of available carbon sources and mineral salts from the burned organic matter, and by the decrease in soil acidity (Ahlgren 1974).

In contrast to the NH_4 release pattern, nitrification showed a definite 3-week lag following the fire. The initial low nitrification rates may be related to the inability of the nitrifying microflora to compete with the other soil microorganisms for available NH_4 (Jones and Richards

[1] Skujins, J. 1977. Effect of modified slash disposal practices on the biochemistry of soils. Final rep., Study FS-INT-1203, 145 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

1977), or to an inhibition of the nitrifiers by mineral salts released during the fire (Heilman 1975).

The steady decrease in available N levels during the winter and spring months may be attributed to immobilization and denitrification reactions by the soil microflora, as well as NO_3 leaching by snowmelt. Increased NO_3 concentrations were found in subsurface soil water and in an adjacent stream, but the amounts lost were too low to affect site productivity (Stark 1979).

Higher levels of available soil N found after prescribed fire may be beneficial for subsequent regeneration (Wells and others 1979), although the potential effects of this added N would appear to be of short duration. Available soil N levels on the clearcut-burned site were comparable to the untreated stand by the next fall following the fire. However, increased organic matter mineralization in the spring, coupled with reduced N uptake due to tree removal, could enhance available N supplies in the early part of the growing season on this site for at least several years.

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1981. Effects of prescribed fire on soil nitrogen levels in a cutover Douglas-fir/western larch forest. USDA For. Serv. Res. Pap. INT-275, 6p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Reports 6 percent of total nitrogen lost and changes in other related soil properties after a clearcut and broadcast burn. The most persistent change (4 years) was a reduction in soil acidity. Forest management implications are discussed.

KEYWORDS: available nitrogen, ammonium, nitrate, nitrifying bacteria, site preparation

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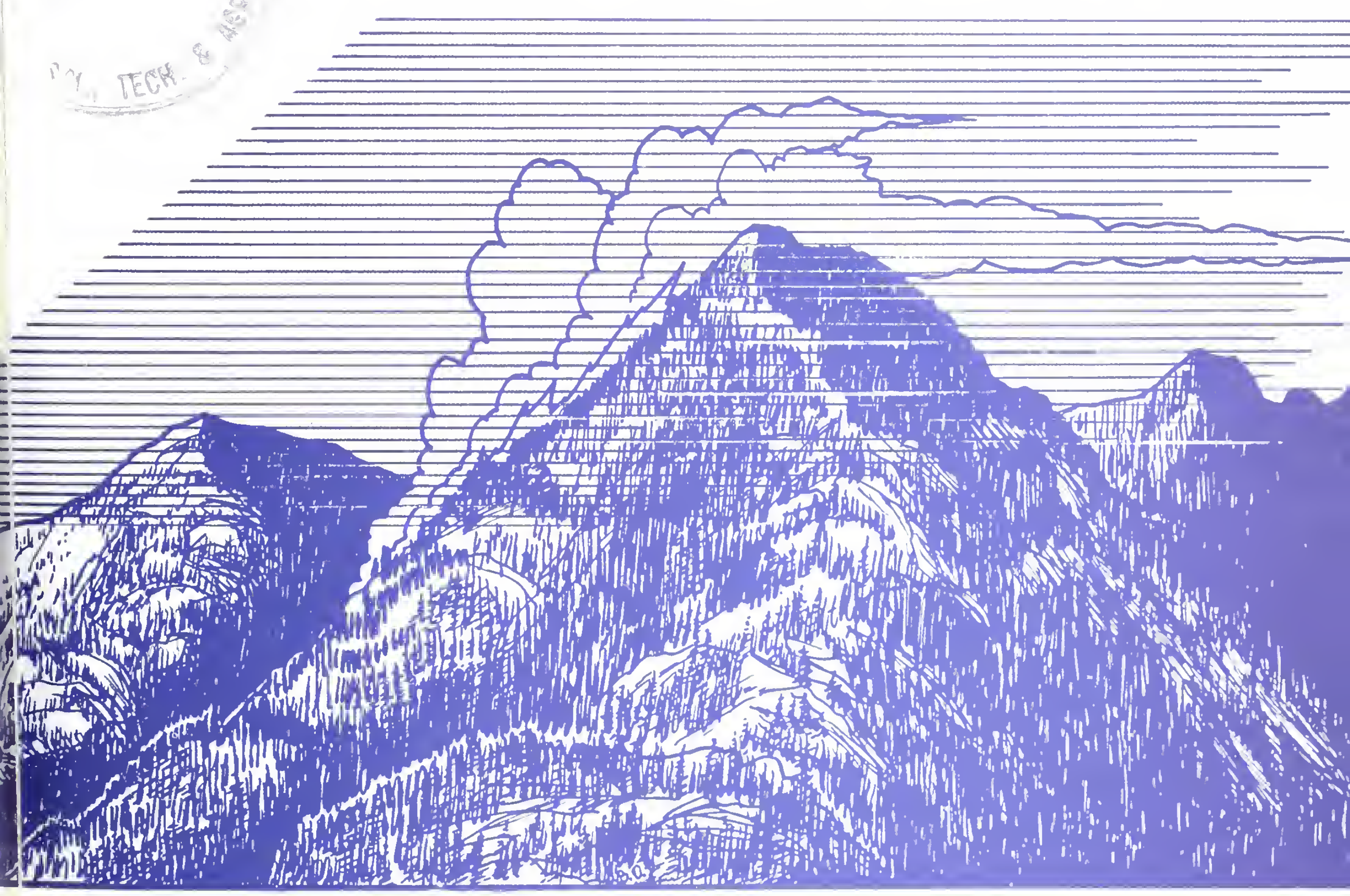
July 1981

Why Windspeeds Increase on High Mountain Slopes at Night

Robert G. Baughman



RESEARCH SUMMARY

Research findings support the contention that the well-documented increase of windspeed on high mountain slopes at night is due to the occurrence of a low-level jet wind. Various aspects of the meteorological situation most likely to produce these nocturnal mountain winds are discussed. An established jet-wind theory (Blackadar 1957) can be used to predict the strength of these mountain winds during the course of an entire night. An example is given of a low-level jet wind that produced strong winds on a ridgetop fire at night.

The purpose of this report is to explain the windspeed increase on mountain slopes at night. Additional work is required to determine such things as the frequency of the winds, the area affected, seasonal variation, and the effect on fire behavior. Also, additional studies are needed to develop the type of procedures required to forecast these nocturnal mountain winds.

THE AUTHOR

ROBERT G. BAUGHMAN was introduced to meteorology while serving as an air-crewman with the U.S. Navy Air Corps during World War II. He later received degrees in meteorology and climatology from the University of Washington (B.S. 1954, M.S. 1957). During the period of 1954 through 1958, he was engaged in arctic and cold regions research while with the U.S. Army Corps of Engineers. In 1958, Baughman joined the USDA Forest Service as a research meteorologist, with responsibility for research on fire-setting lightning storms, weather modification, and forest meteorology. Currently he is a member of the Fire Behavior research work unit at the Northern Forest Fire Laboratory in Missoula, Mont.

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Why Windspeeds Increase on High Mountain Slopes at Night

Robert G. Baughman

INTRODUCTION

The diurnal change of wind velocity on high mountain slopes and ridges differs from that of lower levels. Usually, the wind velocity increases on the higher slopes and may reach a maximum value at night and a minimum during the daytime (Yoshino 1975). The occurrence of these stronger winds blowing on a ridgetop fire at night can prove very frustrating to fire control crews who often count on a nighttime lull in fire activity. Such winds could not only fan a fire, but could also carry firebrands much further than expected and widely disperse smoke and pollution.

The existence of this particular weather phenomenon in mountainous areas has been reported in literature over the past 40 years. Gisborne (1941) declared that on mountaintops the maximum wind velocity is often reached during the night. Barrows (1951) states, "On the upper slopes of the mountains the peak velocities may be reached much later in the day, and frequently at night." Byram (1954) related a low-level jet current to extreme fire behavior. Several of his case-history fires were located in mountainous country. According to Schroeder and Buck (1970), low-level jet winds have not been studied in rough mountain topography; however, the higher peaks and ridges above lowland night inversions may occasionally be subjected to them. Brown and Davis (1973) say "While low-level surface winds are generally weakest at night, the reverse is noted on mountain ridges; that is, ridge winds tend to be stronger at night and weaker during the daytime."

The cause of these nocturnal mountain winds has not been fully explained. A few researchers have related the cause to the occurrence of low-level jet winds, but details are not given (Schroeder and Buck 1970; Lee[1]). A more complete explanation of the windspeed increase on high mountain slopes at night is given here. The key to the explanation is the common occurrence of nocturnal temperature inversions in mountain valleys. The top of the inversion layer provides a smooth fluid interface that enhances the formation of a low-level jet (Hoecker 1965). The mountain slopes and ridges that extend above the surface inversions are exposed to the jet wind and are thus subject to strong surface winds.

Included in the explanation given here is a brief discussion of a particular low-level jet wind theory (by Blackadar 1957) that can be used to predict the strength of these mountain winds during the course of an entire night. Also discussed is the type of synoptic situation most likely to produce these winds. Finally, shown here is an example of a low-level jet wind that produced strong winds on a ridgetop fire at night.

The primary purpose of this report is to offer a reason for stronger windspeeds on high mountain slopes at night. Additional work is required to describe the extent of the problem, at least in terms of fire behavior. This requires studies to determine: the frequency of these winds, the area affected, the season variation, and the effect on fire behavior. Also, additional studies are needed to develop the type of procedures required to forecast these nocturnal mountain winds.

[1] Lee, Glenn M. 1959. Observations of ridge top winds in northeastern Oregon. Unpubl. rep. 3 p. On file at Northern Forest Fire Laboratory, Missoula, Mont.

BACKGROUND INFORMATION

Several low-level jet-wind mechanisms have been proposed (Blackadar 1957; Wexler 1961; Lettau 1967), but only one of these applies over any continental surface, whether it be level or mountainous. According to Blackadar (1957), the low-level wind maxima is best developed on the Great Plains at night; however, examples may be found almost anywhere in the United States during any season of the year. The phenomenon results from rapid relaxation of friction drag at about the time of sunset. During the day, convective mixing produces a relatively deep friction layer above the earth's surface. Air movement in this layer is retarded by frictional drag. At night, thermal convection ceases and the earth's friction layer decreases in vertical extent. Air just above the nighttime friction layer, free of the daytime frictional drag, responds by accelerating under the influence of the unbalanced Coriolis and pressure-gradient forces. During the course of the night the air accelerates beyond the geostrophic value (supergeostrophic) before decreasing again.

The formation of a nocturnal temperature inversion will further damp out vertical mixing and enhance the buildup of a low-level jet wind. It has been observed that temperature inversions occur in mountainous regions at all times of the year. For example, detailed measurements by Hayes (1941) revealed that nocturnal inversions are common during the summer months in the Priest River Valley of northern Idaho. Schroeder and Buck (1970) point out that inversion layers are more common and more intense in mountain valleys than over flat areas and that the height of the inversions is usually below the main ridges. The land surface above the inversions is subject to increased windspeeds.

BLACKADAR JET-WIND THEORY

Blackadar (1957) derived a theory that explained the low-level jet in terms of a mechanism that can produce a diurnal variation of wind velocity in the boundary layer over any continental land surface. He assumed the motion just above the temperature inversion layer is completely horizontal and frictionless, and the horizontal pressure gradient is constant with time. An equation was derived that describes the deviation from the geostrophic wind. The solution is

$$W = W_o \, e^{-ift} \tag{1}$$

where W is the deviation from the geostrophic wind at time t and W_o represents the deviation at an initial time, which may be taken to be the time of sunset (fig. 1). The letter i is the imaginary unit of a complex number and f is the Coriolis parameter.

The flow is one of inertia oscillation. After release of friction, the flow of air accelerates under the unbalanced Coriolis and pressure-gradient forces. The deviation from the geostrophic wind remains constant in magnitude, but is driven constantly to the right by the Coriolis force during the night at a constant angular speed of f radians per second. If continued, the motion would perform a complete revolution. The circle of inertia marks the loci of the end positions of the wind vector as a function of time. The period of a complete revolution is one-half pendulum day (Hess 1959). A supergeostrophic maximum windspeed is reached about $t = \pi/f$ hours after sunset (about 8.5 hours at 45° latitude).

Blackadar's theory permits prediction of the wind distribution during the entire night from initial conditions. Field observations show that the locus of points (head of the wind arrows) actually stretches out into an elliptical form instead of a perfect circle as given by figure 1 (Buajitti and Blackadar 1957). The elliptical path results from gradual relaxation of friction.

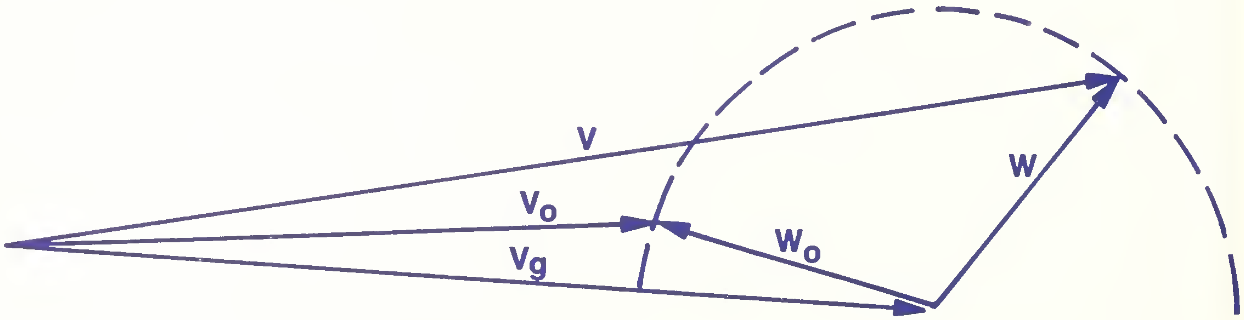

Figure 1.—Development of supergeostrophic winds in the low-level jet (after Blackadar 1957). V_g is the geostrophic wind, V_o the initial wind, and V the true wind. W and W_o are defined in equation 1.

SYNOPTIC CONSIDERATIONS OF THE LOW-LEVEL JET

The sharpness of the wind maximum tends to be enhanced when the geostrophic wind decreases with height (Blackadar 1957). Following this observation, it is useful to examine an expression describing the change of the geostrophic wind with height. Consider the following analysis:

$$\frac{\partial p}{\partial z} = -\rho g \text{ (hydrostatic eq.)} \tag{2}$$

$$p = \rho RT \text{ (eq. of state)} \tag{3}$$

$$fV_g = -\frac{1}{\rho}\frac{\partial p}{\partial n} \text{ (geostrophic wind)} \tag{4}$$

where n is normal to and increases to the left of the velocity vector. Now eliminate ρ using eqs. (2) and (3), then:

$$\frac{1}{p}\frac{\partial p}{\partial z} = -\frac{g}{RT}$$

and then differentiate with respect to n

$$\frac{\partial}{\partial n}\left(\frac{1}{p}\frac{\partial p}{\partial z}\right) = \frac{g}{RT^2}\frac{\partial T}{\partial n} \tag{5}$$

Now write (4) as

$$\frac{1}{p}\frac{\partial p}{\partial n} = -\frac{fV_g}{RT}$$

and differentiate with respect to z

$$\frac{\partial}{\partial z}\left(\frac{1}{p}\frac{\partial p}{\partial n}\right) = \frac{fV_g}{RT^2}\frac{\partial T}{\partial z} - \frac{f}{RT}\frac{\partial V_g}{\partial z} \tag{6}$$

Since

$$\frac{\partial}{\partial n}\left(\frac{1}{p}\frac{\partial p}{\partial z}\right) = \frac{\partial}{\partial z}\left(\frac{1}{p}\frac{\partial p}{\partial n}\right)$$

then

$$\frac{fV_g}{RT^2}\frac{\partial T}{\partial z} - \frac{f}{RT}\frac{\partial V_g}{\partial z} = \frac{g}{RT^2}\frac{\partial T}{\partial n}$$

or

$$\frac{\partial V_g}{\partial z} = \frac{V_g}{T}\frac{\partial T}{\partial z} - \frac{g}{fT}\frac{\partial T}{\partial n} \tag{7}$$

The first term on the right of (7) is less than one-tenth of the second term. Neglecting this term:

$$\frac{\partial V_g}{\partial z} \simeq -\frac{g}{fT}\frac{\partial T}{\partial n} \tag{8}$$

which is a form of the thermal wind equation. According to equation 8, for the geostrophic wind to decrease with height above the jet maximum, the temperature to the left of the geostrophic wind must increase along n. Since low pressure is also to the left of the geostrophic wind this requires the presence of a warm low-pressure system.

Observations have shown this to be the case. Means (1952) found that, for the central United States, supergeostrophic winds are found in low-level jets where isotherms are approximately parallel to the streamlines with warmer air toward lower pressure. Hoecker (1965) noted the meteorological conditions during three southerly low-level jet systems included warm low-pressure area to the west (left) of the jet. Also he noted that the occurrence of a surface nocturnal inversion allows greater increased low-level vertical shear, which favors a higher jet speed for a given initial pressure gradient.

It is important to note that the thermal wind component has a direction parallel to the isotherms of the mean temperature of the layer considered with high temperature to the right. This is just opposite of the situation for a decrease of the geostrophic wind with height. Therefore, in this case, the thermal wind opposes the geostrophic wind. This was proposed in a theoretical hodograph developed by Blackadar and found in observations by Hoecker (1965). In two cases Hoecker found that the thermal wind vector almost directly opposed the sea level geostrophic wind. Also, he states, "The opposition of the sea level geostrophic and thermal wind vectors is indicative of a warm low-pressure system in the region and since a warm low pressure system is shallow, the geostrophic wind (as well as the real wind) should decrease with height." Hoecker suggests (based on his observation in the Oklahoma-Texas area) that "if an adverse thermal wind exists at about 1800 CST along with a southerly low-level flow, and if the adverse thermal wind can be forecast to persist during the following hours of darkness, the boundary-layer jet system (speed maximum at about 300 m above the ground),. . .can be expected to occur that night."

The jet wind does not necessarily have to occur at night. According to Blackadar (1957), the jetlike profile may occur even in the daytime and conversely, the jet effect may not occur at all during the night if the geostrophic wind increases too rapidly upward. Rider (1966) observed low-level jet winds at the White Sands Missile Range. He observed that, although the low-level jet was predominantly a nocturnal phenomenon, with the nose of the jet near the height of the nocturnal temperature inversion, significant low-level wind maxima are sometimes found in the daytime. Also, there were a few cases where a jet formed even though lapse conditions prevailed, and there were cases where a temperature inversion developed during the night but a significant low-level jet was not evident.

REPORTED JET-WIND OBSERVATIONS

Measurements made at Silver Hill, Md., by Gifford (1952) provided clear evidence that windspeeds at the level of the jet maximum (2,000 ft [610 m]) are considerably supergeostrophic. Similar conclusions may be drawn from the analysis of low-level wind maxima at 0300 local time at San Antonio, Tex. (Blackadar 1957). Some other early measurements made at O'Neil, Nebr., during a 6-week period in the fall of 1953, illustrated several well-developed low-altitude wind jets (Barad 1961). Barad asks, "How did so strong and distinct a pattern go so long undetected?" The answer is simply that standard observation techniques were inadequate to find it. Observations on a 1,400-ft (427-m) tower near Dallas, Tex., clearly showed the existence of a low-level wind maximum during periods of temperature inversions (Thuillier and Lappe 1964).

Windspeed observations on high mountain slopes at night are not common. Nevertheless, Lee[7] noted ridgetop windspeeds were considerably stronger at 0300 P.s.t. than at 0800 P.s.t. in the Blue Mountains of northeastern Oregon. Wind profile measurements at Burns, Oreg., indicated a definite wind maximum at low levels during the night. Perhaps Lee was the first to refer to Blackadar's theory as an explanation of the observed strong mountain winds. And as noted before, Rider (1966) also observed low-level jet winds over mountainous terrain.

The recorded occurrence of low-level windspeed maxima in conjunction with a forest fire in mountain areas is apparently quite rare. Byram (1954) observed jet currents over fires in South Dakota and California. Small (1957) reports that careful examination of the Boise Weather Bureau records indicates the presence of a low-level jet point on each day of significant spread by the Robie Creek Fire of 1955 in southern Idaho. Also, Finklin (1973) discussed the possibility of a low-level jet wind affecting the major run of the Sundance Fire in northern Idaho in the fall of 1967.

SUNDANCE FIRE - LOW-LEVEL JET

There is strong evidence that a low-level jet wind also occurred 3 days before the major run of the Sundance Fire. An account of this earlier outbreak of the fire is given by Anderson (1968).

> Late in the evening of August 29, at 2220, Priest Lake Timber Protective Association Headquarters near Coolin, Idaho, received word the fire had jumped the line and was out of control. Men and equipment were evacuated to headquarters. The fire was observed rolling down the hill in the Lee Creek drainage. a northeast wind had prevailed throughout the day and it is assumed this wind, coupled with the normal nighttime downslope currents, resulted in a wind-driven fire moving downslope. Information available from observers indicated the winds were 20-25 mi/h on the fire, but there was calm at Cavanaugh Bay near Coolin. The ground and crown fires were observed to move as a single front, with spotting up to one-half mile ahead. The main advance took place between 2230, August 29, and 0200, August 30, which would give an average rate of spread of 0.80 mi/h.

There was no direct measurement of a surface inversion in the area, but there is little doubt that one occurred during the night of August 29, because the region was under the influence of a high-pressure ridge at the time (Finklin 1973). Also, in an unpublished report (G. A. Verdall, letter in files at the Northern Forest Fire Laboratory, dated Oct. 5, 1967), it was reported, "Cooler air had filled the valley bottom; therefore there was no wind at our location (Cavanaugh Bay)." Verdal went on to say, "What made the fire behavior seem unusual to me was that I was standing in calm air watching a wind driven fire." Also he said, "To me, the fire behavior witnessed at that time was more spectacular and more unexpected than the major run the fire made on September 1."

The fire burned from the top of Sundance Mountain (6,000 ft [1 830 m] m.s.l.) down to about the 4,000 f (1 220 m) level (fig. 2). The windspeed was quite strong on the ridgetop while it was calm some 2 miles away at Cavanaugh Bay (2,500 ft [762 m] m.s.l.). According to the low-level jet-wind theory, this is not an unexpected result, because the ridge was exposed to the jet wind while Cavanaugh Bay was protected by the temperature inversion layer. Upper air information was not available for the fire site, but it was available for Spokane, Wash. about 50 miles (80 km) southwest of the fire. The data clearly show the presence of a low-level jet wind during this early fire outbreak (fig. 3).

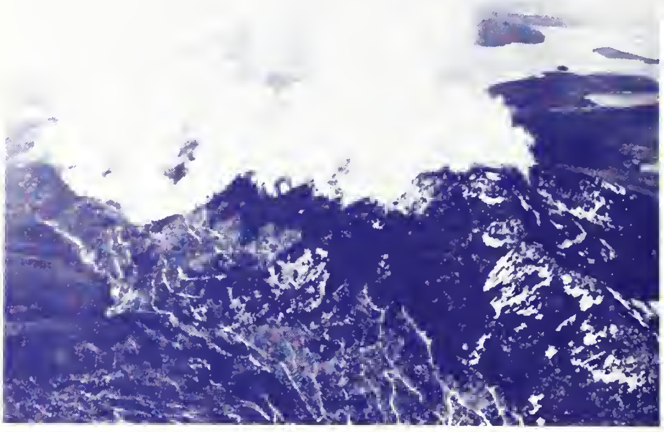

Figure 2.—Sundance Mountain after the fire's night run on August 29, 1967.

The windspeed on the night of August 29-30 was from the east to northeast reaching 15 to 20 mi/h (6.7 to 8.9 m/s) at a nearby mountaintop fire-weather station (Lunch Peak). "These winds were associated with a cool surface high to the northeast, moving southeastward across Alberta and Saskatchewan" (Finklin 1973). The surface map of 0600Z, August 30 (2200 P.s.t., August 29, time of the fire outbreak) revealed the presence of the cold high-pressure system mentioned by Finklin and a small, warm low-pressure system to the southwest of the fire site over eastern Washington. This was just the type of synoptic situation required to produce an enhanced low-level jet wind; that is, opposing thermal and geostrophic wind components. The windspeed profile at 1600 on August 29 (fig. 3) was nearly constant with height up to 8,000 ft (2 440 m). At 2200 (August 29), the time of the fire outbreak, the jet was well formed, reaching a velocity of 20 knots (east wind at 23 mi/h [10 m/s]), at an elevation of 5,000 ft (1 525 m). The jet was still present early the next morning as shown by the 0400 sounding of August 30; still east at 20 knots (10 m/s). Strong winds continued at Lunch Peak during the morning hours decreasing to 10 to 12 mi/h (4.5 to 5.4 m/s) at 1400. The Spokane data for 1100 (August 30) is missing, but the

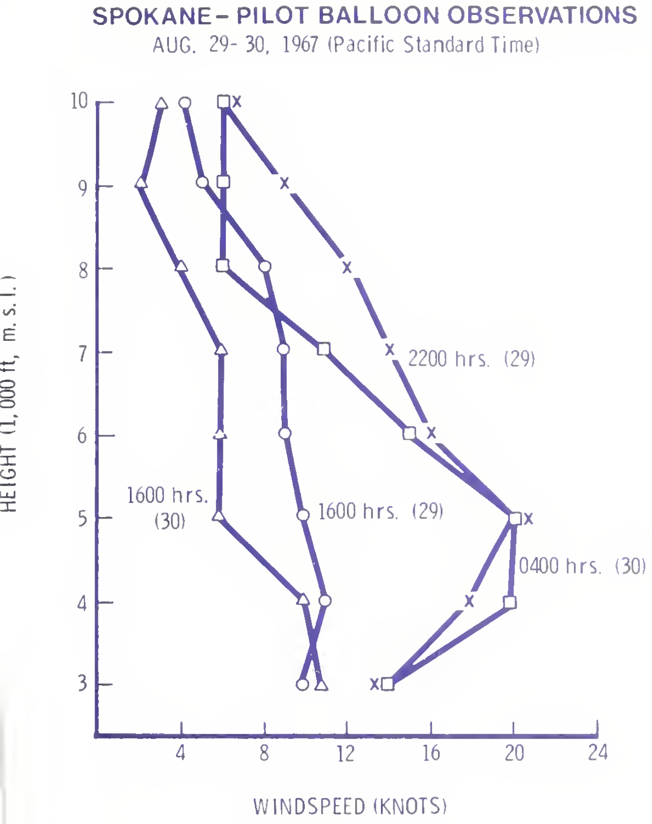

Figure 3.—The Sundance Fire low-level jet wind.

fternoon sounding (1600) showed the wind had died down efore extreme high windspeeds drove the fire northeast uring the major run in early September.

SUMMARY

It is well documented that windspeeds often increase nd may reach maximum values on high mountain slopes uring the nighttime hours. Evidence given here, including ublished information, supports the contention that this eather phenomenon is due to a low-level jet wind. ackadar's low-level jet theory (1957) can be used to help edict the wind velocity during the night from initial nditions. The jet wind is enhanced by the formation a surface temperature inversion and the occurrence of hermal wind component that opposes the geostrophic nd. This latter condition is brought about by the esence of a warm low-pressure system (or cold high-essure system). Because these nocturnal jet winds pose a ever-present threat to fire management activities in high mountainous areas, forecasting techniques should be developed.

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**Intermountain
Forest and Range
Experiment Station**

Research Paper
INT-277

June 1981

Redistributing Wilderness Use Through Information Supplied to Visitors

Robert C. Lucas

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RESEARCH SUMMARY

The USDA Forest Service managers of a large part of the Selway-Bitterroot Wilderness in Montana sought to influence some visitors to shift from heavily used trailheads to more lightly used ones. To do this, they designed a brochure on relative use levels and on how to locate trailheads. They began distributing the brochure in 1974. An evaluation showed overall use patterns were not shifted toward the lightly used trailheads. A majority of visitors never saw the brochure. Only about one-fourth had it before they reached the trailhead, and about one-fourth of these said they used the brochure to choose a trailhead, usually a lightly used one. The number of visitors increased an average of 26 percent per year during the 2-year evaluation, apparently overwhelming the small redistributional effect of the brochure. Information on crowding was not one of the main factors cited by visitors as influencing trailhead choices, suggesting that the brochure's focus was too narrow. This study, and several other similar studies that are reviewed, suggest information programs—which are an attractive, nonauthoritarian, indirect technique—can redistribute use substantially if information about a variety of area conditions is presented to visitors early enough in the location choice process.

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INTRODUCTION

Wilderness managers often want to redistribute some recreational use to achieve management objectives. Among ways managers can do this, one of the most attractive is to provide visitors with information to influence them to redistribute themselves. Little is known, however, about how to make information an effective management tool for redistributing visitor use.

The Use Distribution Problem

Wilderness recreational use is typically distributed unevenly. A few access points usually receive a majority of use, and a small proportion of the trail system commonly accounts for most visitor use (Hendee, Stankey, and Lucas 1978).

Concentrated recreational use can create adverse impacts on wilderness values. Growing use accentuates the problem. Resource impacts proliferate and affect too much land in key areas. The areas receiving highly concentrated use are often not the areas most capable of supporting it. Relatively fragile ecosystems may be heavily used while more durable places receive ittle or no use.

Crowding in popular areas also reduces opportuniies for visitors to experience solitude. Visitors vary in he value they place on solitude (or low density use) and n their definitions of acceptable levels of contact with other wilderness visitors. But often, many visitors go to areas where concentrated use results in more contact with other parties than desired. At the same time, some visitors to lightly used portions of a wilderness may meet fewer people than they would like, or at least far ewer than they would accept. There is a mismatch, as here is between use and ecosystem durability.

Management to Redistribute Use

Wilderness managers may have any of at least three objectives for seeking to shift some use:

1. They may wish to reduce the extremity of the contrasts between lightly and heavily used areas. This would require shifting some use away from the heavily used areas to the less-used places. An even use distribution is not a logical goal for a wilderness because, as mentioned before, both the ecosystem's capability and visitors' desired levels of contact with others vary. However, managers and probably most other people familiar with use conditions in many wildernesses would agree that use is excessively concentrated.

2. Managers may want to increase or decrease use of specific locations within a wilderness to better match use to environmental capability. This would be particularly appropriate where information is available on the relative durability or fragility of different sections. It could also be related to visitor experiences, based on the availability of screened campsites, for example, or to provision of a range of likely encounter levels.

3. Managers may wish to redistribute different types of visitors so that those who prefer lower levels of encounters generally visit lightly used areas offering such opportunities, and those who prefer higher levels of contact go to areas where such experiences are commonly available.

Whatever the objectives, managers have a range of possible management actions for redistributing use. Management actions are of two main types, direct and indirect (Hendee, Stankey, and Lucas 1978). Direct regulation includes rationing use, either for an area as a whole, for each access point, or by campsites. These are powerful tools that could shift use patterns substantially. However, they also are heavy-handed, authoritarian measures, usually with high administrative costs. The impact of such bureaucratic control on a recreational experience, especially a wilderness experience, is likely to be substantial and negative. In some cases, conditions require this trade-off. But indirect management is generally worth trying first, before resorting to direct regulation.

Indirect management is usually not obvious to visitors. Visitor behavior can be modified by management actions such as changing access to make it easier or more difficult; for example, by changing the last part of an access road to a trail. Providing information to visitors to influence their choices of routes is another indirect visitor management technique.

Information as a Use Redistribution Tool

The use of information to redistribute use is a particularly appealing approach (Fazio 1979). It is nonauthoritarian and permits the manager to be a helpful guide rather than someone who restricts and regulates. As a result, conflict and controversy can be avoided. Surveys show that wilderness visitors have high educational levels, indicating an ability to understand and use fairly complex information.

But how effective is information as a tool for use redistribution? This study seeks to help answer this question.

Information can be provided to visitors in many ways and in varying situations, and previous studies under different conditions have shown varying success in modifying use distribution. The evaluation of information as a management technique is strengthened by considering the combined results of several of those studies.

One study showed information can effectively redistribute use outside wilderness settings. Brown and Hunt (1969) experimented with roadside signs and substantially redirected use of highway rest and viewing areas.

An attempt to redistribute campers away from trails and previously used campsites in the Great Gulf Wilderness in New Hampshire relied more on rules (with some explanation) attached to permits, rather than on information about the areas. The attempt failed to achieve the desired behavior (Canon, Adler, and Leonard 1979).

In Colorado's Rawah Wilderness, Schomaker (1975) found that a map of "crowded areas" handed out at the trailhead had no appreciable effect on visitors' choices of travel routes.

In the Boundary Waters Canoe Area in Minnesota, people who had permits for the most heavily used entry points during the 1974 season were sent a packet of information in early spring 1975. The packet included information on use patterns, noting heavily used places and times. It provided information on fishing and wildlife observation opportunities in different areas, and named places where black bear depredations on camps were most common. Rules and regulations and no-motor zones also were presented. Three-fourths of the sampled respondents who visited the area in 1975 felt the information was useful, and about one-third were influenced in their choice of entry point, route, or time of subsequent visits (Lime and Lucas 1977). Visitors who had less previous experience in the area were most often influenced.

An experiment in Yellowstone National Park als succeeded in redistributing a substantial amount of use (Krumpe 1979). A sample of persons applying for back-country camping permits were given a "Trail Selector" that included a map and a brochure with descriptions o lightly used trails. The descriptions were arranged in a decision-tree form. Visitors were asked a series o questions about their preferences for backcountry experiences and guided to suggested routes, depending on their answers. They were asked about preferences for travel along streams, to mountain peaks, to lakes, o off-trail, cross-country travel. For each of these possibilities, several more questions dealing with length o trip, difficulty of the route, and more detailed aspects o the setting led to a suggestion. A sample of othe applicants for permits was used as a comparison contro group and did not get the "Trail Selector." Only 14 percent of the control group chose one of the routes i the "Trail Selector," compared to 37 percent of th experimental group who received it. Less-experience visitors more often chose one of the suggested trails

A study in the Shining Rock Wilderness in Nort Carolina tested an effort to modify campsite choices b means of a brochure describing 10 characteristics o each of five alternatives to a heavily used camping are (Roggenbuck and Berrier 1980). Both the brochur alone and in combination with a personal message wer tested. The approaches did not differ significantly, an both resulted in a significant dispersal of campers to th alternative sites. Visitors with no previous experience i the area were more likely to disperse after receiving th information. Parties who received the personal contac and brochure treatment earlier in the day were mor likely to disperse than those who were contacted late

THE STUDY AND RESEARCH METHODS

Study Area and Management Program

The Stevensville Ranger District of the Bitterro National Forest manages about 100,000 acres in th northeast corner of the over 1 million-acre Selwa Bitterroot Wilderness. The Wilderness is in both Idah and Montana, but the Stevensville Ranger District po tion is all in Montana, on the east slope of the Bitterro Mountains (fig. 1).

Most trails in this area lead up narrow, steep canyon all oriented east-west, to cirque lakes at their uppe western ends. Few connecting trails exist and loop tri are rare. The lakes vary in size and number, but most a about 10 to 12 miles by trail from the road ends.

The managers were concerned about highly co centrated use. Three of 12 trailheads received most the use, and there were problems of badly impact campsites. The other trailheads were considered attra tive and capable of absorbing more use. Therefore, th managers decided to try to shift some use from th heavily used trails to similar but lightly used trails.

To accomplish this, the Ranger District staff d signed a brochure (appendix 1) providing information relative levels of use at each trailhead, expressed as


MILES
0
5
0
5
KILOMETERS
ROADS
TRAILS
Callon Cr.
One
Horse Cr.
Peterson Lk.
Sweeney Cr.
Bass Lk.
Bass Cr.
Kootenai Lks.
Kootenai Cr.
IDAHO
MONTANA
St. Mary Pk.
Stevensville
Big Cr. Lk.
Big Cr.
Glen Lk.
Bryan Lk.
Sweathouse Cr.
Two Lks.
Bear Cr.
Fred Burr Cr.
N
Sheafman Cr.
Mill Cr.
Mill Lk.
Blodgett Cr.
Blodgett Lk.
Hamilton

Figure 1. [illegible]

percent of the total. The brochure also explained how to find each trailhead, which is rendered somewhat difficult by an intricate network of roads through private ranch land in the Bitterroot Valley. These roads must be traveled to reach the trailheads at the base of the mountains. There also was some very limited information on a few heavily impacted campsites.

Distribution of the brochure began in 1974. It was available in boxes on registers at every trailhead (fig. 2) and at the Stevensville Ranger Station, the Forest Supervisor's Office in Hamilton, and the Forest Service Regional Office in Missoula. It also was mailed to people who wrote to these offices inquiring about visiting the Wilderness. The brochure, revised in 1977, is still in use. The current version provides less detail on use distribution, indicating only those four trails most heavily used and pointing out that they account for 70 percent of all use.

Evaluation

The Wilderness Management Research Work Unit evaluated this management effort at the District Ranger's request. The evaluation had four objectives:

1. To determine if use patterns shifted in the desired way, from heavily used to lightly used trails.
2. To determine to what extent visitors were exposed to the brochure; that is, what proportion obtained it, where, and at what stage in the trip planning process.
3. To determine how visitors reacted to the brochure; that is, whether it influenced choices of trails, if it was considered useful, and what changes were suggested.
4. To determine what factors influenced choices of trailheads and if those factors were unrelated to information in the brochure.

The field conditions were the same as they would have been without the study. The Ranger District planned and handled the brochure distribution in the normal way. Trail registers (used as an index of use at each trailhead) were maintained in the usual fashion. Use regulations were essentially unchanged throughout the 1973-75 period of the study.

Use Patterns

Use patterns, by trailheads, for 1974 and 1975 (the first years the brochure was distributed) were compared with 1973, a typical use season that served as the "before treatment" base. Trail register data were used as an index of relative use, expressed as a percentage of the total to make it independent of changes in total use from year to year. These data provided an incomplete measure because some visitors did not register. But the data were assumed to be comparable across the 3 years. We checked trail registration rates by direct, unobtrusive observation in the field at five trailheads in 1974.

Comparisons of relative use were made among individual trails, between all lightly used trails as one group and all heavily used trails as a second group, and among trails grouped into three categories—light, moderate, and heavy use.

Change from 1973 was classified as to whether or not it was in the direction desired. This meant relative use was desired to decrease at heavily used trails an increase at lightly used trails. The moderately used trail did not have a clearly desired change and were no classified. We tested the hypothesis that change was i the desired direction.

Visitor Survey

To measure exposure of visitors to the brochure an people's reactions to it, we sent a mail questionnaire t a sample of people making visits to the study area i 1974 and 1975. The sample list was drawn from registered visitors, and all findings and conclusions appl only to visitors who registered. One person, the on whose name appeared on the permit, was sampled. Thi person is usually the party leader. For the group behavior we were concerned with, this is usually the ke person.

This was a systematic sample with a random start. W sorted trail register cards for each trailhead into day us (in and out the same day) and campers (overnight stays These were ordered by entry dates. After a random star every third camper card and every sixth day user car were chosen for the sample. We sampled campers mor heavily because we felt they were more critical: the penetrate the wilderness more deeply, stay longer, an have greater potential for causing impacts. Also, 197

Figure 2.—Trail register and brochure dispenser box (to the right of the trail register) on the Big Creek trail

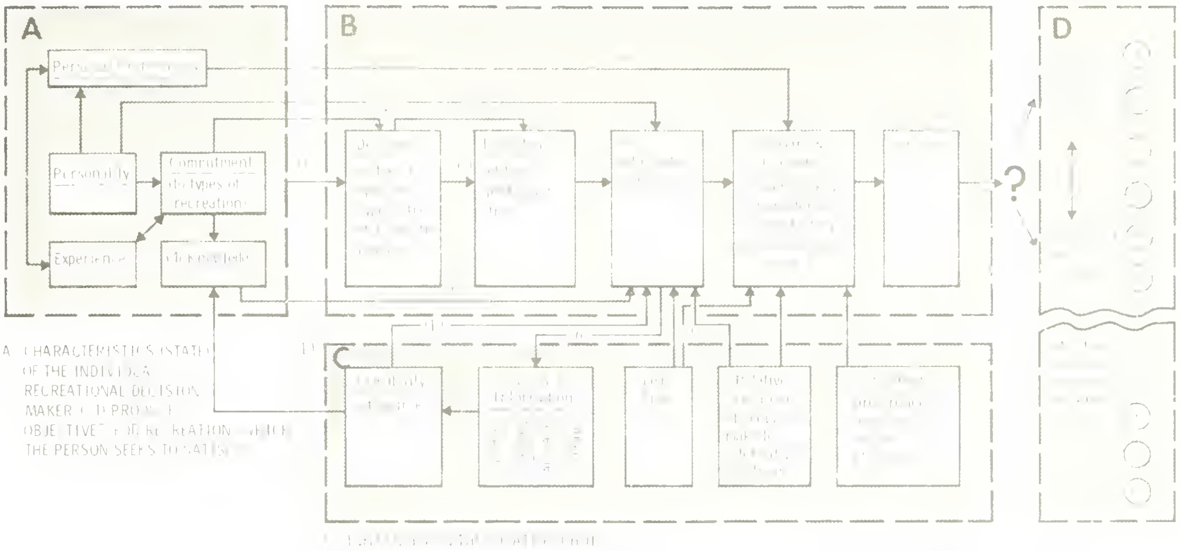

Figure 3—The relationship among the components of recreational location choice behavior. (Numbered components and relationships correspond to descriptions in the theory in the text.)

data indicated almost two-thirds of the visitors were day users; therefore, an unweighted sample would likely yield less detail about campers than seemed desirable. Data from day users were weighted (by 2) to counteract this overrepresentation of campers.

The resulting sample list was 611 names (271 in 1974 and 340 in 1975). Questionnaires were mailed to all 611, and 29 were returned by the Postal Service as undeliverable, leaving a sample list of 582 names and current addresses. Questionnaires were mailed hroughout the summer and fall usually about a month after the visitor's trip. After 3 weeks, a second questionnaire was mailed to nonrespondents. Each year was reated as a separate sample.

Because the sampling frame was visits, it was possible for a person to be sampled more than once a year. n alphabetized mailing file made it possible to detect esampling of the same people. A special cover letter, sed when a person was sampled a second time, xplained that visits were sampled and that because ach trip was different and attitudes can change, a econd response was important. This occurred rarely, ffecting less than 5 percent of the sample. Persons ampled three or more times, however, were excused fter being contacted twice. This may have caused a mall, probably insignificant bias, but consideration for sitors seemed to require this procedure.

The questionnaire requested information concerng a basic description of the trip, prior experience in the rea, possession of the brochure, where and when it as obtained, factors influencing the choice of trailead, the role of the brochure in influencing choice of ailhead, perceived usefulness of the brochure information, and suggestions for its improvement.

Although none of the questions appeared personal or sensitive, respondents' anonymity and confidentiality were protected. Questionnaires were identified only with numbers, and, at the close of each season, all cards in the address files were destroyed.

Analysis and Underlying Theory

Analysis consisted of comparing tabulations using chi-square or gamma to test differences and associations. I developed a general theoretical model of recreational location choice behavior to derive a series of hypotheses about the response of visitors to the brochure. Four major elements in the model are: (1) the characteristics of the person choosing the location; (2) the choice process; (3) influences on the choice; and (4) alternative potential locations with varying characteristics (fig. 3).

The proposed theory consists of the following basic assumptions and postulates about the relationships between components of these four elements.

Assumptions:

1. Visitors seek recreational experiences that satisfy their objectives.

2. The conditions contributing to a satisfactory experience vary among different visitors based (a) on personal preferences, and (b) usually also on preferences of companions, family, and other social pressures.

3. Locations vary in the combination of recreational characteristics they possess, and thus in their desirability for different visitors.

4. Visitors choose locations with incomplete know-

ledge. They are not aware of all alternative locations nor of all the characteristics of each, and some of the information they possess is erroneous.

5. Visitors evaluate and compare locations based on their perceptions of the characteristics of known alternatives.

Postulates:

6. The effort visitors make to obtain information about alternative recreational locations:

a. Increases as the importance of the recreational experience increases (how much is at stake), which in part is a function of length of stay and of personal commitment to the type of recreational experience.

b. Decreases as the amount of information visitors perceive they already have increases, particularly personal familiarity from previous trips.

c. Increases as individual preference for novelty (or risk) increases in comparison to preference for familiarity (or security).

7. Visitor evaluations are based primarily on a few key characteristics that may vary among visitors.

8. The key characteristics are evaluated on a low-resolution scale, essentially as either "satisfactory" or "not satisfactory." The thresholds for "satisfactory" judgments vary among visitors. More detailed information helps people make these threshold decisions.

9. To choose a new alternative location, information must convince a person that it is highly probable a new place is at least as satisfactory (and possibly better) in terms of key characteristics as a familiar place (less so for high-novelty seekers or "explorers").

10. Visitors discount information about new alternatives based on their perception of the credibility of the sources and the information. Increased detail generally results in increased credibility. Information from an agency usually tends to be viewed as less credible than that from friends and acquaintances.

11. Information is most likely to influence decisions if it becomes available during the trip-planning phase, which is usually at home, but sometimes at a Ranger Station or other place. Information received later is less likely to influence decisions because:

a. Changing a decision requires more effort than making the original decision.

b. Additional information after a decision tends to be unwanted because it creates dissonance; most people would rather not *know* they may not have made the best possible choice.

12. Information is most likely to influence decisions if it is received at locations closer to home or farther from the alternative locations. This is because the closer persons are located to one alternative when new information is obtained, the less likely they are to consider other alternatives because the differences in relative travel costs become greater.

In other words, we view recreationists as having a general idea of what they are seeking, as using a crude benefit-cost analysis to determine how much effort they will put into gathering information to pick a location, as being only fairly good information processors with a streak of mental laziness, and as somewhat stubborn about changing their minds after they have chosen a place.

FINDINGS

Changes in Use Patterns

Hypothesis: Lightly used trails will account for a larger proportion of total use, and heavily used trails a smaller proportion, after introduction of the brochure.

Trail register data were the only available index o shifts in use patterns, but these leave much to be desired and require caution in interpretation. Field checking in 1974 showed only 28 percent of the visitors to 5 trailheads registered (Lucas 1975). This was less than half the rate reported in other studies and was no expected. With such low registration rate, moderate fluctuations in registration rates among trailheads from year to year, which could easily occur, would substantially distort the pattern of relative use. Therefore, only large shifts should be viewed as meaningful. Although data on actual visitor behavior are ordinarily the mos convincing evidence, in this case the trail register data unfortunately, cannot be viewed as accurately reflecting real behavior. The data from sampled visitors concerning their response to the brochure may tell us more about its effectiveness.

With these cautions in mind, the trail register data show that in 1974 change was in the desired direction and consistent with the hypothesis, but only weakly so Use of 6 of the 11 trails[1] shifted in the desired direction 2 of 3 heavily used trails had less relative use, but only 4 of 8 lightly used trails had more (table 1).

If because of the low trail register compliance, only changes of over 20 percent from 1973 are considered use of 4 trailheads apparently changed in the desired direction, 3 in the undesired direction, and 4 could be considered not changed significantly, again weakly consistent with the hypothesis.

In terms of use redistribution, 1975 appears to be a disaster. Only 3 of 11 trailheads changed in the desired direction, 1 heavily and 2 lightly used trailheads (table 1). Considering only changes of more than 20 percent, 2 were in the desired direction, 6 were not, and 3 were unchanged. Results are sharply inconsistent with the hypothesis.

Under the three-way classification of use levels, St Mary's Peak, Bear Creek, Mill Creek, and Blodgett Creek are classified as moderately used, without a clearly desired direction of change. In this analysis, 4 of 7 trailheads changed in the desired direction in 1974, but only 2 of 7 in 1975—essentially the same situation described above.

If trailheads are grouped by level of use, and aggregate use compared, the conclusions are the same. In 1974, there was a small change in the desired direction (table 2). The magnitude of change (about 5 percent) is small, however. In 1975, the change is in the undesired direction and, at about 18 percent, is of greater magnitude.

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[1] The trailhead on Fred Burr Creek is blocked by private land; although it had a trail register, it had very little public use (9 parties in 3 years) Sheafman Creek also has no public access and was not mentioned in the brochure. In 3 years, 12 parties signed in at the trail register. Both o these trailheads were omitted from the analysis.

Table 1.—Change in relative use among trailheads. 1973-75

Trailhead	Use level[1]	Percentage of total groups for each year				
		1973	1974	Change[2]	1975	Change[2]
Carlton Creek	L	0.7	0.1	U*[3]	0.3	U*[3]
Sweeney Creek	L	6.8	5.6	U	5.0	U*
Bass Creek	H	16.7	21.5	U*	27.2	U*
Kootenai Creek	H	21.2	16.2	D*	23.9	U
St. Mary's Peak	L	10.2	12.0	D	4.5	U*
Big Creek	H	16.1	13.7	D	12.4	D*
Glen Lake	L	3.0	4.1	D*	3.5	D
Sweathouse Creek	L	1.4	2.7	D*	1.1	U*
Bear Creek	L	8.1	7.8	U	7.9	U
Mill Creek	L	7.8	5.1	U*	3.4	U*
Blodgett Creek	L	8.3	11.1	D*	10.7	D*

[1] L = lightly used, H = heavily used

[2] D = change in desired direction, U = change in undesired direction relative to 1973

[3] * = change from 1973 exceeded 20 percent of 1973 value

Table 2.—Change in relative aggregate use, for trailheads classified by level of use

Trailhead class	N	Percent of total groups for each year				
		1973	1974	Change	1975	Change[1]
Lightly used	8	46.1	48.5	D	36.5*[2]	U
Heavily used	3	53.9	51.5	D	63.5	U
Lightly used	4	11.8	12.5	D	10.0	U
Moderately used	4	34.3	36.0	-	26.5*	-
Heavily used	3	53.9	51.5	D	63.5	U

[1] D = change in desired direction, U = change in undesired direction

[2] * = change from 1973 exceeded 20 percent of 1973 value

If a three-way grouping is used, the conclusions remain unchanged (table 2). It is apparent that the 1975 change towards increased relative use of the heavily used trails came more at the expense of the 4 moderately used trails (with a 23 percent decline from 1973), rather than the lightly used trails.

Based solely on the use patterns as reflected by trail register data, the brochure was not effective. The pattern of concentrated use apparently was intensifying in the second year of the evaluation, which is the opposite of the expected growing effect of the brochure over time. We thought that by the second year more people would have obtained the brochure and more would have it during the decision phase.

This does not necessarily mean information is a useless tool for redistributing use. First, there was no experimental control so we don't know how use patterns might have shifted over the 2 years without the brochure. The changes could have been even worse.

Second, the crudeness of the use index must be taken into account. It is unlikely the brochure was in fact highly effective, given the pattern of trail register data or the 3 years. But there is at least some chance that the marked deterioration suggested in 1975 was the result of changes in registration rates, not actual shifts in use.

Finally, visitor awareness, use, and evaluation of the brochure must also be considered before dismissing this information campaign as ineffective. These topics are covered next.

Visitor Responses to the Brochure

Visitors' responses to the brochure were probed with a mail questionnaire. With one followup mailing we received an 82 percent return, or 503 of 611 mailed. Excluding questionnaires returned by the Postal Service as undeliverable raises the response rate to 86 percent, or 503 of 582. This high response creates considerable confidence in the representativeness of the results, at least for visitors who registered. Nonrespondents were not contacted.

Reaching Visitors

Hypothesis: The proportion of visitors with a copy of the brochure will increase over time.

In order to have any possible effect, people first must be exposed to the brochure or other information device.

Most visitor groups had not seen the brochure when they entered the area: 54 percent said they did not have a copy, 46 percent did. The proportion exposed to the brochure increased from 44 percent in 1974 to 47 percent in 1975, which supports the hypothesis, although the difference is not statistically significant. The figures are reasonably consistent with observations in conjunction with checking trail register compliance. About 37 percent of the parties observed took a brochure from the dispenser on the trail register, which was where most visitors obtained the brochure. Some of these people observed may have already had another brochure. Others may not have noticed the brochure dispenser or simply not have chosen to take one.

Some visitors (13 percent) said they obtained brochures later, after the sampled trip. This proportion declined from 17 percent in 1974 to 10 percent in 1975 as more visitors already had the brochure before their visit.

The trailhead was by far the dominant source of the brochure when data from 1974 and 1975 are combined, as shown in the following tabulation:

Brochure obtained from:	**Percentage**
Trailhead, this trip	45
Trailhead, previous trip	32
Ranger Station	5
National Forest office	3
Regional office	4
By mail	1
From friends	6
Don't remember	4

Almost half of all visitors with brochures obtained them at the trailhead as their trip started. About one-third of visitors with brochures had obtained brochures at a trailhead on a previous trip. The next most important source was "from friends," but accounted for only 6 percent. The other sources, all of which involved contact with the managing agency, were low and were an even smaller proportion of all visitors. For example, only about 2 percent of all visitors obtained a brochure at the Stevensville Ranger Station, although it is less than 10 miles from several of the trailheads.

Hypothesis: The proportion of visitors who obtained brochures before reaching the trailhead will be higher at the lightly used trailheads than at the heavily used trailheads. (The brochures obtained early enough to influence choice of trailhead should result in more people choosing lightly used trails.)

The proportion of visitors with the brochure varied among the trailheads; the proportion who obtained the brochure **before** they reached the trailhead (about half of those with the brochure) was higher at the lightly used trailheads than at the heavily used trailheads. At lightly used trailheads, 35 percent of the visitor groups had a brochure before they reached the trail, compared to only 20 percent at the heavily used trails, a statistically significant difference.[2] This is consistent with the hypothesis.

Hypothesis: The proportion of visitors who obtained brochures only at the trailhead will not differ between lightly and heavily used trailheads. (These brochures were obtained too late to be effective.)

The proportion of visitors who obtained brochures at the trailhead on the sampled trip was the same for heavily and lightly used trails, 21 percent in both cases. This supports the hypothesis.

This means that visitors exposed to the brochure early in the decision process, probably before they had committed themselves to a trailhead, were more likely to choose a lightly used trailhead than visitors in general, but that brochures obtained after arriving at the trailhead had no effect on that trip.

Certain types of visitors were more likely to have the brochure than others, but some hypothesized, expected differences were not found, and some unexpected differences were found (table 3).

Hypothesis: A smaller proportion of day users will have obtained brochures than will have campers. (Day users are less likely to register, and brochures were avilable at trail registers. Day users probably plan trips less carefully, with less information seeking and less contact with managers.)

As expected, campers were more likely to have the brochure than were day users, 48 percent compared to 43 percent (table 4). This difference is not significant at the 0.05 level, although it is at 0.10. Much day use is very brief and may not involve much effort in choosing a location with particular attributes. The field observations in 1974 showed that only 17 percent of weekend visitors, a very large proportion of whom were day users, took a brochure at trailheads, compared to 51 percent on weekdays, when campers were more common.

Hypothesis: A smaller proportion of horsemen will have obtained brochures than hikers. (Horsemen register less often, may be more often local people already familiar with the area, and may be more limited in choice of areas because some are not well suited to horse travel.)

As expected, a smaller proportion of horse users had brochures, but the difference was small and not significant (table 3). The sample of horse users was also small.

Hypothesis: A smaller proportion of local people will have brochures than nonlocal people. (Local people are more likely to be familiar with the area and have established trail preferences, and they may not seek additional information or contact the managers as often as other visitors. Some live close to particular trailheads.)

Contrary to expectations, local people from the lower Bitterroot Valley were more likely to have brochures than other visitors. For Montana visitors (over 80 percent of the total), exposure to the brochure dropped the farther from the study area the visitors lived.

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[2] Chi-square equaled 18.08 with one degree of freedom, which is significant beyond the 0.001 level.

Table 3.—Proportions of different types of visitors with the brochure at the time of the sampled trip

Type of visitor	Number	Percent with brochure	Significance[1]
Length of stay			
Day users	220	43	N.S
Campers	383	48	
Method of travel			
Hikers	478	46	N.S.
Horse users	25	44	
Residence			
Local area	126	56	0.01
Missoula area	267	46	
Other Montana	20	36	
Out-of-State	90	40	
Experience with Selway-Bitterroot			
First trip	136	40	N.S.
Previous trips	367	48	
Experience with trailhead			
First trip	267	46	N.S.
Previous trips	236	46	

[1] Considered not significant (N.S.) if not significant at the 0.05 level, at least, as tested by chi-square

Table 4.—Proportion of different types of visitors with brochures reporting their choice of trailhead was influenced by the brochure

Type of visitor	Number[1]	Percent influenced[1]	Significance
Time brochure obtained			
Obtained brochure before trailhead	186	41	0.001
Obtained brochure only at trailhead	153	4	
Use level of trailhead			
Lightly used	176	30	0.02
Heavily used	161	19	
Method of travel			
Hiked	215	24	N.S.
Rode horses	9	32	
Hiked with packstock	4	50	
All horse users	13	36	
Residence			
Local area	61	26	N.S.
Missoula	121	23	
Other Montana	6	20	
Out-of-State	39	29	
Experience with Selway-Bitterroot Wilderness			
First trip	55	18	N.S.
Previous trips	176	26	
Experience with trailhead			
First trip	126	34	0.001
Previous trips	105	14	

[1] Numbers shown are for the actual, raw sample, which was used for chi-square tests. The percentages, however, are based on properly weighted data (Day users were sampled more lightly and had to be weighted to be comparable to campers.)

Hypothesis: A smaller proportion of visitors who have previously visited the Selway-Bitterroot, and especially the trailhead they visited, will have the brochure. (People familiar with an area may seek information less and already have established preferences for certain trails.)

Visitors making their first trip into the Selway-Bitterroot Wilderness had the brochure less often than people who had made previous visits (table 3), but the difference was not statistically significant. This does not support the hypothesis. We thought experienced visitors would be less motivated to obtain additional information, but apparently this is not the case. Experienced visitors may also have had more opportunities on earlier, recent trips to obtain the brochure.

There also was no difference in brochure exposure between persons making their first visit to the specific trailhead and visitors who were already familiar with the trailhead (table 3.) This is also contrary to the hypothesis, which was based on the belief that visitors going to a new trailhaed would be more eager for information.

Influencing Visitors

Although reaching a large proportion of the visitors with the brochure was a necessary first step, it was not enough. Were visitors' choices influenced by that exposure to the brochure?

About one-fourth of the visitors who had the brochure reported that their choice of trailhead on the trip was influenced by it. However, this constituted only 11 percent of all sampled visitors. This percentage increased only slightly (from 11 to 12) from 1974 to 1975 even though there was a somewhat wider exposure to the brochure the second year. The proportion of visitors with the brochure who said it influenced their choice of trailhead did not change between the years.

Hypothesis: The proportion of visitors who report the brochure influenced their choice of trailhead will be higher among those who obtained the brochure before the trip than those who obtained it at the trailhead. (The assumption is that by the time visitors reach a trailhead, it is too late in the decision process to influence that trip.)

Visitors who obtained the brochure before they reached the trailhead were much more likely to report that the brochure influenced their choice than were those who did not get the brochure until they arrived at the trailhead—41 percent compared to only 4 percent (table 4). This difference is statistically significant at the 0.001 level and supports the hypothesis.

For those who reported that their choice of trailhead was influenced, the most commonly reported type of influence was "general information about the area," such as on the existence of trails, opportunities for loop trips, presence of lakes, and approximate distances (table 5). The next most common answer was "chose a less-used trailhead," given by 30 percent of the visitors who said they were influenced. This is 13 percent of all visitors who had the brochure before reaching the trailhead, but only about 3 percent of all visitors.

Hypothesis: The proportion of visitors who report that their behavior was influenced by the brochure will be higher on the lightly used trailheads than on heavily used trailheads.

The proportion of visitors to the lightly used trails who said their choice of trailhead was influenced by the brochure was higher than for visitors to heavily used trails (table 4). The difference between the two figures—30 and 19 percent—is statistically significant beyond the 0.05 level and supports the hypothesis.

Hypothesis: A smaller proportion of horsemen will report choices influenced by the brochure than will hikers.

The sample of horse users was small, but the proportion reporting that their choice of trailhead was influenced was higher than for hikers. This is the opposite of the hypothesis, although the differences fall short of statistical significance (table 5).

Hypothesis: A smaller proportion of local people will report choices influenced by the brochure than will nonlocal people.

The association of place of residence with strength of the brochure's influence was not particularly strong (table 5). The pattern repeats that for brochure exposure: high for local people, declining within Montana

Table 5.—Responses to open-ended questions—"Please explain how"—by visitors who reported their choice of trailhead was affected by the brochure[1]

Type of influence on choice	Number[2]	Percent of respondents[2]
General information	24	48
Chose less-used area	17	30
Used "How-to-find trailhead" information	7	15
Information on attractions	5	9
Photographs of area	2	3
Other	8	14
No answer	3	5

[1] All answers by each respondent were classified and tabulated (no one gave more than two answers). Thus, the number of responses (66) totals more than the number of respondents (57).

[2] The actual number of responses before weighting is shown, but percentages are based on weighted sample.

as people live more distantly, and rising again for out-of-State visitors. The differences are not statistically significant, but in any case, the hypothesis is not supported.

Hypothesis: A smaller proportion of visitors who are experienced with the Selway-Bitterroot, and especially with the trailhead they visited, will report choices influenced by the brochure.

More visitors who had made previous visits were influenced than first-timers (table 5). The difference was not quite great enough for statistical significance, however. The hypothesis was not supported for general experience with the area.

The hypothesis was supported, however, for experience with the trailhead chosen (table 5). Over a third of the visitors who had the brochure and had visited a trailhead new to them said they were influenced by the brochure. This was more than twice as great as the proportion of people who had been to the trailhead before who said they were influenced, and the difference is statistically significant. The pattern of answers for the two types of experience—general and specific trailhead—suggests that the more generally experienced visitors seek and use information more and often use it to go to new trailheads.

Hypothesis: The proportion of visitors who report that later trips were influenced will be higher than the proportion reporting that the original, sampled trip was influenced. (This assumes that information must be received by visitors before reaching the trailhead to be effective.)

There is a "delayed action" effect. About 13 percent of the respondents who did not have the brochure at the time of the trip said they got the brochure later, and over half of these people took trips again before they got a questionnaire. Over half (57 percent) of these said their later trips were influenced by the brochure. The sample size was too small to analyze the effect of where the brochure was obtained. The proportion of later trips influenced was higher than for the original, sampled trips (57 percent compared to 24), statistically significant at the 0.001 level. This supports the hypothesis.

Visitors who obtained the brochure at the trailhead on the sampled trip may also have been influenced on later trips, but this was not investigated.

Visitor Opinion of the Brochure

Visitors were asked to evaluate the two main types of information in the brochure: on how to find trailheads and on relative use levels. The perceived level of usefulness was very similar for both (table 6). Few visitors felt the information was of no use, and a majority found it "useful" or "very useful." Over one-fourth had no answer, probably because many of them had not read the brochure, although they said they had seen it.

Visitors were also asked why they rated the brochure as they did. The trailhead location information was described as "generally useful" by 45 percent; 16 percent said it was useful because signs were poor. About 19 percent said it was not useful to them because they already knew the way, and 12 percent said it was not detailed enough.

The information on use levels was viewed as useful by 51 percent because it showed crowded areas, and by 3 percent because it had some horse use information. On the negative side, 12 percent said the use information was inaccurate, 7 percent said information on use levels was not important to them, and 3 percent said they had already made a choice of place to visit.

We also solicited open-ended comments about the brochure in general. About one-third of those who had seen the brochure commented, and almost all comments were positive or constructive. About 11 percent of those who had seen the brochure volunteered that it was good or helpful. About 13 percent wanted more detailed information, including distances, travel times, trail steepness, and other conditions. A few (2 percent) suggested the map cover a larger area. About 10 percent made other suggestions, such as to include information on fishing, cross-country skiing, and other activities.

Only 1 percent made negative comments such as

Table 6.—Evaluation of usefulness of the brochure by visitors exposed to it

	Percent of total response	
	Information about trailhead location	Information about relative use
Useless	6	7
Some use	18	15
Useful	24	26
Very useful	26	25
No answer	26	29

Table 7.—Reasons given for choice of trailhead by visitors

Reasons	Number	Percentage[1]
Scenery	137	23
Convenience	123	22
Friend's advice	87	16
Good place to fish	81	14
Novelty, variety	73	14
Easy trail	68	12
Familiarity	57	10
"Right type of trail"	56	9
Less crowded	27	4
Good place to hike	17	3
Good place for nature study	21	3
Trail on ridge or to peak	20	3
Good place to hunt	11	3
Forest Service brochure	4	1
Other	88	16
No reason	3	1

[1] Some visitors gave more than one reason, thus percentages add to more than 100

"waste of money." The request for open-ended comments also asked whether the brochure should be continued. Over 97 percent of those expressing an opinion favored continuation, although about 60 percent did not comment, which is not unusual for open-ended questions.

Factors in Visitor Location Choices

To provide a comparison with the factors stressed in the brochure, we asked visitors what influenced their choice of trailhead. The leading factors mentioned were scenery, convenience (closeness to home), advice of friends, fishing, easy trails, and two opposite reasons—novelty and familiarity (table 7).

Some of these factors are beyond direct Forest Service influence; they cannot be modified to alter use. Scenery, for example, cannot be changed within wilderness. Such features could still be described and used as appeals or repellents in information programs. Use levels, or crowding, by itself does not seem to be a major element, at least not in these volunteered comments. Fishing opportunities were cited by three times as many visitors as crowding.

DISCUSSION AND CONCLUSIONS

The effort by the managers to use information to redistribute visitors to the Selway-Bitterroot did not succeed in reducing the concentration of use on a few popular trails. The measure of use distribution changes is crude, and there are aspects of visitor opinions and reported behavior that should temper negative conclusions. However, the bottom line still is that the effort apparently did not achieve its objectives.

There are several reasons for the brochure's general ineffectiveness. Its distribution was limited—most visitors never saw it, and only about one-fourth had it before they reached the trailhead.

The content of the brochure had three weaknesses. First, it probably had too narrow a focus. It stressed use and crowding, which was not a major decision factor for many visitors. Fishing was not mentioned, and scenic quality was only touched on for two trails. Ease or difficulty of trails was mentioned in passing for only two trailheads.

Second, the information may have been too limited in detail. The use information only showed relative numbers entering at each trailhead and a few overused campsites. There was no information on camping use levels at destinations, such as lakes, or how use divided at forks in the trails. Especially in an area like this one with a large amount of day use, much of which is limited to the first few miles of trail, more detailed use distribution information might have influenced more visitors.

Third, a number of respondents indicated a lack of confidence in the accuracy of the use information. They commented on the low compliance at the trail registers, which seemed to be widely recognized. They were right; the use data were low in accuracy.

Many visitors felt the brochure could be improved. Most asked for more detailed information and for information on other aspects in addition to use levels.

The types of visitors common to the area probably made it more difficult to influence use patterns than in some other places. Most visitors lived nearby; for some, trailheads were almost in their backyards. The three heavily used trails are all in the northern half of the area, in the direction of Missoula, where over half of the visitors originated. Many visitors were already familiar with the area; new information could not be entered on a blank slate but had to compete with substantial, prior knowledge, some of which may have conflicted with information in the brochure.

On the positive side, most visitors who obtained the brochure found it useful, and almost all who expressed an opinion felt it should be continued. A higher proportion of groups who obtained the brochure before they reached the trailhead entered on lightly used trails compared to the total visitor population. About one-fourth of those with the brochure said they used it to choose a trailhead, and this proportion was higher on the lightly used trails than the heavily used ones. On lightly used trails, about 40 percent of those who had the brochure before they reached the trailhead reported their choices were influenced.

These types of desired location choices were apparently too small a part of total use, which grew rapidly during the study (an average increase of 26 percent per year, based on trail register data), to overcome trends toward greater concentration of use.

MANAGEMENT IMPLICATIONS

The results of this study, together with those of four other studies reviewed earlier (Schomaker 1975, Lime and Lucas 1977, Krumpe 1979, and Roggenbuck and Berrier 1980), indicate that the effect of information on wilderness use distributions can range from none to substantial. Information must be used in particular ways to be a useful management tool:

1. Information campaigns must be geared to management objectives. Managers must decide if they want to bring about a general redistribution (say from heavy to light use areas), or site-specific redistribution (probably a more appropriate objective), or help visitors match their desires and experiences better (a very appropriate objective and probably the easiest to achieve). Each objective or group of objectives needs to guide the design and conduct of the information campaign

2. The information must be delivered to a large proportion of visitors.

3. The information must be delivered early enough in the recreation location choice process to be of use to visitors. After people have arrived at an access point it is too late to influence that trip, although later trips might be affected.

4. Information provided should cover a variety of attributes of the environmental, use, and managerial setting. Different visitors have different objectives and will respond to varying types of information in different ways.

5. Considerable detail seems to be desired and perhaps necessary to compete with previous know-

ledge and advice of friends. More detailed information also may improve the credibility of information.

6. An information campaign cannot rely entirely on written material. Other research (Fazio 1979) has shown that brochures are often a much less important channel of communication than face-to-face communication. In the North Carolina Wilderness (Roggenbuck and Berrier 1980), personal contact was no more effective than a brochure alone for total use, but it did increase effectiveness with some types of visitors.

7. Some ethical issues of truth in information campaigns need to be faced. Some overused areas may, in fact, be very attractive, with good fishing, easy trails, and so on. Certainly, false information can never be used, but ethical guidelines are less clear on issues of selectivity, completeness, and emphasis.

8. Finally, managers must be sensitive to the danger of providing too much detailed information and taking away the sense of exploration and discovery that contributes to recreational experiences for many people.

Communication and education still look like promising tools for managing wilderness use. They are well worth the careful, skillful effort required for them to help achieve objectives of protecting wilderness and providing opportunities for wilderness recreational experiences.

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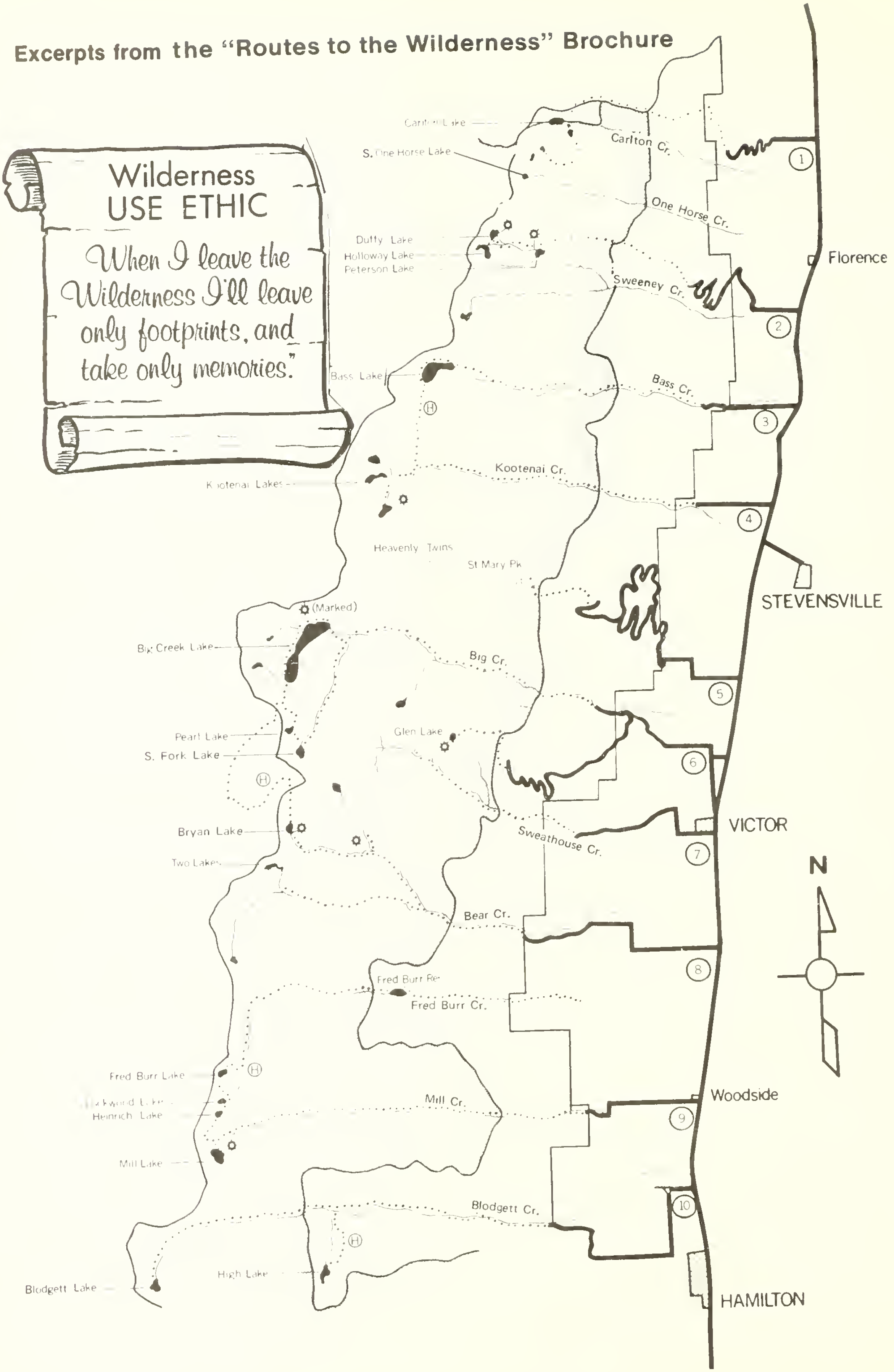
APPENDIX

Excerpts from the "Routes to the Wilderness" Brochure



① **CARLTON LAKE TRAIL** The access road is located 5.4 miles south of Lolo and 4.8 miles north of Florence. It is 4.5 miles from the sign on Highway 93 to the jeep road. As indicated by the Wilderness Trail Graph, this area is used very little by visitors. What is shown on the map as a trail to Carlton Lake is actually a jeep road. From there, the Wilderness trail heads into One Horse Canyon, an area which provides excellent opportunities for cross country exploring. Included in this area are two main lakes, Reed Lake and South One Horse Lake.

② **SWEENEY CREEK TRAIL . . .** To locate this access road, look for the Sweeney Creek Store, approximately 1.3 miles south of Florence or 8 miles north of the Stevensville turn off. There is a sign on the highway. This trail begins at the end of a logging road approximately 6.5 miles from Highway 93. The trail head is at 7,000 feet elevation. The trail leads to Peterson and Duffy Lakes. Campers should avoid using worn campsites which are shown on the map.

③ **BASS CREEK TRAIL . . .** The access road is about 4 miles south of Florence or 3.8 miles north of the Stevensville turn-off. A sign is located on the highway. From this sign follow the paved road to Charles WatersCampground, this is 2¾ miles. The trail head is at the west end of the Charles Waters Campground. A loop trip might be considered when planning your outing as Bass Creek and Kootenai Creek trails connect. We suggest the trip be made from Bass Creek to Kootenai Creek to reduce steep climbing.

④ **KOOTENAI CREEK TRAIL . . .** The access road to this trail is 7 miles south of Florence or [illegible] miles north of the Stevensville turn off. From the sign on the Highway, it is 2 miles to the trail head.

⑤ **ST. MARY PEAK TRAIL . . .** The access road is 3.4 miles south of the Stevensville turn-off and 4 miles north of Victor. From the sign on the Highway it is 12 miles to the trail head which is at an elevation of about 7000 feet. By trail it is 4 miles to St. Mary Peak where an outstanding view is offered of the Heavenly Twins and other peaks in the Bitterroot Mountain Range. This area is a good starting point for cross-country trips.

⑥ **BIG CREEK TRAIL - GLEN LAKE TRAIL . . .** The access road is located 6 miles south of the Stevensville turn-off, or 2 miles north of Victor. From the sign on the Highway it is 4½ miles to the trail head. This is the most heavily used trail on the District. To help restore overused sites, designated areas around Big Creek Lake are closed to overnight camping. Stock use is limited to through traffic and must remain on the trail. There are several possibilities for loop trips in this drainage either by trail or cross-country. To locate the Glen Lake Trail, take the same access road from Highway 93. Following the Forest Service signs, go past the Big Creek turnoff and continue for about 8 miles on the main road. The trail take-off is marked with a sign.

⑦ **SWEATHOUSE CREEK TRAIL . . .** This access route is in the town of Victor, one block south of the main street. Travel west for one mile and turn right at 'T' intersection. Then drive north for ½ mile and turn west. The access road passes through the yard of a private residence. From this point continue west, through a gate, for 1¼ miles (Do not cross Sweathouse Creek Bridge). You must walk up an old road from the parking (wide spot in road) area ¾ mile to the trail head. Entry to Sweathouse is through private land. Land owner permission is required to enter this canyon.
Sweathouse Falls is located about one mile outside the Wilderness Boundary.

⑧ **BEAR CREEK TRAIL . . .** Location of the access road is 3 miles south of Victor or 4 miles north of Woodside. A sign marks the turn-off from Highway 93. The trail head is 6 miles from the Highway. Within Bear Creek, there are three drainages, South Fork, Middle Fork, and North Fork. The North Fork is the only tributary where travel may be difficult. These forks contain some of the most outstanding scenery on the District.

⑨ **MILL CREEK TRAIL . . .** Location of the access road is in the Town of Woodside. From the Woodside intersection on Highway 93, travel west for about 2.5 miles and turn left at the 'T' intersection. The Forest Service access road is a few hundred feet beyond the Mill Creek crossing. The trailhead is at the end of this road. A loop trip may be taken from Mill Canyon into the Fred Burr drainage. Entry to Fred Burr Canyon is through private land. Land owner permission is required to enter as there is a locked gate.

⑩ **BLODGETT CREEK TRAIL . . .** The access road is 2 miles north of downtown Hamilton or 2 miles south of Woodside. There is a sign on Highway 93. The road makes numerous turns before reaching the trailhead, so watch carefully for Forest Service signs giving direction. The trail head is 6½ miles from Highway 93.

The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

The Intermountain Station includes the States of Montana, Idaho, Utah, Nevada, and western Wyoming. About 273 million acres, or 85 percent, of the land area in the Station territory are classified as forest and rangeland. These lands include grasslands, deserts, shrublands, alpine areas, and well-stocked forests. They supply fiber for forest industries; minerals for energy and industrial development; and water for domestic and industrial consumption. They also provide recreation opportunities for millions of visitors each year.

Field programs and research work units of the Station 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 the 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)

ERRATA

Lucas, Robert C. Redistributing wilderness use through information supplied to visitors. Res. Pap. INT-277. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1981. 15 p.

Research Summary (inside front cover)

Sentence beginning on tenth line should read:

Only about one-fourth had it before they reached the trailhead, and about 40 percent of these said they used the brochure to choose a trailhead, usually a lightly used one.

Page 8, column 2, line 27: Reference should be to table 3 instead of table 4.

Page 9, table 3: Number of campers should be 282, not 383.

Page 9, table 4: The first four numbers in the column "Number" should be 127, 104, 121, and 110. Numbers now shown are weighted numbers.

Page 12, column 2, lines 20 and 21

Last sentence in paragraph should read:

About 40 percent of those who had the brochure before they reached the trailhead reported their choices were influenced.

United States
Department of
Agriculture

Forest Service

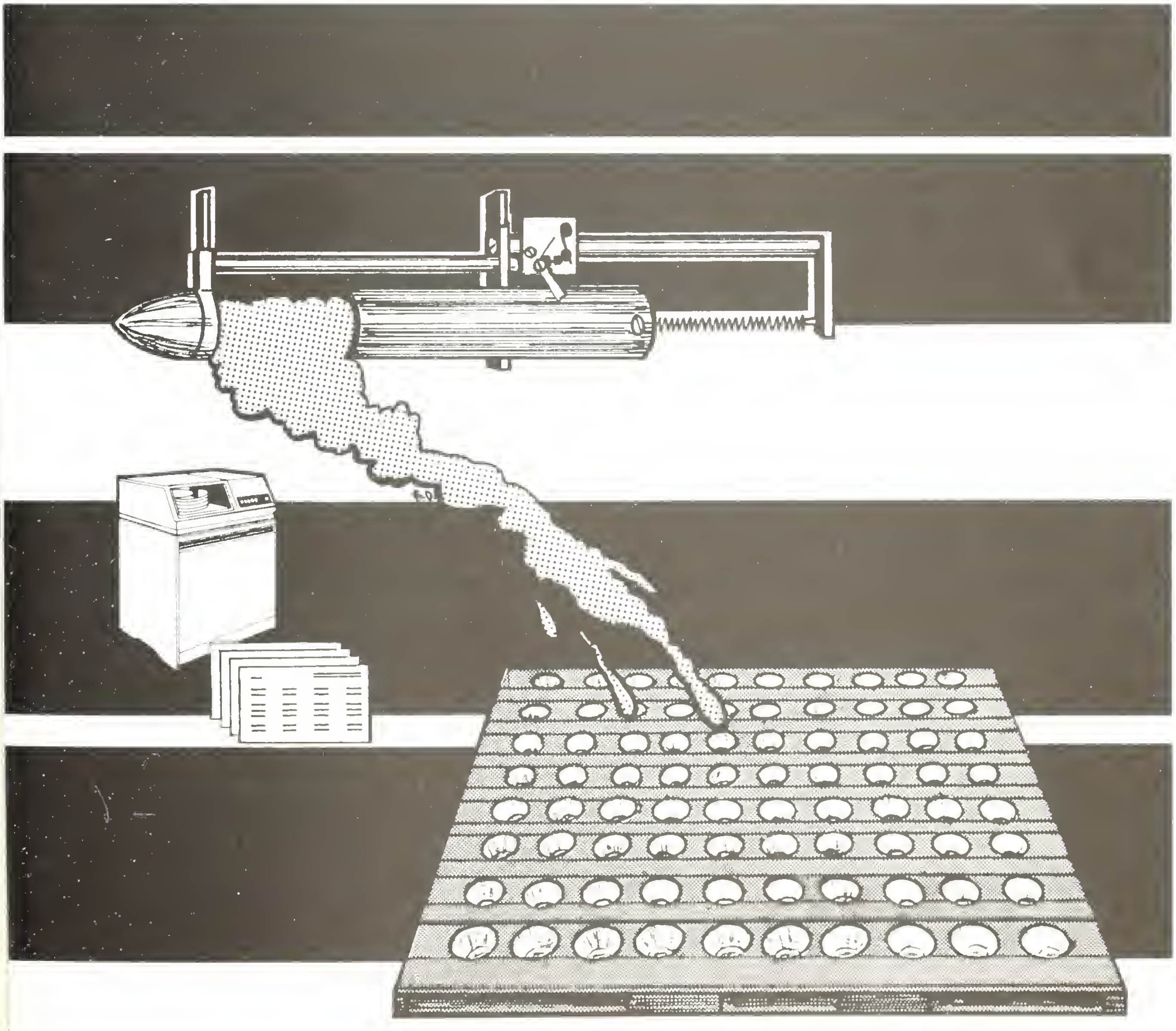
**Intermountain
Forest and Range
Experiment Station**

Research Paper
INT-278

August 1981

Correlating Laboratory Air Drop Data with Retardant Rheological Properties

Wayne P. Van Meter
Charles W. George



Research Summary

Based on the hypothesis that the spatial distribution on the ground of fire retardant materials, dropped from fixed-wing aircraft, must be a result of the physical properties of the retardant, a series of experiments has been run to measure the dispersal patterns obtained with materials of known density, viscosity, yield stress, surface tension, effective viscosity, and modulus of elasticity. The objective is the capability of predicting the relative size of the dispersal pattern from measurements made in the laboratory.

The experiments employed a 40 mi/h (64.4 km/h) wind tunnel airstream and 100 ml samples released 30 inches (76.2 cm) above the surface. An array of cups recessed into the surface trapped samples for weighing.

Correlation of the data shows that each of the six physical-chemical properties mentioned contributes to determining the size of the dispersal pattern. Deleting any one of them degrades the quality of the correlation, but effective viscosity (or elasticity) and density seem to be more important than the others. From other work (Andersen and others 1976) the effective viscosity has been found important in determining the droplet size distribution resulting from dispersal at any given aircraft speed.

Recommendations are made for future study that include refined wind tunnel experiments and correlation of these with accurately monitored full-scale field tests.

The Authors

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August 1981

Correlating Laboratory Air Drop Data with Retardant Rheological Properties

**Wayne P. Van Meter
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NTRODUCTION

Aircraft of several types have been used for nearly 30 ears to deliver water or water-based mixtures onto fuel materials in the course of attempts to control or extinguish wildfires. Over the years, numerous revisions have been made of techniques and changes of mixture composition. Most resulted from attempts to improve the distribution of he retardant, its wetting or coating action on the fuel, or its actual performance once it had been applied.

For example, it was recognized early that the thickness, r viscosity, of the retardant has some effect on the beavior of a freefalling, coherent mass of liquid (Davis 1959). Full-scale field tests in 1955 to 1959, using simultaneous drops of different compositions, showed by simple comarison that thickened materials reached the ground in a more coherent mass and in a shorter total length of time han water alone.

Other studies (MacPhearson 1967, Swanson and others 1978) have been directed toward characterizing aircraft nd tank mechanism performance. There have been everal experimental studies (Wilcox and others 1961) and t least one theoretical study (Garcia and Wilcox 1961) of he behavior of liquid volumes of various sizes falling from est in still air.

In actual practice, viscosity is the most common, and usally the only measurement used to monitor and control he mix of retardant formulations in field operations. Alhough viscosity can usually be related to a formulations reparation, it is known that the viscosity of a retardant oes not directly relate to its aerial delivery characteristics nd performance. It may be possible, however, through quantification of additional retardant physical-chemical heological) properties, and using new and more sophistiated instrumentation and techniques, to determine and elate more appropriately these properties to the retardants ull-scale field performance.

The purpose of the work has been to explore some measurements that could be made and to identify those hat more appropriately relate to aerial delivery, deformation, breakup, dispersion, and distribution on the ground under actual drop conditions. Most of the experimental work was done in 1970 and reported in an in-house document by the Northern Forest Fire Laboratory. Since then instrumentation has become available for measuring the elastic properties of fluids, and other important related studies have been conducted (Andersen and others 1974a, 1974b, and 1976) placing an additional value on the original effort. The present report embodies recent (1979) elasticity data, considers the findings of Andersen and others (1974a, 1974b, and 1976) and includes a more thorough data analysis. In the following two sections, the equipment and material used will be described and their performance qualitatively, but critically, described.

EQUIPMENT AND MATERIALS

Attapulgite clay-water, Colloid 26 (modified polysaccharide)-water, and CMC (sodium carboxymethyl cellulose)-water mixtures were prepared from material samples supplied by manufacturers from stocks used in blending brand name retardant products. The Fire-Trol™ retardant sample came from stocks at the Missoula Region 1 Airtanker Retardant Base. The Arcadian Poly-N™ used was from a test sample of 10-34-0 concentrate supplied by the manufacturer. The Phos-Chek™ samples also were supplied directly by the manufacturer. The CMC type is a standard product and the Colloid 26 type comprises three samples containing enough thickener to produce Brookfield viscosities of about 800, 1500, and 2200 centipoises. In each case, the formulation was made by adding the indicated amount (table 1) a little at a time for about 1 2 minute into 500 ml of distilled water in a Waring blender running at its "slow" setting for exactly 2 minutes. The mixture was stored overnight in a closed jar before being used in wind tunnel tests or in physical property measurements.

Brookfield viscosities [illegible] were obtained from [illegible] field Viscometer model LVF equipped with [illegible] of rotation at [illegible] making the measurement.

Table 1.--Test samples and their mixing ratios

Sample	Material	Amount/ 500 ml water
Att 1	Attapulgite clay	80.0 g
Att 2	Attapulgite clay	40.0 g
Att 3	Attapulgite clay	25.0 g
Att 4	Attapulgite clay	60.0 g
FT 1	Fire-Trol 100	166.0 g
FT 2	Fire-Trol 100	166.0 g
CMC 1	CMC	7.0 g
CMC 2	CMC	3.5 g
CMC 3	CMC	5.0 g
CMC 4	CMC	2.0 g
PC 7	Phos-Chek 202	68.3 g
PC 3	Phos-Chek 202	68.3 g
XA 7	Colloid 26	8.0 g
XA 3	Colloid 26	2.0 g
PC 3	Phos-Chek 202XA	68.3 g
PC 4	Phos-Chek 202XA	68.3 g
PC 5	Phos-Chek 202XA	68.3 g
PN 1	10-34-0 concentrate (Arcadian Poly-N)	167 ml
PN 2	10-34-0 concentrate (Arcadian Poly-N)	84 ml
PN 3	10-34-0 concentrate (Arcadian Poly-N)	125 ml

Note: Phos-Chek XA formulations were thickened with Colloid 26.

Densities were measured in Pyrex pycnometers containing about 30 ml each.

Using a Haake Rotovisco™, rotational viscometer, data could be obtained from which the yield stress could be derived. By varying the speed of rotation of the rotor, values of shear stress were observed for a series of values of the rate of shear. When these values are plotted and the curve extended to zero rate of shear the shear stress axis intercept is defined as the yield stress. An alternative method, which yields similar values, involves plotting on log-log coordinates the shear stress against the rate of shear and finding the stress at the point at which the curve departs from linearity. A medium viscosity measuring beaker and MV-I and MV-II rotors were used.

In order to measure the surface tension of the liquids, a tensiometer of the "jolly balance" type was devised (fig. 1).

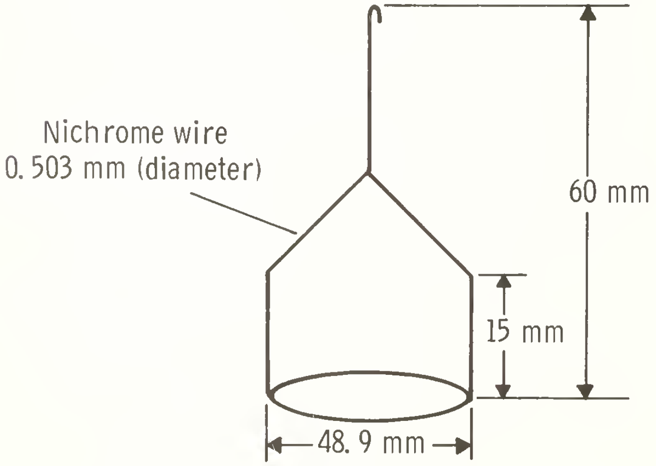


Figure 1.--Tensiometer ring.

The sample vessel, a 4-in (10 cm) Petri dish, rests on a pla form about 8 in (20 cm) long, hinged to a solid support o one end and suspended by a waxed linen cord at the othe end. The cord is fastened to the shaft of a synchronou motor. The motor speed and shaft diameter are chosen s that the vertical (downward) rate of motion of the center o the sample is about 12 mm per minute. A wire ring i suspended in such a way that the plane of the ring is parall to the surface of the sample and its weight is borne by microbalance-arm attachment on a Statham strain gag The gage has a 60-g capacity, while the 2-3/4-in (7 cm beam arm has a mechanical advantage of 10.

The strain gage signal is amplified by a Statham Universal Readout (Model UR5) and recorded by a Bausch an Lombe VOM5 recorder. Calibration is effected by adjustin sensitivity and balance controls until hanging a 3-g weigh on the balance hook (the ring already being in place causes the recorder pen to move from exactly zero to exactly full scale.

Air velocity in the wind tunnel was controlled at 40 mi/ (64.4 km/h) (± 0.5 mi/h (± 0.8 km/h) estimated fluctuatio limit). The conditions of temperature, pressure, an humidity that were not controlled were in the ranges of 82 to 85° F, 680 to 685 mm Hg (total), and 20 to 22 percent relative humidity. The wind tunnel is of square cross sectio 36 by 36 inches (91.4 cm).

The sample release mechanism holds 98.4 ml of liquid. consists of a spring-actuated cylindrical container whic on release, moves away from a flat, gasketed end plat sliding over a fixed piston. The chamber is 3.7 in (94 mm) i length by 1.4 in (36.5 mm) inside diameter. The liquid contained in the horizontal cylinder and between the end plat and the piston is thus left free to fall with zero initial momentum. Liquid-tight closure is provided by a 1/16- b 1-3/8 in (1.6 by 34.9 mm) rubber O-ring recessed into th edge of the piston and by a silicone rubber facing (G.E. "RTV") on the end plate. The mechanism is filled through 1/2-inch (12.7 mm) hole in the end plate. Figure 2 show the sample release mechanism in a closed and open or release position.

Figure 2.--Sample release mechanism shown in a closed (a) and release (b) position.

The pattern measurement system is an array of 480 poly-lined paper cups (average lip diameter 4.59 cm) positioned in 1-3/4 in (4.44 cm) holes spaced 3 in (7.62 cm) center-to-center in 1/4-in (0.635 cm) plywood sheets (fig. 3). The array is 10 cups wide and 48 long (parallel to wind direction). The plywood is mounted on 1-in (2.54 cm) blocks to allow the cup rims to be flush with the upper surface of the tray. Masking tape strips are effective in preventing dislodging of cups by holding the upwind edge of the lip against the tray. The vertical distance between the center line of the release mechanism cylinder and the tray surface is 30-1/2 in (77.5 cm).

Figure 3.--Sample cup tray, one of six trays that are placed side by side and used simultaneously.

Photographic observation of the release of liquid in the vind tunnel was conducted using two different camera and ight combinations. In order to determine whether the reease mechanism functioned rapidly enough and to observe directly the sequence of motions and shapes during dispersal, a high speed motion picture camera was used (Traid 200). Four 320-watt floodlights were located inside he tunnel, downwind, about 6 ft (1.83 m) from the release point. Another light (500 watts) was located outside the unnel, facing inward at the lower left corner of the tunnel vindow, making an angle of about 60 degrees with the camera's line-of-sight. Camera-to-subject distance was about 10 ft (3.05 m). The film was Kodak High Speed Ektachrome Type B. Four different materials (CMC 2, CMC 4, PC 1, and water; see compositions and properties n table 1 and table 2) were each photographed twice, once vith a 25-mm lens and once with a 75-mm lens.

To make measurements of the relative distributions of droplet sizes in midair after breakup of the main liquid mass, a Graflex Crown Graphic camera with a Kodak Ektar 4.5 lens was employed at f22. Subject distance was about 3-1/2 ft (1.07 m). Stroboscopic light sources (Synctron 00B, Dormitizer Co.) were used, one to the left at about 5 degrees to the camera direction, the other below and lightly to the right.

To avoid a highlight reflecting from the back wall of the unnel, the camera was aimed upward at a slight angle (15 r 20 degrees from horizontal). Film was Polaroid Land Packets Type 55 P/N.

The apparent sizes of droplets, as viewed through the yepiece reticle of a 12.5x binocular microscope, were compared to that of a 12-in (30.5 cm) ruler, photographed suspended under the release mechanism.

Equipment Performance

The measurement of viscosity with the Brookfield instrument has been, and should remain, popular because it is rapid, simple, and reproducible. Since the retardant materials are non-Newtonian in behavior, the viscosity as measured with the Rotovisco can agree with that of the Brookfield at only one rate of shear (for the one chosen Brookfield shear rate).

The use of the Rotovisco to measure yield stress is briefly mentioned by Van Wazer and others (1963). According to W. W. Morgenthaler (personal conversation), this method involves rapid engaging and disengaging of the rotor drive gears, producing enough rotation of the drive shaft to give a dynamometer signal (measurement of torque), but not enough to move the rotor much at all. The yield stress, then, is the maximum force that can be applied to the rotor without causing rotation. In the work being reported here, attempts also were made to measure yield stress by slowly turning the beaker, by hand, and observing the stress produced before any shearing occurred. Neither of these techniques worked well. It is not easy to rotate the shaft a desired amount with the gear lever, and duplicate run data did not agree. The log-log graphs of shear stress against shear rate are smooth enough to be believable; it is almost always possible to identify the point where linearity ceases and duplicates give similar values. Samples that contain large amounts of attapulgite clay yield more uncertain results because shearing by the measuring instrument increases viscosity and yield stress.

The measurement of surface tension was verified by comparing experimental results on certain pure liquids with values found in standard reference books. For example, the accepted value for water at 25° C is 72.3 dynes/cm. The observed value was 73.2 dynes/cm. Similar comparisons were seen for ethanol, chloroform, and acetone. The apparent value was independent of the rate of motion of the sample platform, both for rates somewhat slower and considerably (two or three times) faster than the one used here. The effect of temperature on the surface tension is only a few hundredths of a dyne per centimeter over a range of several degrees. This is at least 10 times smaller than usual differences between replicate samples. It is quite important, however, to be sure that the sample vessel and the ring are carefully washed, thoroughly rinsed, and untouched prior to each run. It is also true that careful attention must be paid to preserving the shape of the wire ring and its horizontal attitude when suspended from the balance hook. This adjustment also includes achieving, as nearly as possible, simultaneous release of all parts of the ring from the liquid surface. Accuracy is lost if the ring breaks loose from one side and swings.

To secure dependable operation of the mechanism used to release the retardant sample in the wind tunnel airstream, it was necessary to lubricate the O-ring with a few drops of light mineral oil, which was applied to the inside of the cylinder behind the piston. It is likely that the need for lubricant could be eliminated by using an O-ring with slightly larger diameter and by adjusting the groove depth to cause slightly less pressure against the inner wall of the cylinder.

Table 2.--Sample composition, properties, and dispersal pattern areas

Sample			Date	Composition		Density (d)	Brookfield viscosity (N_b)	Yield stress (Y)	Surface tension (S)	Dispersal pattern areas		
										$D>10$	$D>1.8$	Total, $D>T$
						g/ml	Centipoise	Dyne/cm^2	Dyne/cm	-------Percentages-----		
Attapulgite + water	Att	1A	7/16	13.8	percent clay	1.071	4240	450	73.0	2.3	9.4	37.7
	Att	1B	7/29	13 8	percent clay	1.075	[1]N M.	480	77.2	2.5	9.4	38.8
	Att	2A	7/15	7.41	percent clay	1 041	490	37	71.6	2.9	11.7	58.8
	Att	2B	7/29	7.41	percent clay	1.039	670	72	73.4	4.6	22.7	55.4
	Att	3A	8/1	4 76	percent clay	1.025	190	5	71.9	3.5	18.1	65.4
	Att	4A	8/22	10.7	percent clay	1.046	2865	320	75.1	N.M.	N.M.	N.M.
Fire-Trol 100	FT	1A	7/29	9.0	percent clay	1 144	2240	170	78.3	5.6	36.5	76.5
	FT	1B	8/1	9.0	percent clay	1.140	2415	200	76.7	4.6	29.2	80.4
	FT	2A	8/22	9.0	percent clay	1.147	2850	230	77.8	N.M.	N.M.	N.M.
CMC + water	CMC	1A	7/16	1.38	percent CMC	1.002	780	20	70.5	4.4	11.1	36.5
	CMC	1B	7/29	1.38	percent CMC	1.004	1005	20	72.7	4 6	18.8	35.6
	CMC	2A	7/15	70	percent CMC	999	150	20	72.4	4.2	15.8	37.9
	CMC	2B	7/24	70	percent CMC	.999	155	20	72.3	1.9	22.1	69.4
	CMC	3A	8/22	99	percent CMC	1.003	260	10	73.1	N.M.	N.M.	N.M.
	CMC	4A	7/24	40	percent CMC	999	55	30	72.9	4.0	14.6	63.6
Phos-Chek 202 (CMC)	PC	1A	7/24	1.02	percent CMC	1 070	410	5	64.6	3.8	10.2	76.5
	PC	1B	7/30	1.02	percent CMC	1.070	650	20	63.2	4 6	11.7	69.2
	PC	6A	8/22	1 02	percent CMC	1.075	1125	60	70.9	N.M.	N.M.	N.M.
Colloid 26	XA	1A	7/30	1.57	percent XA	987	9050	800	N.M.	4.0	5.8	10.0
	XA	3A	8/1	.40	percent XA	.999	200	15	71.1	5.0	27.7	61.7
Phos-Chek 202 XA (Colloid 26)	PC	3A	7/30	800	cP	1.059	N M	50	70.1	4.8	20.6	63.1
	PC	3B	7/31	800	cP	1.070	1040	70	71.4	5.4	26.1	66.1
	PC	4A	7/31	800	cP	1.070	1680	120	69.9	5.6	14.6	59.4
	PC	4B	7/31	1500	cP	1.071	845	100	70.3	4 2	17.7	66.3
	PC	4C	8/22	1500	cP	1.068	1555	75	67.4	N.M.	N.M.	N.M.
	PC	5A	7/31	2200	cP	1.070	2010	180	71 6	6.7	26.5	60.4
Arcadian Poly-N 10-34-0	PN	1A	7/23	1 3		1.119	25	8	76.6	6.3	36.7	74.0
	PN	1B	7/25	1.3		1 118	25	8	79.3	6.3	29.0	66.7
	PN	2A	7/23	1 6		1.069	25	8	79.0	1.9	19.8	64.8
	PN	2B	7/25	1 6		1.081	25	8	79.0	1.9	19.8	64.8
	PN	3A	8/22	1 4		1 103	25	8	77 6	N M.	N M.	N.M.
Water	W	1A	7/22			.999	0	0	73.2	1.3	8.8	59.2
	W	1B	8/1			.999	0	0	73.2	3.5	30.6	67.3
	W	2A	7/22			.999	0	0	73.2	2.9	18.8	63.8
	W	2B	7/30			999	0	0	73.2	3.3	18.1	63.6

N M Values not measured or omitted due to equipment malfunction

The indicated data are used for further analysis which is discussed later

Special mixtures supplied by the manufacturer Thickener has been adjusted to give the specified viscosity

Because of the adherence of some of the sample material to the end plate and piston of the release mechanism and the spreading of some along the outside of the cylinder by the airstream, the volume released into the air is about 90 percent of the cylinder's volume. This applies to Phos-Chek and Fire-Trol of nominal viscosities.

The average length of time for complete opening of the sample release mechanism was 0.082 second (as measured from high-speed photographs of several retardant releases). The release was fast enough that the motion of the main portion of the sample was negligible during movement of the cylinder. The front portion of the sample, within a centimeter or so of the end plate, had begun to fall and to enter the airstream by the time the cylinder reached th end of its travel.

The impact of the cylinder on the recoil pads causes th whole mechanism to vibrate. No disturbance occurs at th front, because the sample has moved out of contact wit the end plate. At the rear, a small wave or ridge of liquid sometimes propelled downward by the piston movin against the portion of the sample adjacent to it. Samp cups were handled and weighed as quickly as possible minimize error caused by evaporation of water. A fe double weighings of cups, containing small, but measu able, amounts of material, showed that losses ranged fro 10 to 20 percent. Losses from larger samples were muc ess. The average tare weight was 1.01 ± 0.02 g/cup. The ikely weighing error was ± 0.01 g. Weights less than 0.03 g vere recorded as "trace." Overlays of Saran Wrap were ised to cover the samples as soon as the cups were renoved from the wind tunnel trays.

The cup contents data were reduced to milligrams of reardant per square centimeter of horizontal surface area ind entered on scale drawing plots of the cup array. Conours of equal density were drawn by enclosing all points vhose density values fell at or above certain arbitrary alues, namely: 1.8, 3, 10, 50, and 200 mg/cm². The areas epresented within these contours were computed by ounting the number of cups involved and dividing by 480, he total number of cups in the trays. The data from one un, Fire-Trol 100 (FT 1B, 8/1 of table 2), were handled in a vay that was more time consuming, but might have been nore meaningful. Iso-density contours were located for .0, 3.0, 5.0, 10.0, 20, 50, and 100 by interpolating between eighboring cup positions to find discrete points of interal density value. The areas enclosed in these contours vere measured with a planimeter. Neither the gross apearance of the dispersal pattern nor the numerical area alues were different enough from the more simple method o indicate significant error. The areas were the same withn a few percent of their own sizes.

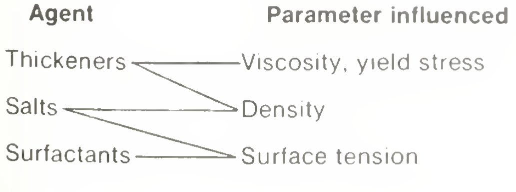
The single exposure photos made with the Graflex camra and stroboscopic light source do reveal much more deail about the configuration of the liquid and the sizes of the rops than do any of the single-frame prints from the Traid 00 film. Successive events in the dispersal of any one samle, however, are not revealed. Also, only about one-half of percent of a given 100 ml charge appears in any one raflex photo in the form of droplets that are small enough ot to be subject to further breakup before impact. Conequently, the validity of drop-size distribution relationhips and further analysis is questionable.

Synchronization of the Graflex shutter action with the osition of the falling liquid must be made independent of ne human eye-hand reflex if this technique is used again. Ione of the photos obtained were really well-centered in ne field of view. Automatic shutter actuators and photolectric sensors would enhance photo quality.

In evaluating the photographic setup and determining vhether enough of a given sample was in the field to make ome drop-size measurements possible, we saved time by sing Polaroid Land film. Better control of exposures vould make it possible to use ordinary film, chosen for ptimum speed and grain size. With the Polaroid film, nuch of the size estimation data carries an estimated ncertainty of from +10 to +50 percent of the indicated liameters.

ORRELATIONS

The diagram below indicates some general relationships nat are worth noting:



There are three major types of ingredients in one column and three measurable physical properties in the other. Viscosity and yield stress seem always to be related, although not always directly proportional to each other. All of the thickeners have an effect on viscosity and yield stress, none have much effect on the surface tension of the mixture. The polymers and gums have essentially no effect on density, whereas the clays have considerable effect. The concentration of salts affects density and surface tension, but has virtually no influence on viscosity. Any surface active agent has a more pronounced effect on surface tension than either of the other two ingredient types has on any of the measured properties.

Distinct differences can be observed among the several materials tested, both in the sequence of events in midair during breakup and in the dispersal pattern on the impact surface. These differences can only be due to mechanical effects (forces) acting between the two fluids as the retardant penetrates the airstream. Thus, it is reasonable to expect variations in physical properties to be associated with changes in dispersal behavior. The simplest of such relationships would be a linear or regular curvilinear trace when numerical values of two such quantities are graphically compared.

Yield Stress and Viscosity Versus Area

In figures 4 and 5, the variations of the total area covered with yield stress and viscosity are shown. The data for Colloid 26 are meager, and the general shape of the curve is inferred by those of the other materials. The trends are in agreement with experience and intuitive expectations, the more resistant a fluid is to shearing forces, the smaller will be the volume of space occupied by droplets when the initial breakup and dispersal has used up all the momentum imparted by the aircraft's forward speed.

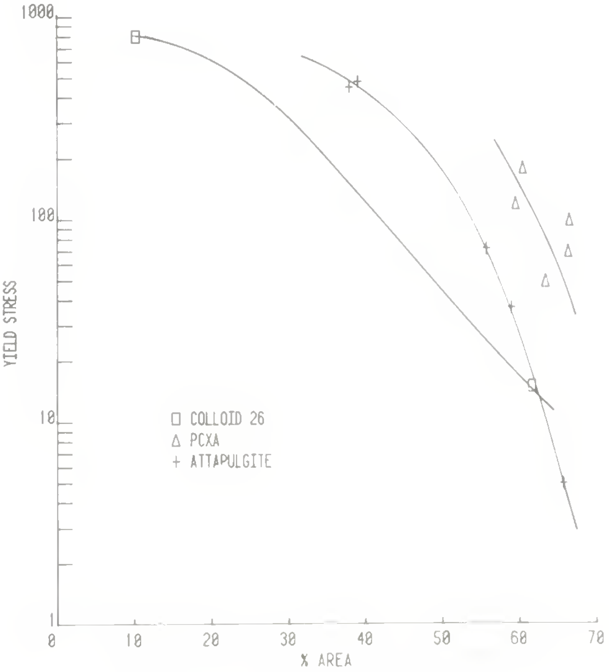


Figure 4.--Pattern coverage as a function of yield stress.

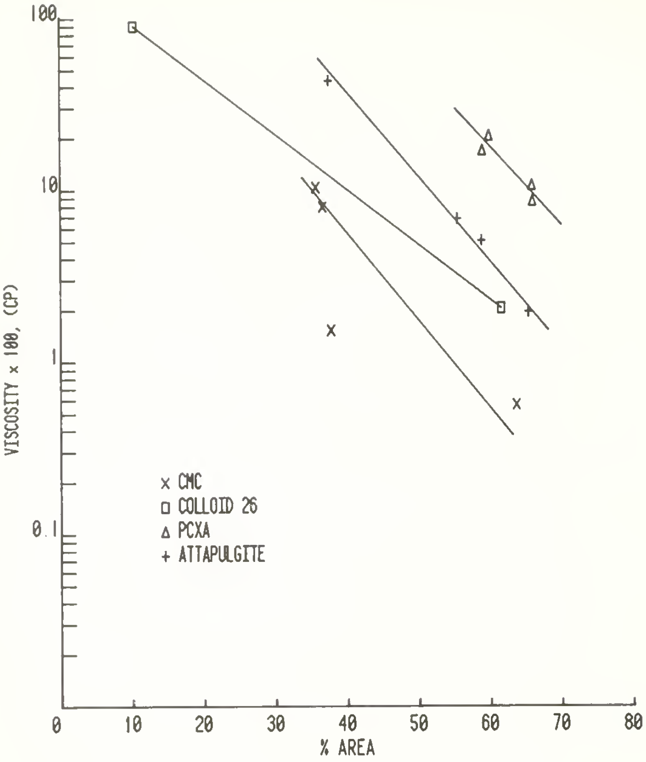


Figure 5.--Pattern coverage as a function of viscosity.

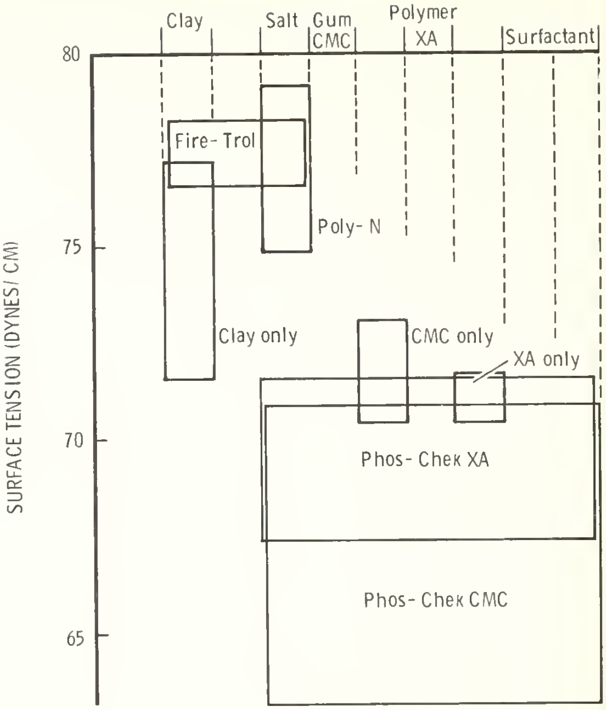


Figure 6.--Surface tension of test samples. Rectangles indicate the primary ingredients and the ranges of surface tension values observed.

Surface Tension

When all the samples run were considered in the order of their surface tensions, a significant grouping appears (fig. 6). The precision of the measurement is felt to be in the order of ± 2 dyne/cm. Nearly all of the values for the two-component mixtures (water and CMC, attapulgite clay, or Colloid 26) lie within ± 2 dynes/cm of the value for water alone (73.2 dynes/cm). When ammonium phosphate alone is present (as in 10-34-0) the surface tension is high. When clay is present with the salt (Fire-Trol), the salt has the same effect it has when alone. The marked depression of the surface tension in Phos-Chek mixtures cannot be logically ascribed to CMC and Colloid 26; neither has any effect alone. The corrosion inhibitor in all Phos-Chek formulations has a chemical identity that should cause it to have considerable potency as a surface active agent. When this material is solublized in distilled water at the same mass per volume concentration at which it occurs in Phos-Chek retardant mixed for use, the observed surface tension is about 60 dynes/cm.

Droplet Size Distribution

The measurement of the size distribution of droplets during the breakup process produced the graphs shown in figure 7. A high, narrow peak would indicate that the material tended to produce a uniform spray and that many drops would be of about the same size. The highest frequency observed was for 1.4-mm drops of pure water. Two other materials showed values nearly as high, however, and the difference may not be significant. It is clear that a trend exists, with high viscosity in the absence of salt (Att) producing the widest range of sizable frequencies. As salt content is increased, or as viscosity is decreased, the shape and position of the drop size distribution curve approaches that of water.

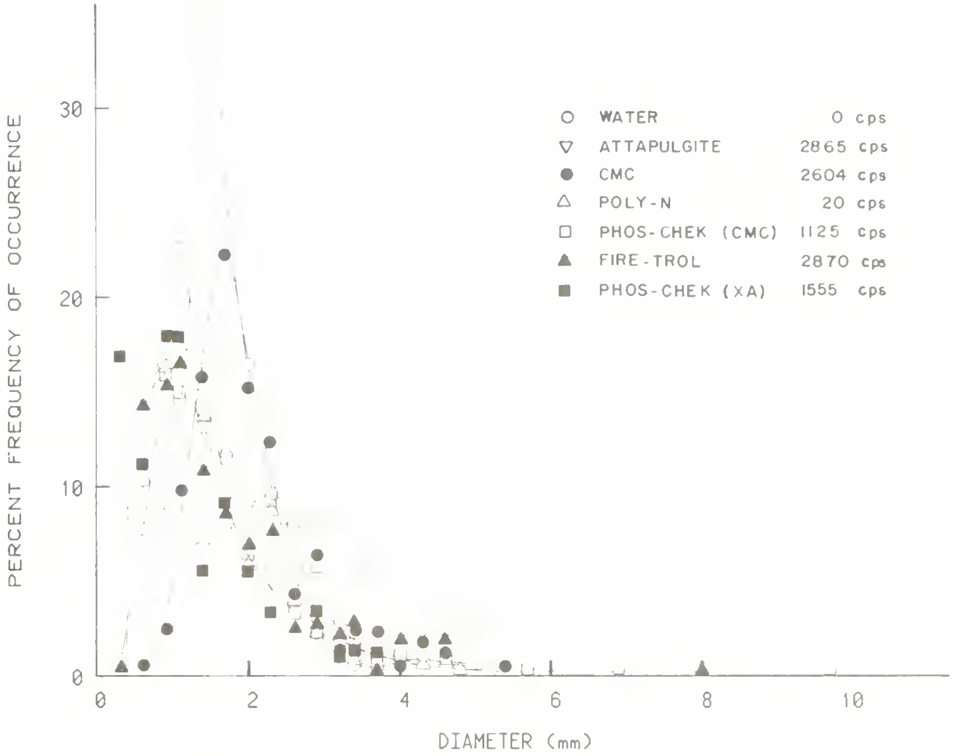


Figure 7.--Frequency of occurrence of droplets by diameter.

The droplet size distribution results should be regarded with caution for two major reasons. The photographic-optical method of comparison was not verified by any independent means to ensure that parallax or image quality was not introducing sizable error. Also, the object-camera distance was short enough that the limited depth of field caused only the drops near the centerline of the pattern to be in focus. Many were not visible at all, and size perception may have been incorrect for those not in sharp focus that were measured. In addition, a total of only 1,450 drops were measured from seven photographs. The statistical base is not strong, and reproducibility was not demonstrated.

Pattern Area Predictions

Correlation of the density, surface tension, and rheological properties with the drop pattern areas was accomplished by a computer program which generated the best linear least squares fit and supplied an analysis of variance and the coefficients of the equations. The data were handled in two phases. The first utilized 21 sets of data (those in table 2, excluding those for which pattern areas are not given, Poly-N, and water). The expression used in the computations has the form:

Dispersal pattern area = D (density) + N_b *(Brookfield viscosity)* + Y (yield stress) + S(surface tension) + constant, where the symbols D, N_b etc. are coefficients determined as a result of the analysis, and the parenthesized quantities identify numerical data items.

The results are given in the first three lines of table 3, where the main body of the table displays the coefficients of the above equation which yield the regression coefficient, r^2, found in the last column.

The second phase employed elasticity data. Samples were prepared (during 1979), using the original stocks of clay, CMC, and Colloid 26, that replicated the mixtures that produced some of the pattern area data in table 2. Elasticity and viscosity data were measured on these 1979 samples. It is assumed that values of the effective viscosity and of the modulus of elasticity, calculated from elasticity measurements made in 1979, can be used with the pattern areas and other data measured in 1970 on essentially identical materials. Six of the samples shown in table 2 have been chosen as those most closely resembling the 1979 samples in terms of their Brookfield viscosities, yield stresses, and surface tensions. They were identified in table 2 (see footnote 2) and by sample number in Part A of table 4. The values given for the effective viscosity and the modulus of elasticity were determined from original Rotovisco data using several known relationships.

Apparent viscosity $(N_a) = U\,S_c\,k$

where.
U the rotational speed or gear setting of instrument
S_c scale reading of instrument (a measure of existing torque)
k an instrumental constant derived from the rotor and cup dimensions

Table 3.--Linear regression coefficients for different levels of pattern coverage

Number of data sets	Coverage level	Density (d)	Brookfield viscosity (N_b)	Yield stress (Y)	Surface tension (S)	Modulus[1] of elasticity (G)	Regression constant	Regression coefficient
		g/ml	*Centipoise*	*Dyne/cm²*	*Dyne/cm*	*Dyne/cm²*		
	$D>1.8$	56.81	0.00446	0.0798	1.428		-142.0	[3]0.635
21	$D>t$[2]	245.6	-.00446	-.00993	-.475		-158.2	[3].758
	$D>t$	246.0	-.00539		-.519		-155.4	.758
	$D>1.8$	58.98	-.00190	.0444	1.152	-0.00188	-124.3	[3].708
	$D>1.8$	55.44		.0233	1.450	-.00189	-142.2	.708
	$D>1.8$	70.66	-.00383	.0342	.986		-125.1	.554
	$D>1.8$	78.24	-.00775	.1099		-.00187	-60.93	.699
	$D>1.8$	51.57	.00204		1.777	-.00187	-161.9	.705
	$D>1.8$		.00355	-.0165	2.662	-.00197	-172.2	.671
11	$D>t$	226.8	-.0295	.3512	-2.542	-.00375	9.186	[3].929
	$D>t$	250.1	-.0334	.3310	-2.873		7.634	.802
	$D>t$	184.3	-.0166	.2066		-.00379	-130.7	.919
	$D>t$	168.1	.00168		2.412	-.00368	-288.4	.884
	$D>t$	171.7		.0237	2.108	-.00391	-270.1	.889
	$D>t$		-.00857	.1172	3.266	-.00411	-174.9	.813

[1] Modulus of elasticity (G) determined from measurements and calculations during subsequent tests and discussed later in this paper

[2] t = trace

[3] Indicates those sets of coefficients producing figures 8, 9, 10, and 11.

Table 4.--Rheological properties and pattern area data

Specimen code	Density (d)	Brookfield viscosity (N_b)	Yield stress (Y)	Surface tension (S)	Effective viscosity (N_e)	Modulus of elasticity (G)	Pattern area $D>1.8$	Pattern area $D>t$
	g/ml	*Centipoise*	*Dyne/cm²*	*Dyne/cm*	*Centipoise*	*Dyne/cm²*	*- - - - -Percent- - - - -*	
A.[1]								
Att-2A	1.041	490.0	37	71.6	20	648	11.7	58.8
CMC-1A	1.002	780.0	20	70.5	134	1,934	11.1	36.5
CMC-2A	.999	150.0	20	72.4	45	839	15.8	37.9
CMC-4A	.999	55.0	30	72.9	59	64	14.6	63.6
XA-1A	.987	9,050.0	800	71.0	137	14,970	5.8	10.0
XA-3A	.999	200.0	15	71.1	31	162	27.7	61.7
B.[2]								
PC-XA-K	1.071	800.0	63	71.0	125	649	20.0	65.0
PC-XA-K	1.074	1,500.0	100	71.0	191	819	22.0	60.0
PC-259	1.092	87.5	39	75.0	34	5,770	18.0	57.0
FT-100	1.105	1,600.0	193	77.0	78	1,523	37.0	77.0
FT-100	1.104	2,150.0	242	77.0	98	2,229	29.0	80.0

[1] The effective viscosity and modulus of elasticity were measured on replicate specimens during 1979. All other data are from table 2

[2] All measurements were made in 1979, except that pattern area percentages are taken from table 2 using values (in some cases averages) from samples in table 2 of composition and properties most similar to those of the 1979 samples.

Recoverable shear (elastic strain, s) = ϕ / c

where: ϕ = angle of relaxation instrumentally observed (a measure of elasticity)

c = an instrument constant

Using these relationships the effective viscosity and modulus of elasticity are calculated:

Effective viscosity (N_e) = $N_a\ (1 + s)$

Modulus of elasticity (G) = $\dfrac{s\ a\ c}{\phi}$

where: a = an instrumental constant characteristic of the rotor and cup.

The second phase also included five commercial retardant samples, prepared and studied in 1979, in order to provide a wider range of density values. Density, Brookfield viscosity, and yield stress data for these were compared with those of similar materials in table 2. Estimated values of pattern area percentages were assigned to the 1979 samples (for which wind tunnel data could not be obtained) based on identical or averaged values of the pattern area from table 2. The complete data sets for these samples are shown in Part B of table 4.

The results of the regression analyses of the 11 data sets shown in table 4 are given in the latter part of table 3. Because the effective viscosity and the modulus of elasticity are both functions of the same two measured quantities, ϕ and S, the inclusion of both in a regression computation would be redundant. Values of the effective viscosity are given in table 4, but were not used in the computation; thus it does not appear in table 3.

Dispersal pattern area D(density) + N_b (Brookfield viscosity) + Y(yield stress) + S(surface tension) + G(modulus of elasticity) + constant

Blanks in table 3 indicate those variables which were omitted for that computation. This allows some estimation of the relative importance of that variable to the quality of the correlation.

Figures 8, 9, 10, and 11 represent graphically the four computations indicated by footnote 3 in table 3. Each of the 11 (or 21) sets of data generates one point for each of the two pattern areas used.

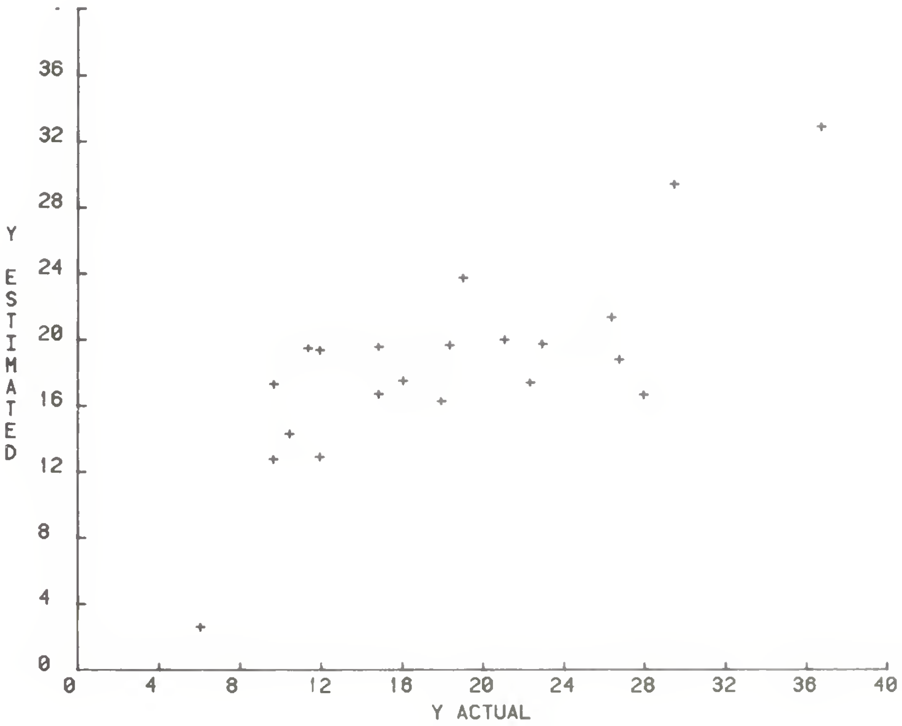


Figure 8.--Plot of pattern areas observed (actual) against those predicted by the model based on 21 data sets of four variables at density > 1.8 percent.

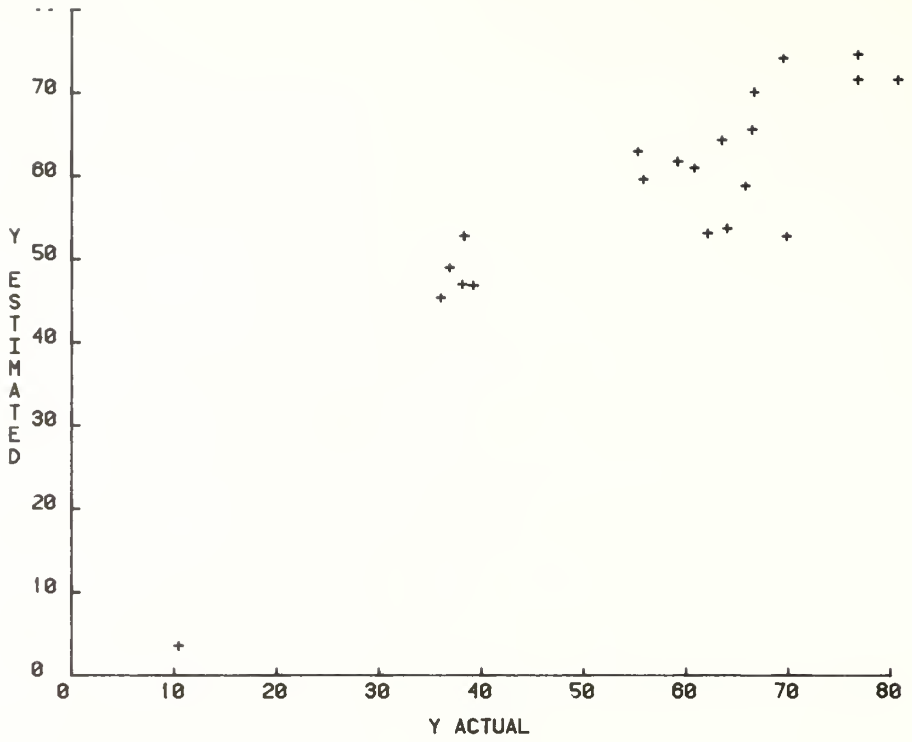


Figure 9.--Plot of pattern areas observed (actual) against those predicted by the model based on 21 data sets of four variables at density > trace.

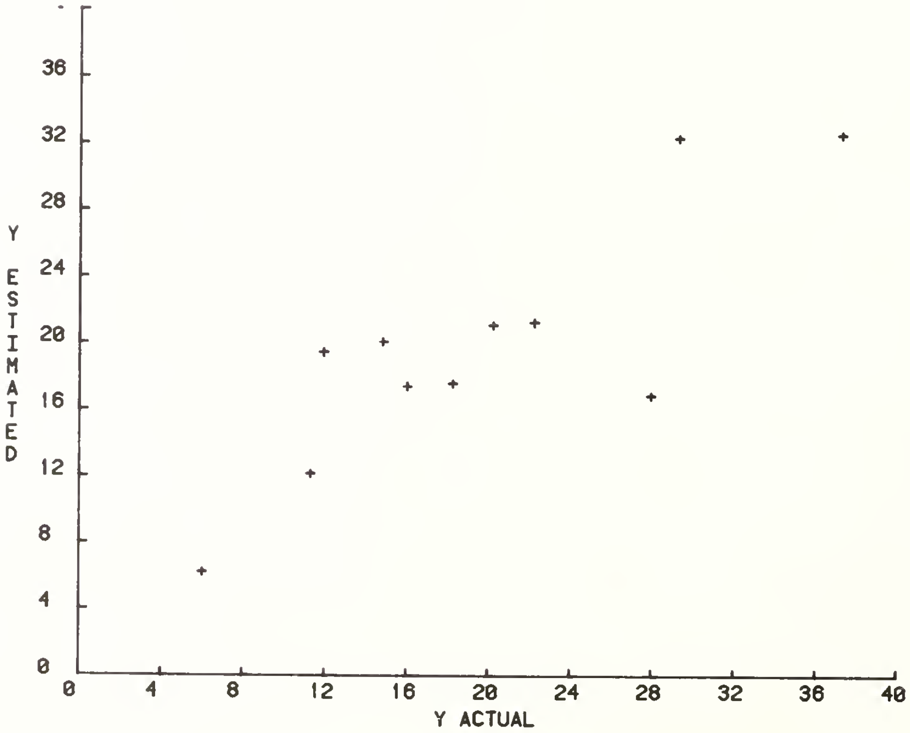


Figure 10.--Plot of pattern areas observed (actual) against those predicted by the model based on 11 data sets of six variables at density > 1.8 percent.

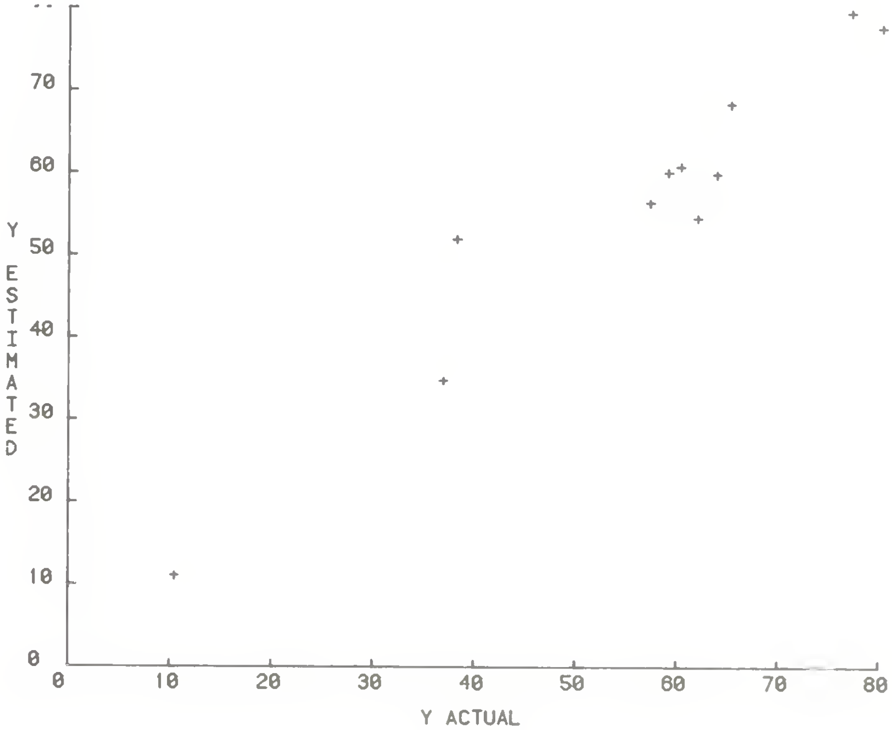


Figure 11.--Plot of pattern areas observed (actual) against those predicted by the model based on 11 data sets of six variables at density > trace.

CONCLUSIONS

The regression coefficients given in table 3 indicate that a definitely useful level of capability is present for predicting the relative size of drop pattern areas from physical and rheological data. The graphs of figures 8 through 11 (especially figures 10 and 11) make the same statement. The correlation is slightly better for coverage at the trace level.

The elimination of each of the variables, one at a time, indicates (table 3) that the modulus of elasticity is the variable to which the regression coefficient is the most sensitive. Density seems to be the next most influential variable. Deleting two or more variables leads to much more drastic decrease in the value of r^2.

Some retardant performance criteria can be modeled on theoretical considerations. An example is the treatment of droplet size by using fluid dynamic theory (Andersen and others 1976). The present attempt to relate pattern area to a diverse set of partially unrelated but conveniently available measurements has been approached in an empirical way, and the assumption of a linear relationship is arbitrary.

It is attractive to suspect that the intermediate coverage cited, 1.8 mg/cm^2, might correspond approximately to some level found to be effective in field practice. This is not correct, however; coverage levels seen in this study are five to 10 times lower than those recommended for actual wildfire control. It is equally important to note that the 30-inch (76.2 cm) drop distance in 40 mi/h (64.4 km/h) wind did not, at least for thickened materials, allow fully developed dispersal of the fluids into droplets of ultimate size. In most cases, the specimens were still being accelerated (sheared) by the horizontal airstream when they landed on the cup array.

It seems apparent from these results that a sizable collection of data from full scale airdrops should yield a model usable for maximizing airtanker performance. A significant reservoir of such data already exists, some as a result of studies directed toward the retardants themselves (George and Blakely 1973) and others toward the development of improved airtanker equipment and techniques (George 1975, Swanson and others 1978). Much of the necessary data is not contained in the reports themselves, but is on file at the Northern Forest Fire Laboratory (NFFL), Missoula, Mont. In using these data, rheological data would have to be obtained by preparing retardant specimens essentially identical to those used in the airdrops. This is feasible because stocks of identical component materials are in storage at the Northern Forest Fire Laboratory. In practical use, the model would need to take into account drop heights (altitude above terrain), airspeed, and details of the aircraft tank and gate system.

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Laboratory measurements of rheological properties of fire retardant materials have been correlated with wind tunnel area distribution experiments to develop a model that predicts the relative area of the pattern of retardant dropped from aircraft.

KEYWORDS: fire retardant, air drop, rheology

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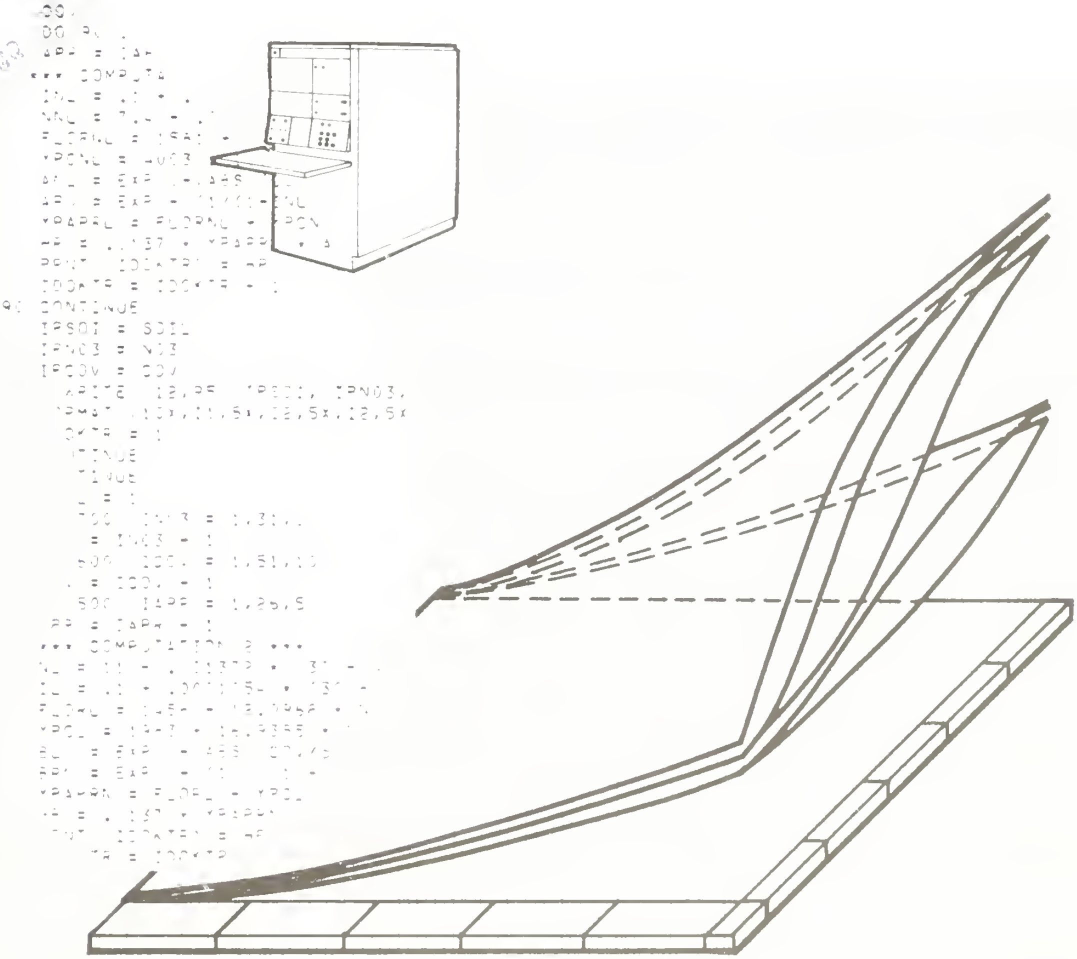
**Intermountain
Forest and Range
Experiment Station**

Research Paper
INT-279

July 1981

Mathematical Hypothesis for Herbage Production Potential on Pinyon - Juniper Areas

Warren P. Clary
and
Chester E. Jensen



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CHESTER E. JENSEN, retired, served as principal statistician for the Intermountain Forest and Range Experiment Station from 1967-1980. He held the same position at the Northeastern and Central States Forest Experiment Stations prior to coming to the Intermountain Station. Mr. Jensen, who holds a Master of Forestry degree from Michigan State University, received graduate training in statistics at Iowa State University.

RESEARCH SUMMARY

Herbage production potential of clearcut pinyon-juniper areas can be of critical interest to land managers. Published information is the basis for the theorized form of the relation between such potential and annual precipitation, original tree cover, soil nitrification level, and presence or absence of limestone soil. The fundamental expected effects appear to exist in a small data set from north-central Arizona. Estimates of specific forms and scales of the effects are made from data trends, within the constraints of expectation. Validation or at least rescaling (refitting) of the resulting interactive mathematical model to data from areas of application is recommended as a precondition for interim field use. A Fortran IV computer program for table output from the model is included.

CONTENTS

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Mathematical Hypothesis for Herbage Production Potential on Pinyon - Juniper Areas

INTRODUCTION

Our concern here is the estimation of herbage production potential on wooded sites being considered for conversion to grassland. The relation between such production potential and four major variables affecting it is discussed. A mathematical model for the relation is presented along with a Fortran IV program to produce tabled model output. Some empirical inputs to the model were derived from data collected in the pinyon-juniper type of north-central Arizona.

The general form of the relationship is expected to apply to pinyon-juniper areas of the West and may have conceptual relevance to other woody plant communities. Testing or refitting of the mathematical model to data from other woodland or shrub communities may result in suitable prediction models for use by local land managers.

HYPOTHESIS--COMPONENT SOURCES

Herbage production values for 19 clearcut pinyon-juniper sites in north-central Arizona were subjected to regression screening processes for the simple additive effects of a variety of independent variables measured on these same sites (Clary and Jameson 1981). These simple hypotheses were regarded as having some theoretical basis and as being generally meaningful. The most useful of the effects appeared to be annual precipitation, tree cover, soil nitrates, and presence or absence of limestone soils.

We attempt in this paper to develop a model more rigorously tuned to the interactive nature of the relation wherein the effects of some or all of the independent variables change, depending on the levels of others. This model is proposed as a reasonable approximation of the true relation. The basic model structure was developed from information available in the literature, but specific coefficients were estimated from the Arizona data set.

DISCUSSION OF HYPOTHESIS COMPONENTS

Annual precipitation (APR) is the source of soil moisture needed for plant growth on most terrestrial sites. Also, as is known, regional differences in the capacity of land to produce plant matter are strongly and positively related to APR (Coe and others 1976; Sims and Singh 1978, Webb and others 1978). These circumstances, along with the widespread availability of APR information,[1] have led to its inclusion in the model as a prime and convenient indicator of regional differences in productivity.

Within a region of limited APR-range, gross differences in soil parent material can be expected to have a major effect on plant response to APR. In particular, reduced plant production on limestone-derived soils compared to that on many other soils is evidently a worldwide phenomenon (Whittaker and Niering 1968), although some variations to this can occur (Ffolliott and Clary 1975). This reduced production seems to be most likely to occur in areas where soils are poorly developed and are derived from relatively pure limestone parent material. It is least likely to occur where soils are highly developed from soil parent material with substantial amounts of impurities (Jenny 1941). Generally, the trend across arid and humid climates is for natural plant communities supported by limestone soils to exhibit a more xeric character than adjacent communities on other soils. This xeric nature is often characterized by reduced plant densities, different species composition, or changes in community physiognomy. Thus, we expect herbage yields to be generally lower on the limestone soils than on many nearby soils.

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[1] [illegible]

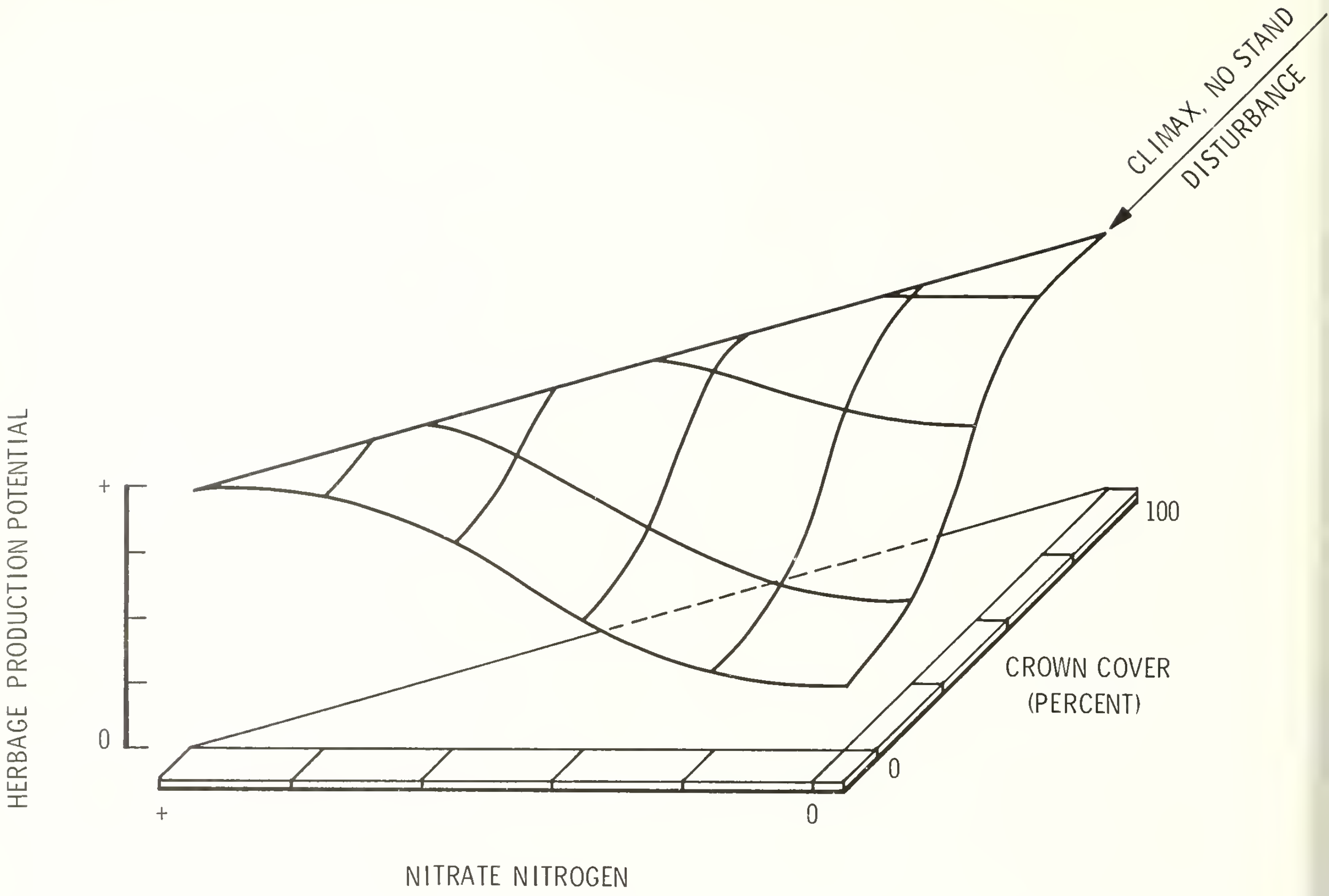

Figure 1.--The hypothesized relation between herbage production potential, nitrate-nitrogen level, and crown cove percent.

Within a region of limited APR-range and soil parent material (limestone versus other), site productivity can be expected to vary by reason of local differences in such environmental factors as topography and microclimate. The long-term integrated effects of these factors are reflected in the amount of tree cover developed for climax stands; so cover constitutes an excellent within-region index to site quality. Cable (1975), Clary and others (1966), and Pechanec and others (1954), have documented the positive relation between the amount of original woody-plant cover and, subsequent to removal of this cover, the amount of herbaceous plant growth in semiarid ecosystems. The hypothesized herbage production/cover relation is pictured at the right edge of figure 1. When climax cover is scant, the site is expected to be poor and potential herbage production low. As cover increases, both site and potential herbage production improve, the latter possibly reaching the asymptote shown over the upper range of cover.

When cutting, catastrophic fires, and other recent disturbances have decimated the climax cover to a greater or lesser extent, cover is no longer an uncompromised measure of site productivity. Under these circumstances, a supplementary index to productivity is needed. Studies conducted in both grassland and forest ecosystems suggest that ecosystems at the climax stage inhibit nitrification (Rice and Pancholy 1972, 1973). Release of a site, through disturbance of the climax overstory, coul be expected to result in conditions again favorable to th accumulation of nitrates (model acronym NO3) in the soi to the extent permitted by residual climax trees (Vitouse and Melillo 1979).

With no residual trees, the opportunity exists for th accumulation of NO3 to a level determined by the characteristics of the site (Jenny 1941). The level of accumulation will of course differ among sites because each i unique in its exact combination of characteristics. Accumulation could vary as indicated by the full range of NO3 a zero cover in figure 1. The sigmoidal form for herbage production over NO3 was assumed to be approximately correct because experience in the agronomic field has show diminishing returns from higher nutrient levels (Blac 1957) and results in semiarid natural ecosystems hav shown that only very modest nutrient levels can be effectively utilized by such systems (Hyder and others 1975).

It is assumed that when climax cover reaches a maximu virtually no nitrification takes place. Thus, the surfac shown in figure 1 is truncated on the diagonal at the rear because maximum soil nitrates and maximum tree cover a not expected to occur simultaneously. The interacti nature of NO3 and climax cover is apparent in that herba production potential varies differently over NO3, depen ing on the level of climax overstory.

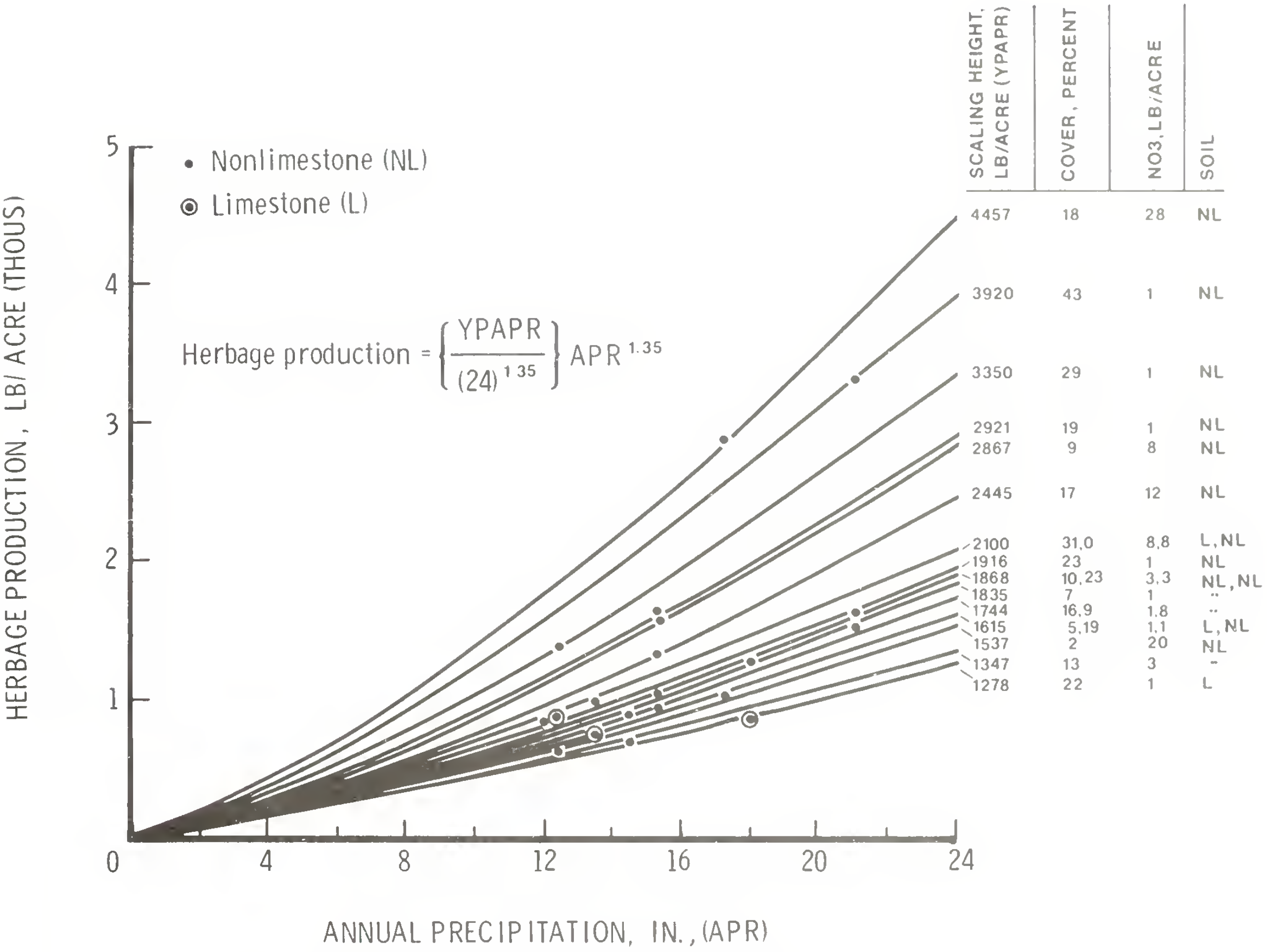

Figure 2.--Family of annual precipitation curves relating to individual data points.

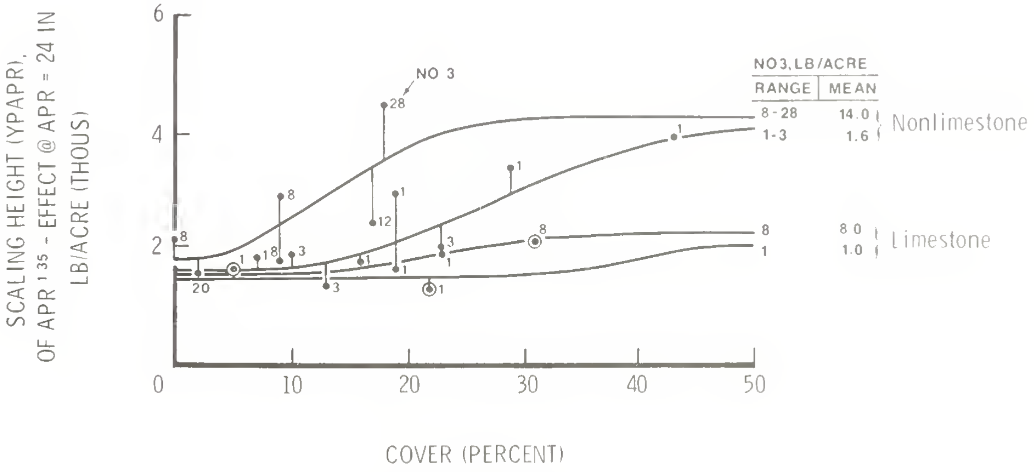

Figure 3.--Scaling height for the annual precipitation effect in relation to cover percent, nitrate-nitrogen, and limestone soils (presence or absence).

HYPOTHESIS DEVELOPMENT AND ASSOCIATED HERBAGE PRODUCTION POTENTIALS

Estimates of specific forms and scales for the effects of the independent variables were made from data trends, within the general constraints of the hypothesized model. In the modeling process, APR-effects were quantified first, followed in order by cover, nitrification, and limestone. The form of the relation was described mathematically according to Jensen and Homeyer (1970, 1971) and Jensen (1973, 1976, 1979). This modeling process was used since it is highly sensitive to curvilinear interaction, characteristic of the expected relation. Some procedural detail is presented for those who may be interested in validating the form and internal scales of the model with data from new areas. Methods are also shown for simple rescaling (refitting) of the existing model in its entirety, to data from new areas.

The expected effect for APR on biomass production is, of course, positive. Experience in the 5- to 25-inch (13- to 64-cm) precipitation zones of the Intermountain Area of the West (Packer and others 1979, Stevens and others 1974) suggests a flat to slightly concave-upward curve form. APR to the 1.35 power ($APR^{1.35}$) appeared to be appropriate for the Arizona data (Jensen and Homeyer 1971). Forced through both zero and each herbage production value, APR-effects were extended to APR=24 inches (61 cm) (fig. 2) The APR-effect was scaled at that point to the scaling height (YPAPR) for the Arizona data. YPAPR was then explored for expected limestone-, sigmoidal cover-, and N-effects (fig. 3) (Some steps in the model development [fig. 2 and 3, and the Fortran IV program] are illustrated in English units only. Model output [fig. 4 and table 1] is shown in both English and SI units.)

The expected negative limestone effect appeared to be at least supported by the very few observations available on limestone soils, and the expected cover- and NO3-effects were also fairly well expressed (fig. 3). The rather strong trend indicated by the six data points of the upper line (NL, NO3 = 14.0), together with experience-based knowledge that average-high productivity is not likely to exceed 4,500 lb/acre (5 040 kg/ha) (Stevens and others 1974), resulted in specification of a sigmoid that asymptotes conservatively at 4,200 lb/acre (4 704 kg/ha). It is possible that the asymptote could be higher. The complete sigmoid is reasonably well portrayed by the 10 data points for the second line from the top (NL, NO3 = 1.6).

The sigmoids of the two bottom lines (L, NO3 = 8.0 and 1.0) are highly conjectural, but the greatly reduced scale of these effects is one of the more important features of the model. In general, the sigmoidal forms shown in figure 3 can be visualized as representing sections of figure 1 at different NO3 levels and with different scaling factors.

The sigmoidal forms over cover were described using e^{-k} (Jensen and Homeyer 1970, Jensen 1979). Associated intercepts (FLORNL, FLORL), changing power (NNL, NL), inflection points (INL, IL), and scaling heights (YPCNL, YPCL) were all expressed as power functions of NO3 (Jensen and Homeyer 1971; Jensen 1973, 1976). Note that separate equations are developed for limestone and nonlimestone soils with each being displayed at two or three NO3 levels in figure 4.

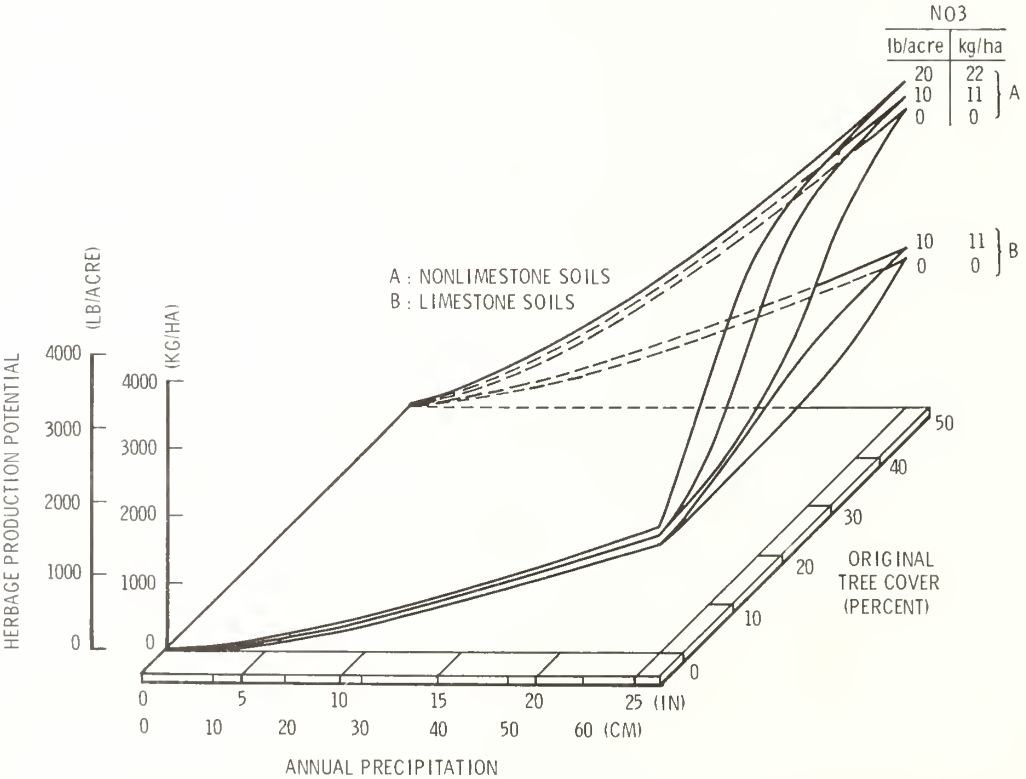

Figure 4.--Herbage production potential: the hypothesized interactive relation involving annual precipitation, presence or absence of limestone soils, tree crown cover, and nitrate nitrogen in the soil.

Table 1.--Modeled herbage production potentials for selected combinations of annual precipitation, presence or absence of limestone soils, tree crown cover, and nitrate-nitrogen in the soil

				Annual precipitation, inches (cm)									
Soil	NO3		Cover	5	(13)	10	(25)	15	(38)	20	(51)	25	(64)
	Lb/acre	*(kg/ha)*[1]	*Percent*	*Forage production, lb acre (kg ha)*									
Lime	0	(0)	0	169	(189)	430	(482)	744	(833)	1,096	(1 228)	1,482	(1 660)
			10	169	(189)	430	(482)	744	(833)	1,096	(1 228)	1,482	(1 660)
			20	169	(189)	430	(482)	744	(833)	1,097	(1 229)	1,483	(1 661)
			30	170	(190)	434	(486)	751	(841)	1,107	(1 240)	1,496	(1 676)
			40	186	(208)	473	(530)	818	(916)	1,207	(1 351)	1,631	(1 827)
			50	229	(256)	585	(655)	1,011	(1 132)	1,491	(1 670)	2,015	(2 257)
	10	(11)	0	183	(205)	466	(522)	805	(902)	1,187	(1 329)	1,605	(1 798)
			10	183	(205)	467	(523)	807	(904)	1,190	(1 333)	1,608	(1 801)
			20	220	(246)	562	(629)	971	(1 088)	1,431	(1 603)	1,935	(2 167)
			30	247	(277)	631	(707)	1,090	(1 221)	1,608	(1 801)	2,173	(2 437)
			[2]40	249	(279)	635	(711)	1,098	(1 230)	1,618	(1 813)	2,187	(2 449)
Nonlime	0	(0)	0	183	(205)	466	(522)	806	(903)	1,189	(1 332)	1,606	(1 799)
			10	195	(218)	497	(557)	859	(962)	1,266	(1 418)	1,712	(1 917)
			20	233	(261)	593	(664)	1,026	(1 149)	1,513	(1 695)	2,045	(2 270)
			30	312	(349)	796	(892)	1,376	(1 541)	2,029	(2 272)	2,742	(3 071)
			40	413	(463)	1,052	(1 178)	1,818	(2 036)	2,681	(3 003)	3,623	(4 058)
			50	463	(519)	1,181	(1 323)	2,041	(2 286)	3,010	(3 371)	4,068	(4 556)
	10	(11)	0	197	(221)	502	(562)	868	(972)	1,280	(1 434)	1,730	(1 938)
			10	233	(261)	593	(664)	1,029	(1 152)	1,517	(1 699)	2,050	(2 296)
			20	377	(422)	960	(1 075)	1,660	(1 859)	2,448	(2 742)	3,308	(3 705)
			30	467	(523)	1,190	(1 333)	2,058	(2 305)	3,034	(3 398)	4,101	(4 593)
			40	482	(540)	1,230	(1 378)	2,126	(2 381)	3,135	(3 511)	4,237	(4 745)
	20	(22)	0	211	(236)	538	(603)	930	(1 042)	1,371	(1 536)	1,853	(2 075)
			10	352	(394)	897	(1 005)	1,552	(1 738)	2,288	(2 563)	3,092	(3 463)
			20	475	(532)	1,212	(1 357)	2,095	(2 346)	3,089	(3 460)	4,175	(4 676)
			30	501	(561)	1,276	(1 429)	2,207	(2 472)	3,254	(3 645)	4,398	(4 926)
	30	(34)	0	225	(252)	573	(642)	991	(1 110)	1,462	(1 637)	1,976	(2 213)
			10	408	(457)	1,039	(1 164)	1,796	(2 012)	2,648	(2 966)	3,579	(4 008)
			20	506	(567)	1,289	(1 444)	2,229	(2 496)	3,287	(3 681)	4,442	(4 975)

---

[1] SI units in parentheses

[2] The table is asymmetric because maximum values of NO3 and cover are not expected to occur simultaneously (see fig. 1)

For each model then, we are able to specify the basic APR-effect as:

$$HP = \left\{ \frac{YPAPR}{(24)^{1.35}} \right\} * (APR)^{1.35}$$

where:

YPAPR = INTERCEPT + SCALAR FOR THE SIGMOIDS* SIGMOIDS OVER COVER.

YPAPRL is used in the model for lime soils.

YPAPRN is used in the model for nonlime soils.

INTERCEPTS:

NON-LIME: FLORNL = 1581 + 12.0968 * NO3
LIME: FLORL = 1458 + 12.0968 * NO3

SCALARS FOR SIGMOIDS:

NON-LIME: YPCNL = 4003 + 16.9355 * NO3 - FLORNL
LIME: YPCL = 1983 + 16.9355 * NO3 - FLORL

SIGMOIDS OVER COVER:

$$\left(\frac{e^{-\left|\frac{\frac{COVER}{50}-1}{1-INFL}\right|^{N}} - e^{-\left\{\frac{1}{1-INFL}\right\}^{N}}}{1-e^{-\left\{\frac{1}{1-INFL}\right\}^{N}}} \right)$$

INFLECTION POINTS (INFL):

NON-LIME: INL $= 0.1 + 0.0006869 * (30\text{-}NO3)^{1.9}$
LIME: IL $= 0.1 + 0.0001054 * (30\text{-}NO3)^{2.6}$

SIGMOIDAL POWER (N):

NON-LIME: NNL $= 7.4 - 0.003067 * (30\text{-}NO3)^{2.2}$
LIME: NL $= 11.0 - 0.001372 * (30\text{-}NO3)^{2.6}$

LIMITS:

$0 \leq$ cover ≤ 50, IF cover > 50, HP = HP @ cover = 50
$0 \leq$ APR ≤ 25
$0 \leq$ NO3 ≤ 30, IF NO3 > 30, HP = HP @ NO3 = 30

After derivation from both prior knowledge and the data at hand, the model was mathematically readjusted to the data with a relatively simple coefficient that forces the fitted model through zero,

$$b = \Sigma XY/\Sigma X^2$$

where X = the model herbage production value for specified levels of APR, cover, and NO3; and Y = the related observed value of herbage production. A weighting factor of $1/Y^n$ was evaluated and discarded since it was poorly related to the variance about the least-squares fitted model ($R^2 = 0.03$). The b-value for the 19 observations was 0.9618 or, in other words, the initially derived model was about 4 percent high with respect to the least-squares fit. For the final model R^2 is 0.84 and $s_{y.x}$ is about 287 lb/acre (321 kg/ha). Values for the relation are given in table 1.

Note that $s_{y.x}$ is likely to be underestimated here since unknown degrees of freedom are sacrificed in exploiting the data as explained. Models developed in this way are probably best used as advanced hypotheses, to be tested and scaled ($b = \Sigma XY/\Sigma X^2$) to new data sets. In the absence of better information such models can, of course, be used as interim predictors with suitable caution.

A Fortran IV computer program for table output from the model follows:

```
; DGC FORTRAN IV REV 05.52NS

; C      ***  PROGRAM NAME = CHET
; C      ***  PERFORM CALCULATIONS FOR LIME AND NON-LIME SOIL
; C      ***  USEING VARIABLES N03, COVER AND APR
;         DIMENSION PRNT(6)
;         REAL NNL, INL, NL, IL, N03
;         IPSOI = 0
;         IPN03 = 0
;         IPCOV = 0
;         IDOKTR = 1
;         SOIL = 0
;         WRITE (12,5)
;       5 FORMAT (46X,"ANNUAL PRECIPITATION")
;         WRITE (12,10)
;      10 FORMAT (8X,"SOIL",3X,"N03",3X,"COVER",10X,"0",7X,"5",6X,"10",6X,"1
;        -5",6X,"20",6X,"25")
;         WRITE (12,15)
;      15 FORMAT (1X,"--------------------------------------------------------
;        ----------------------------------")
;         DO 200 IN03 = 1,31,10
;         N03 = IN03 - 1
;         DO 100 ICOV = 1,51,10
;         COV = ICOV - 1
;         DO 90 IAPR = 1,26,5
;         APR = IAPR - 1
; C      *** COMPUTATION 1
;         INL = .1 + .0006869 * (30 - N03) ** 1.9
;         NNL = 7.4 - .003067 * (30 - N03) ** 2.2
;         FLORNL = 1581 + 12.0968 * N03
;         YPCNL = 4003 + 16.9355 * N03 - FLORNL
;         ANL = EXP (-(ABS((COV/50-1) / (1-INL))**NNL))
;         ARN = EXP(-((1/(1-INL))**NNL))
;         YPAPR = FLORNL + YPCNL * ((ANL - ARN) / (1-ARN))
;         HP = .0137 * YPAPR * APR ** 1.35 * .9618
;         PRNT (IDOKTR) = HP
;         IDOKTR = IDOKTR + 1
;      90 CONTINUE
;         IPSOI = SOIL
;         IPN03 = N03
;         IPCOV = COV
;           WRITE (12,95) IPSOI, IPN03, IPCOV, PRNT
;      95 FORMAT (10X,I1,5X,I2,5X,I2,5X,6F8.0)
;         IDOKTR = 1
;     100 CONTINUE
;     200 CONTINUE
;         SOIL = 1
;         DO 700  IN03 = 1,31,10
;         N03 = IN03 - 1
;         DO 600  ICOV = 1,51,10
;         COV = ICOV - 1
;         DO 500  IAPR = 1,26,5
;         APR = IAPR - 1
; C      *** COMPUTATION 2 ***
;         NL = 11 - .001372 * (30 - N03) ** 2.6
;         IL = .1 + .0001054 * (30 - N03) ** 2.6
;         FLORL = 1458 + 12.0968 * N03
;         YPCL = 1983 + 16.9355 * N03 - FLORL
;         BLN = EXP (-(ABS((COV/50-1) / (1 - IL)) ** NL))
;         BRN = EXP (-((1 / (1 - IL)) ** NL))
;         YPL = FLORL + YPCL * ((BLN - BRN) / (1 - BRN))
;         HP = .0137 * YPL * APR ** 1.35
;         PRNT (IDOKTR) = HP * .9618



;         IDOKTR = IDOKTR + 1
;     500 CONTINUE
;         IPSOI = SOIL
;         IPN03 = N03
;         IPCOV = COV
;         WRITE (12,95) IPSOI, IPN03, IPCOV, PRNT
;         IDOKTR = 1
;     600 CONTINUE
;     700 CONTINUE
;         STOP
;         END
```

Note that all statements within the brackets comprise the Fortran IV program necessary to output of tables values presented in the paper. This should run on any computer subject to minor changes to accommodate programing peculiarities of the system: e.g., "PRINT" in place of "WRITE" is appropriate for IBM systems.

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Herbage production potential of clearcut pinyon-juniper areas can be of critical interest to land managers. Published information is the basis for the theorized form of the relation between such potential and annual precipitation, original tree cover, soil nitrification level, and presence or absence of limestone soil. The fundamental expected effects appear to exist in a small data set from north-central Arizona. Estimates of specific forms and scales of the effects are made from data trends, within the constraints of expectation. Validation or at least rescaling (refitting) of the resulting interactive mathematical model to data from areas of application is recommended as a precondition for interim field use. A Fortran IV computer program for table output from the model is included

KEYWORDS: hypothesis, mathematical model, herbage production, pinyon-juniper, precipitation, cover, nitrate, soil type

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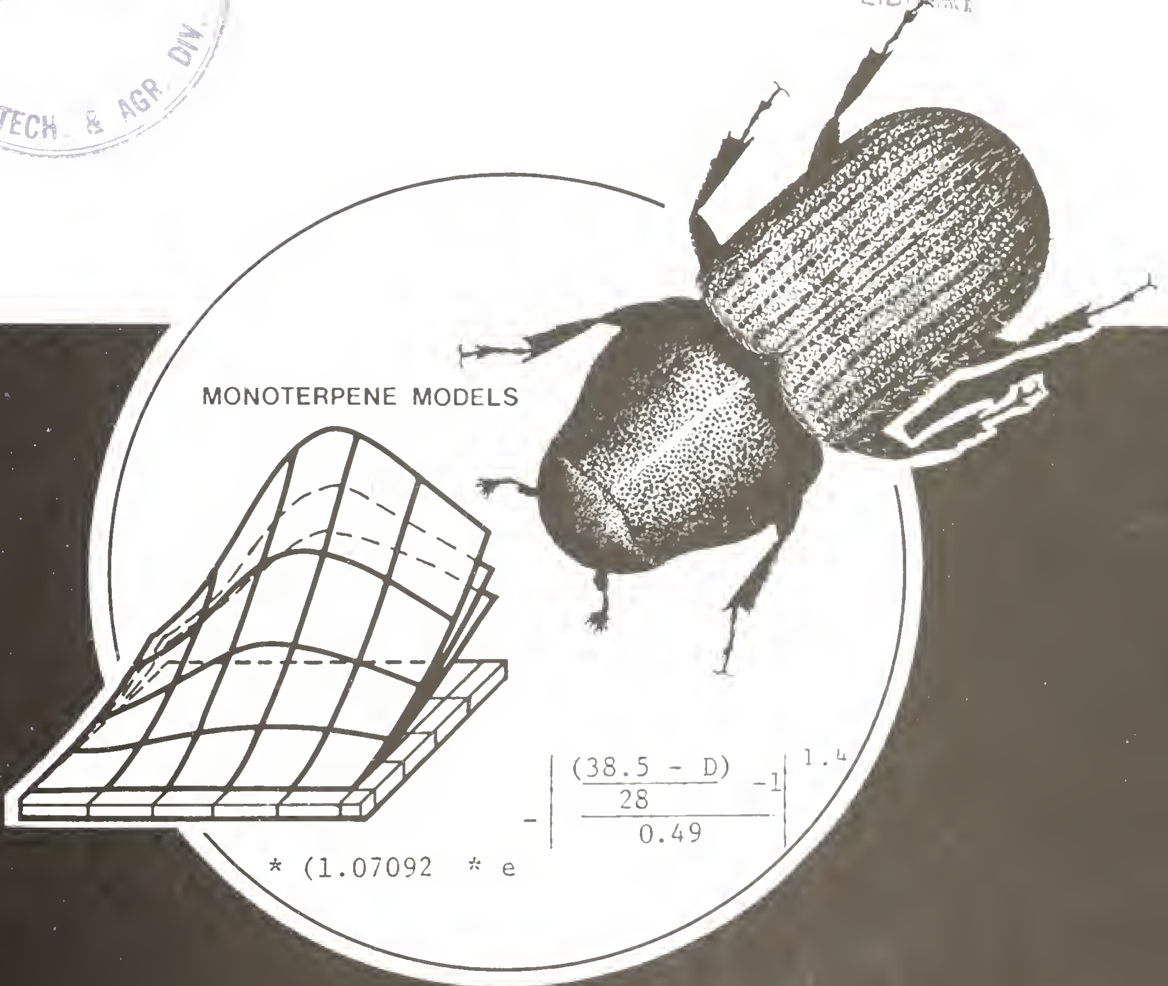
July 1981

Monoterpenes of Lodgepole Pine Phloem as Related to Mountain Pine Beetles

Walter E. Cole, E. Park Guymon, and Chester E. Jensen



THE AUTHORS

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RESEARCH SUMMARY

Phloem samples taken from 86 healthy lodgepole pine trees at three points in the 1975 growing season were analyzed fo content of dry matter, starch, various forms of sugar and nitrogen, and of selected monoterpenes. Means for July 10 and 31 were significantly lower than those of June 6 for dry matter soluble reducing sugars, nitrogen, and monoterpenes Starches and other sugars were higher. β-phellandrene was, b far, the most prevalent of the monoterpenes. Dry matter in th phloem contained an extremely small amount of monoterpen by weight but, of this, individual monoterpenes were distribute in about the same proportions found in pure oleoresin by othe researchers. Monoterpene contents from the last (July 31) samples were significantly, although weakly, related to the linea positive effects of phloem thickness and radial growth. An inte active hypothesis is developed for terpene content as a functio of phloem thickness, radial growth, and tree diameter. Her high concentrations of monoterpenes coincide with larger tre diameters, the expected region of high mountain pine beetl survival.

CONTENTS

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Monoterpenes of Lodgepole Pine Phloem as Related to Mountain Pine Beetles

Walter E. Cole, E. Park Guymon, and Chester E. Jensen

NTRODUCTION

The role of food quantity in mountain pine beetle (MPB) population dynamics in lodgepole pine is well-documented in he literature. The thickness of phloem within trees in a stand determines whether the insect can prosper there. Beetles tend o select trees that possess the thickest phloem in a stand where trees have similar diameters, and they often select that portion of an individual tree having the thickest phloem (Roe and Amman 1970). The mountain pine beetle is food-limited in hose stands of lodgepole pine where developmental temperaures are optimum (Cole and Amman 1969). When beetles have killed most of the larger, thick-phloem trees, they are forced to attack and raise brood in the smaller residual trees. These trees have reduced capacity for supporting brood development because of generally thinner phloem. Subsequently, the populaion declines (Cole and others 1976).

While the role of phloem quantity in beetle population dynamics is well documented, that of phloem quality is not. Smith 1965) has shown that vapors of the monoterpenes from western white pine (*Pinus ponderosa*) vary in toxicity to the western pine beetle (*Dendroctonus brevicomis*) in the following descending order: limonene Δ_3-carene myrcene β-pinene β-pinene control. The monoterpene composition of oleoresin in lodgepole pine (*Pinus contorta* var. *murrayana*) was β-phellandrene, 69.4 percent; α-pinene, 6.4 percent, Δ_3-carene, 8.9 percent; β-pinene, 5.7 percent; myrcene, 3.9 percent; camphene, 0.5 percent, limonene, 2.4 percent, sabinene, 2.1 percent; and α-phellandrene, 0.7 percent (Smith 1964).

In most terpene studies where a variety of pine species were considered, cortical oleoresin differed qualitatively between species but not within species. Coyne and Keith (1972) found no distinct differentiation, either qualitatively or quantitatively, between monoterpene composition of loblolly (*P. taeda*) and slash (*P. elliotii*) pines within or outside of known southern pine beetle outbreaks. Monoterpenes provide bases for distinguishing host species but not for distinguishing resistant trees from check trees (Coyne and Critchfield 1974). Hanover (1975) identified an apparent genetic hierarchical regulation of the major terpene fractions in lodgepole pine. These discrete genetic variations may relate to pest (insect) behavioral patterns, as indicated by differing resistance levels of trees to their respective pest species.

A continuing question is whether tree-to-tree differences in phloem constituents, particularly the monoterpenes, are coincident with the characteristic MPB attack and survival pattern. Alpha-pinene has been the usual monoterpene used in experimentation with pheromones and beetle behavior. However, Moeck (1980) mentions that α-pinene is not an effective pheromone component in lodgepole pine. While peripheral information has been developed in this study, the emphasis has been on monoterpene content of the phloem and its relation to tree characteristics previously found to be linked to MPB population dynamics.

MATERIALS AND METHODS

We took three 5.08 by 5.08 cm phloem samples at breast height from each of 86 uninfested trees distributed over 20 acres (8.1 ha) on the Cache National Forest in 1975. Trees ranged from 12.7 to 50.8 cm in diameter at breast height (d.b.h.). Samples were taken three times during the season: June 6, July 10, and July 31. The samples were transported to the laboratory and frozen on the same day they were removed from the trees. Two samples per tree were analyzed as described later, and one sample stored (frozen) as a backup sample.

The samples were stored in the lab at −25° C. Each of the first two phloem samples were separated from the bark and ground in a Wiley grinder at 20-mesh size by freezing the sample in liquid nitrogen and by passing large amounts of dry ice through the grinder to keep the grinder cold.

Soluble nitrogen and soluble sugars were extracted with 80 percent ethanol. Insoluble products underwent chemical digestion in order to convert them into a soluble form that could be analyzed. Insoluble nitrogen in the sample was converted to ammonia by repeated digestion with a 20 percent sulfuric acid and cleaned with hydrogen peroxide (Hodges and others 1968).

To analyze terpenes, 0.2 to 0.3 g of the ground phloem was placed in a vial with 2 ml of isopropyl ether (free of alcohols, chromatoquality reagent) in a sealed vial and shaken for at least 2 days. We then put 10 microliters of this solution in a Varian Aerograph series 1700 gas chromatograph with a flame ionization detector. The identification and quantity of each component was determined by running dilute standards of the pure components. The peaks were cut out, and the quantity of each component determined from its peak weight. We used a 1.83-m column packed with Porapack Q because the water in the sample from the phloem did not affect this column packing. The injector temperature was 275° C, detector temperature 250° C, carrier gas (high purity helium) 40 psi, and column temperature was programmed from 50° to 250° C at 10° per minute. Ultra high purity hydrogen and air were used for hydrogen detection.

Laboratory analysis was focused on monoterpenes, soluble nitrogen, total nitrogen, reducing sugars, starches, pentoses, and hexoses. Nitrogen was analyzed by the colorimetric Nessler Method (Jacobs 1965). Insoluble nitrogen was determined as the difference between total nitrogen and soluble nitrogen. Sugars, hexoses, and pentoses were determined at the same time with the cysteine and sulfuric acid general reaction on carbohydrates (Dische 1955). Their absorption spectra were then read at 320 mu and 405 mu, which allows the determination of both sugars. Reducing sugars were determined by methods discussed in Dische (1955). Starches were hydrolyzed and then determined by the same procedure as the sugars.

DATA ANALYSIS

Presented in table 1 are average percentages of the phloem (by weight) and associated standard deviations found in dry matter, sugars, starch, nitrogen, and monoterpenes for the trees sampled. Means for June 6 were compared statistically with comparable means at (a) July 10 and (b) July 31.

To establish possible links between tree characteristics and phloem constituents, the latter were fitted as linear functions of all combinations of six pertinent tree characteristics: d.b.h., percent crown length of total tree height, height, phloem thickness, average radial growth for the 5 years prior to sampling, and age.

Results of the regression screen are summarized in table 2 and show that rather weak regression information (R^2) was developed throughout. The July 31 monoterpenes were, however, most strongly related to the tree characteristics evaluated. While even the strongest of these, phloem depth and growth, seem of marginal strength ($0.14 \leq R^2 \leq 0.34$), they do confirm the presence of associated linear, positive increases in monoterpenes. The results provide an information base necessary to the development of more advanced hypotheses, to l evaluated with new data when available. In this case, an i teractive hypothesis was developed from the July 31 data. V used two of the variables exhibiting the strongest linear effe (phloem thickness and growth) and one weak variable (d.b.l that proved reasonably strong in past MPB dynamics mode

Table 1.—Selected lodgepole pine phloem constituents, perc by weight.

Constituent	June 6		July 10		July 31	
	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
	------ *Percent of total phloem weight* --					
Dry matter	54.6	12.7	45.2	4.1	41.4	4.
	-Percent of phloem		*dry matter weig*			
Soluble pentoses	2.0	.56	6.0	1.16	4.7	1.
Soluble hexoses	1.5	.43	4.3	.61	6.3	1.
Total	3.5	.96	10.3	1.61	11.0	1.
All pentoses	3.7	.98	11.4	2.72	8.2	1.
All hexoses	2.7	.81	7.8	1.60	11.6	2.
Total	6.4	1.62	19.2	3.57	19.8	3.
Soluble reduced sugars	3.3	1.70	2.2	.82	1.8	.
Starch	3.0	1.01	9.0	3.18	8.8	2.
Insouble nitrogen	.13	.04	.11	.02	.11	.
Total nitrogen	.18	.07	.13	.03	.12	.
Monoterpenes						
α-pinene	.052	.058	.039	.033	.030	.
β-phellandrene	.203	.277	.140	.124	.144	.
3-terpenes (3-carene + myrcene + α-pinene)	.120	.192	.077	.067	.064	.
Total	.375	.447	.256	.203	.238	.

Here, "total terpene" data for July 31 were partitioned ov the ranges of phloem thickness, tree growth, and tree d.b.h. a were explored graphically for interactive effects. The da appeared to support a three-way interaction characterized b positive, shallow concave-upward effects for phloem thickne and growth; a more-or-less bell-shaped effect for d.b.h., ma imizing at about 10.5 inches (26.67 cm); and convergence t zero with low growth and phloem thickness. The d.b.h. effec not oriented at zero but is not meaningful at zero anyway. The effects were in general accord with the mountain pine bee preference for larger, more vigorous trees, although the rath strong negative trend in terpene content for larger trees - d.b.h. > 10.5 inches (26.67 cm) — was not. Neverthele d.b.h. was retained in the model and the resulting fo dimensional relation was formulated mathematically using techniques specified by Jensen (1973, 1976, 1979) and Jens and Homeyer (1970, 1971), and was refitted to the data set fr which it was partially derived, by weighted[1] least squares. T final hypothesized form ($R^2 = 0.39$, $s_{y \cdot x} \doteq 0.15$) is sho graphically in figure 1 and mathematically in appendix table

---

[1] Variance about the initial model $\hat{Y}$ was expressed as a function of $\hat{Y}$. inverse of this, $1/\hat{Y}^{2.7}$, was used as the fitting weight.

le 2.—Summary of significant (Pr 0.05) coefficients of determination (R^2) for the linear regression screens of independent variables for three sampling dates

	Main effects[1]										
								Terpenes			
e and ependent able	Dry matter	Soluble pentoses	Soluble hexoses	Total soluble sugars	Total pentoses	Starch	Total nitrogen	Total	α-pinene	β-phellan- drene	β-pinene carene myrcene
IE 6	Coefficient of determination (R^2)										
meter at east height (D)											
gth of crown, of total ght								0 12	0 08	0.10	0 12 05
em thickness (P)								18		13	.09
wth, average annual yr. radial (G)			0.06	0.05				28	11	24	15
		0.05	.07	.06			0.05	.07		.08	09
								Additive effects			
							P, G	30	11	25	16
							P, G, D	.30	12	.26	18
Y 10											
meter at east height (D)											
gth of crown, of total ght						0.07					
em thickness (P)			.12	.08			.06	07	07	07	07
wth, average annual yr. radial (G)			.05	.04							
			.09	.05		.06					
								Additive effects			
							P, G	07	07	07	07
							P, G, D	10	10	10	10
Y 31											
meter at east height (D)								06		08	07
gth of crown, of total ght			.08		10	.04		18		18	18
em thickness (P)	.06	.04		.06				30	18	34	26
wth, average annual yr. radial (G)			.07	.07			08	24	14	26	26
	.10										
								Additive effects			
							P, G	35	21	39	34
							P, G, D	35	22	39	34

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[1] otal hexoses and total sugars were screened with nonsignificant results

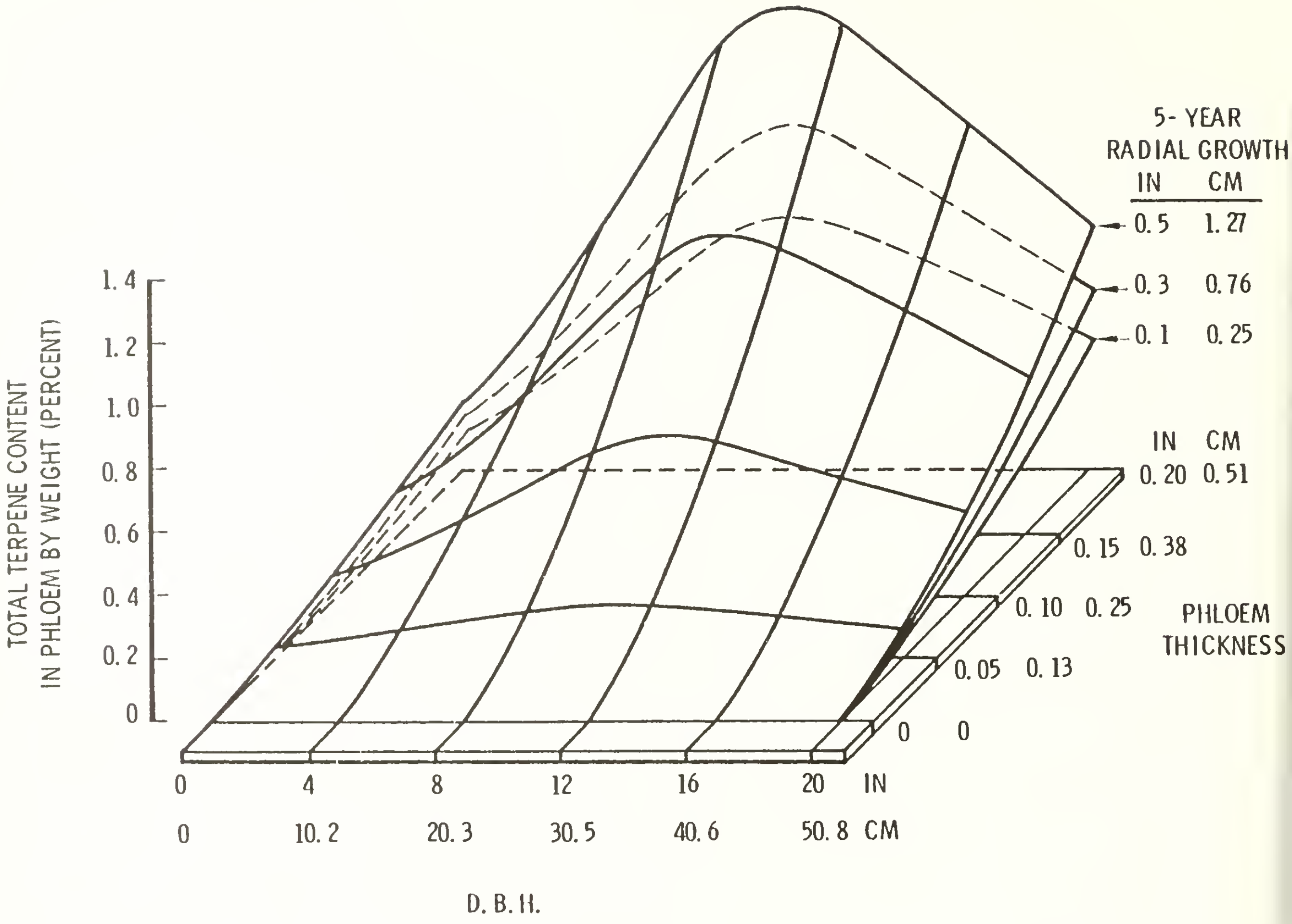

Figure 1. — Hypothesis: total monoterpene percentage of lodgepole pine phloem dry weight, as a function of d.b.h., phloem thickness, and average radial growth.

The July 31 monoterpene percent of phloem dry weight in trees ranged from 0.03 to 1.10 percent. Almost 40 percent of the variance ($R^2 = 0.39$) about the mean of 0.238 was explained by the regression of monoterpene percent on the strongly interacting independent variables, phloem thickness, growth, and tree diameter (fig. 1).

The unexpected bell-shaped effect over d.b.h. is somewhat deceptive because there is a rather strong correlation between phloem and d.b.h. The d.b.h. effect is better characterized by the monoterpene trace over the d.b.h.-phloem line of correlation (fig. 2). There it can be seen that monoterpene content reaches a maximum at about 13 inches (33 cm) and, although the tren is slightly down thereafter, content at 20 inches (51 cm) st exceeds that for 8-inches (20 cm) trees.

Component monoterpenes were explored with much th same results as for the monoterpene sum. So, the mathema cal **form** for the sum was adopted for the components and wa scaled to the data for each component using weighted (1/$\hat{Y}^2$ least squares (fig. 3). The coefficients for component mode were subsequently adjusted to equal, in sum, that for the a component model. As a result, contents for the sum of comp nents equal that of the all-monoterpene model at all combin tions of d.b.h., phloem, and growth.

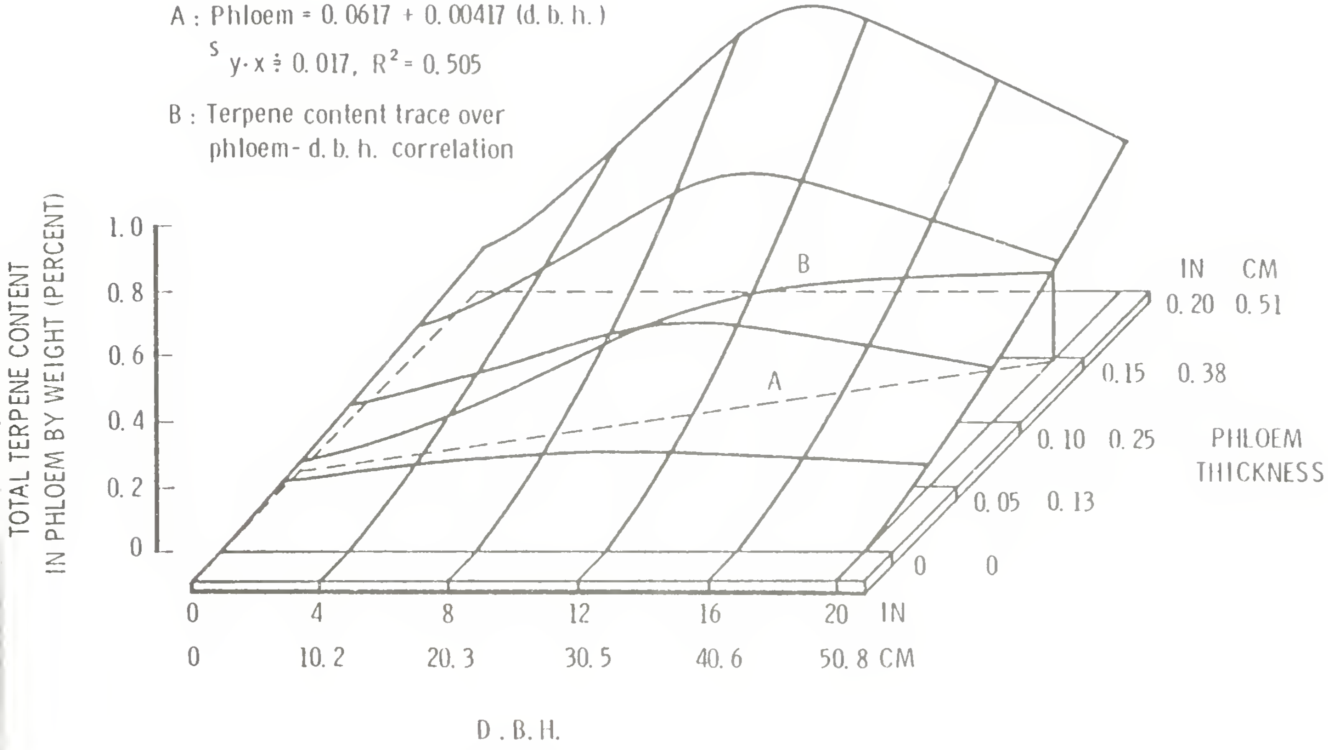

Figure 2. — Hypothesis: total monoterpene percentage of lodgepole pine phloem dry weight, trace over d.b.h./phloem correlation at average annual radial growth (0.159 inches, 0.404 cm).

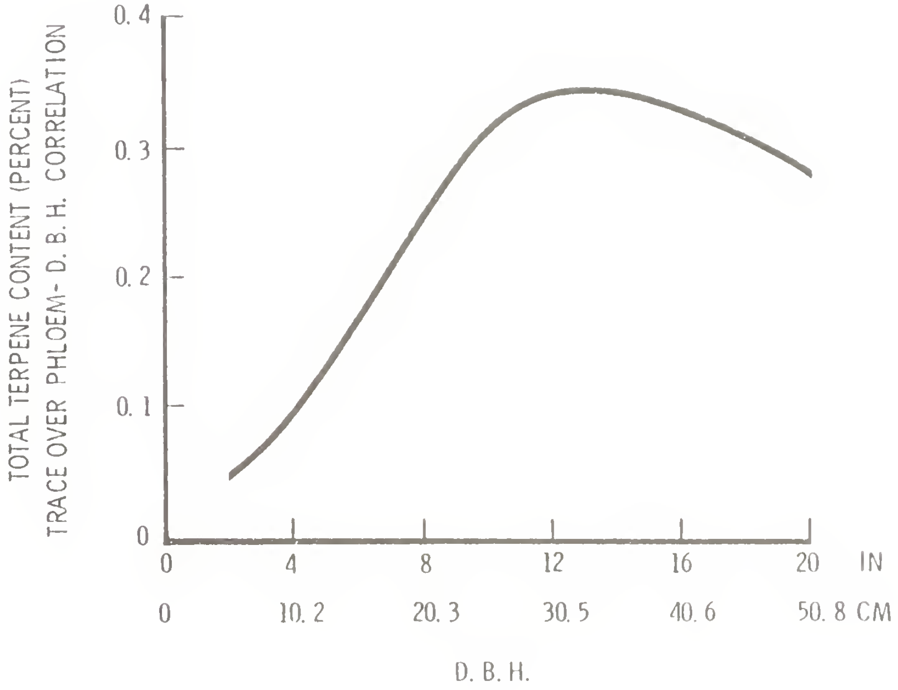

Figure 3. — Hypothesis: total monoterpene percentage, of lodgepole pine phloem dry weight over d.b.h. and phloem thickness at average annual radial growth (0 159 inches, 0 404 cm)

RESULTS

Means and associated standard deviations are shown in table 1 for all phloem contents evaluated in this study. Numbers of sample trees varied from 79 to 86 depending on date of sample and phloem component analyzed.

Means for July 10 and 31 were consistently lower than those of June 6 for dry matter, soluble reducing sugars, nitrogen, and monoterpenes. Differences were significant ($Pr < 0.05$) for the first three components and less so for the monoterpenes ($0.10 \leq Pr \leq 0.05$). Starches and other sugars showed increases from June 6 ($Pr < 0.05$).

We found monoterpene percentage of the phloem dry weight to be extremely small (0.238) and, of this, individual monoterpenes were distributed in about the same proportion as found by Smith (1964) in "pure" oleoresin (table 3). And, in either case, β-phellandrene is by far the largest monoterpene component, followed by the 3-terpene group and α-pinene, respectively. Note that the averages are greater in larger trees with thicker phloem (and vice versa) according to the interactive hypothesis (fig. 1). Too, the expected trend over the d.b.h.-phloem trace (fig. 2) increases to a peak at about 13 inches (33 cm) d.b.h., decreasing thereafter to a low at 20 inches (51 cm) comparable to that at about 9 inches (23 cm).

Note that the percentages of phloem dry weight reported in table 1 and in figures 1 through 3 are based on the monoterpenes measured in this study only. A small reduction in percentages for components could be expected with upward adjustment of the monoterpene sum by 6 percent, to achieve comparability to Smith's (1964) percentages (table 3).

Table 3.—Proportional distribution of monoterpenes: "pure" oleoresin versus phloem dry matter

Monoterpenes	In "pure" oleoresin (Smith 1964)	In phloem dry matter this study, 7/31/75[1]
	Percent by weight	
α-pinene	6.4	11.9
β-phellandrene	69.4	57.0
3-terpenes (3-carene + myrcene + α-pinene)	18.5	25.4
Others (camphene + limonene + sabinene + α-phellandrene)	5.7	(5.7)
Total	100.0	100.0

[1] Original percentage adjusted for 5.7 percent of "others" not evaluated.

DISCUSSION

The inference limitations in this study are rather server because the sample trees involved are from a single, infinitel small stand relative to the whole. But in the absence of stronge information on lodgepole pine phloem, our findings provide data-base opportunity to develop hypotheses for more exter sive study.

Table 1 contains mean percentages and standard deviation for a variety of phloem components, all of which are likely t have some impact on MPB population dynamics. The data o sugars, starch, and nitrogen are simply documented here fc general interest. We note, however, that most sugars an starch are at low levels in the spring and that soluble reducin sugars, nitrogen, and monoterpenes are relatively high. Thes trends follow expectations based on seasonal tree physiolog but because all but monoterpene relations to tree characteris tics appeared to be extremely weak (table 2), we did not attem to develop such information further.

Respective (but very low) concentrations of monoterpenes the phloem are parallel in proportions of the monoterpene su to those found by Smith (1964) in pure oleoresin produced lodgepole pine (table 3). Beta-phellandrene in both studie proved to be, by far, the largest component of the monote penes, and so might easily have the greatest impact on MP activities. We note that while α-pinene has been found to be effective pheromone in western white pine, it is not for lodgepo (Moeck 1980).

But whether it is β-phellandrene or some lesser component the monoterpenes, concentrations in the phloem appear fro the hypothesis developed (fig. 2), to increase with tree vigor a size, up to an optimum d.b.h. of about 13 inches (33 cm).

It has been established from past research that thresh diameters in lodgepole pine for successful MPB reproducti are generally in the 8-inch (20-cm) to 9-inch (23-cm) range. A reproduction success is known to be high in larger, more vig rous trees. This information, together with the coincidence relatively high monoterpene content for larger trees (9-inch [23-cm] to 20-inches [51cm] d.b.h.; see fig. 3), is perhaps su gestive of an attractant role for any one or all of the monot penes. It would also appear that monoterpene toxicity lev studies by Smith (1965) are apparently not being reached in t phloem, based on the level of MPB success in larger trees

The hypothesis developed in this study (fig. 1-3 and appe dix) should help to identify points of future study emphasis a may be rescaled (as a unit) and evaluated for performance new data sets (Jensen 1979).

APPENDIX

Table 4.—Hypothesis values for figure 1. Monoterpene percentage of lodgepole pine phloem dry weight. All-monoterpene % 1.10301 * (model)[1]

Average annual radial growth		Phloem thickness		D.b.h.						
				4	8	10.5	12	16	20	*(inches)*
				10.2	20.3	26.7	30.5	40.6	50.8	*(cm)*
Inches	*cm*	*Inches*	*cm*							
0.1	0.25	0.05	0.13	0.045	0.084	0.094	0.090	0.070	0.049	
		.10	.25	.130	.246	.276	.263	.204	.143	
		.15	.38	.244	.463	.516	.492	.382	.268	
		.20	.51	.381	.723	.807	.769	.597	.418	
.3	.76	.05	.13	.060	.114	.127	.122	.094	.066	
		.10	.25	.176	.335	.374	.356	.277	.194	
		.15	.38	.330	.627	.700	.668	.518	.363	
		.20	.51	.516	.979	1.094	1.043	.810	.567	
.5	1.27	.05	.13	.081	.154	.172	.164	.127	.089	
		.10	.25	.238	.451	.504	.480	.373	.261	
		.15	.38	.446	.846	.945	.901	.699	.490	
		.20	.51	.695	1.321	1.476	1.407	1.092	.765	

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[1] The enclosed areas are represented by one or more data points. The same is true for the monoterpene component tables that follow.

Table 5.—Hypothesis values for monoterpene components, percentage of lodgepole pine phloem dry weight (no related figure in text)

Average annual radial growth		Phloem thickness		D.b.h.						
				4	8	10.5	12	16	20	*(inches)*
				10.2	20.3	26.7	30.5	40.6	50.8	*(cm)*
Inches	*cm*	*Inches*	*cm*							
				*α-pinene % = 0.15787 * (model)*						
0.1	0.25	0.05	0.13	0.007	0.012	0.014	0.013	0.010	0.007	
		.10	.25	.019	.036	.040	.038	.029	.020	
		.15	.38	.034	.066	.074	.070	.055	.038	
		.20	.51	.055	.014	.115	.110	.085	.060	
.3	.76	.05	.13	.008	.016	.018	.017	.014	.009	
		.10	.25	.025	.048	.053	.051	.040	.028	
		.15	.38	.048	.090	.100	.096	.074	.052	
		.20	.51	.074	.139	.157	.149	.116	.081	
.5	1.27	.05	.13	.011	.022	.025	.023	.018	.013	
		.10	.25	.034	.064	.072	.069	.053	.037	
		.15	.38	.064	.122	.135	.129	.100	.070	
		.20	.51	.100	.189	.211	.201	.156	.109	
				*β-phellandrene % = 0.64292 * (model)*						
0.1	0.25	0.05	0.13	0.026	0.049	0.055	0.052	0.041	0.028	
		.10	.25	.075	.144	.161	.153	.119	.083	
		.15	.38	.142	.270	.301	.287	.223	.156	
		.20	.51	.221	.420	.470	.449	.348	.244	
.3	.76	.05	.13	.035	.066	.074	.071	.055	.039	
		.10	.25	.102	.194	.218	.208	.161	.113	
		.15	.38	.192	.365	.408	.389	.302	.212	
		.20	.51	.300	.571	.637	.608	.472	.330	
.5	1.27	.05	.13	.047	.090	.100	.096	.074	.052	
		.10	.25	.138	.263	.293	.280	.217	.152	
		.15	.38	.260	.493	.551	.525	.408	.285	
		.20	.51	.406	.770	.860	.820	.637	.446	
				*(β-pinene + 3-carene + myrcene) % = 0.30222 * (model)*						
0.1	0.25	0.05	0.13	0.012	0.023	0.026	0.025	0.019	0.013	
		.10	.25	.035	.068	.075	.072	.056	.039	
		.15	.38	.067	.126	.141	.135	.105	.073	
		.20	.51	.105	.198	.221	.211	.164	.115	
.3	.76	.05	.13	.017	.032	.035	.033	.026	.018	
		.10	.25	.049	.091	.102	.098	.076	.053	
		.15	.38	.090	.172	.192	.183	.142	.099	
		.20	.51	.141	.269	.300	.286	.222	.155	
.5	1.27	.05	.13	.022	.043	.047	.045	.035	.024	
		.10	.25	.066	.124	.139	.132	.102	.072	
		.15	.38	.122	.231	.259	.247	.192	.134	
		.20	.51	.191	.362	.405	.385	.299	.210	

Table 6.—Hypothesis values for figures 2 and 3. Monoterpene percentage of lodgepole pine dry weight, at average annual radial growth 0.159 inches (0.404 cm), average for 86 trees. Percent by weight of phloem at average annual radial growth 0.159 inches (0.404 cm)

Component	Phloem thickness		D.b.h.						
			4	8	10.5	12	16	20	*(inches)*
			10.2	20.3	26.7	30.5	40.6	50.8	*(cm)*
	Inches	*cm*							
α-pinene	0.05	0.13	0.007	0.013	0.015	0.014	0.011	0 008	
	.10	.25	.020	.038	043	041	.032	022	
	.15	.38	.038	.072	081	.077	.060	.042	
	.20	.51	.059	.113	126	120	.093	.065	
β-phellandrene	.05	.13	.028	.053	.060	.057	.044	031	
	.10	.25	.082	.157	.175	.167	.129	.091	
	.15	.38	.155	.293	.328	.312	.243	.170	
	.20	.51	.242	.458	.512	.488	379	265	
β-pinene + 3-carene + myrcene	.05	.13	.013	.025	.028	.027	.021	.015	
	.10	.25	.039	.074	.082	.078	.061	.043	
	.15	.38	.073	.138	.154	.147	114	.080	
	.20	.51	.114	.215	.241	.229	.178	.125	
All terpenes (sum of those above)	.05	.13	.048	.092	.102	.098	.076	.053	
	.10	.25	.142	.269	.300	.286	.222	.156	
	.15	.38	.265	.504	.563	.536	.416	.292	
	.20	.51	.414	.786	.879	.837	650	455	

Table 7.—Mathematical descriptors for figures 1-3 and appendix tables 4, 5, and 6.

Monoterpene Models

Percent monoterpene content = $(21.0621 * YPP * P^{1.\cdot}) * K_i$

For $D < 10.5$

$$YPP = YPD * \left(1.00165 * e^{-\left|\frac{\frac{(D+8.5)}{19} - 1}{0.395}\right|} - 0.00165\right)$$

For $D > 10.5$

$$YPP = YPD * \left(1.07092 * e^{-\left|\frac{\frac{(38.5 - D)}{28} - 1}{0.49}\right|} - 0.07092\right)$$

For $0 < D < 22$

$YPD = 0.38 + 1.0292 * G^{1.1}$

	R^2	$S_{y \cdot x}$
K_1 = 1.10301, all monoterpenes	0.387	0 150
K_2 = 0.64292, β-phellandrene	0.402	0 098
K_3 = 0.30222, β-phinene + 3-carene + myrcene	0.352	0 044
K_4 = 0.15787, α-pinene	0.213	0.023

where
P = phloem thickness, inches,
D = tree d.b.h., inches;
G = average annual radial growth, last 5 years, inches

Limits
$0 < P < 0.25,\ 0 < D < 25,\ 0 < G < 0.5$

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[1] Conservative estimates

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Phloem samples taken from 86 healthy lodgepole pine trees were analyzed for content of dry matter, starch, various forms of sugar and nitrogen, and of selected monoterpenes. β-phellandrene was, by far, the most prevalent of the monoterpenes. An interactive hypothesis is developed for terpene content as a function of phloem thickness, radial growth, and tree diameter. Here, high concentrations of monoterpenes coincide with upper tree diameters, the expected region of high mountain pine beetle survival success.

KEYWORDS: phloem constituents, lodgepole pine, *Pinus contorta* var. *latifolia*, sugars, starch, nitrogen, monoterpenes, mountain pine beetle, *Dendroctonus ponderosae*.

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Rate of Woody Residue Incorporation into Northern Rocky Mountain Forest Soils

A.E. Harvey, M.J. Larsen, and M.F. Jurgensen

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RESEARCH SUMMARY

Research has shown organic matter, particularly decayed wood, imparts important properties to forest soils of the Northern Rocky Mountains. In order to maintain or reconstitute high quality soils in managed forests, the production time for incorporation of soil organic materials must be considered in the long-term management process.

The research contained in this report indicates lag periods of approximately 100 to 300 years between the time wood is produced on a forested site and the time it becomes incorporated into the soil organic mantle. Habitat type had a major influence on time period and on the tendency of an ecosystem to equilibrate with wood biomass concentrated as undecayed soil-surface residue or as extensively decayed materials incorporated into the soil profile. The cool-moist system accumulated residue. The warm-moist system accumulated decayed wood in the soil. Douglas-fir was the most common species of wood found in the soils of these experimental sites.

In order to reconstitute adequate supplies of decayed wood in soils depleted in this resource, lag periods in the 100- to 300-year range can be expected. Also, when managing harvest residue as parent materials for soil wood, Douglas-fir is a preferred species.

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INTRODUCTION

Maintenance of high organic matter levels in cultivated soils has long been recognized as important to site quality. In forest soils the rapid accumulation of organic litter and frequent requirement of a mineral seedbed for regeneration obscures the importance of long-term organic matter requirements.

Persistence of wood in forest soils has been recognized for some time (McFee and Stone 1966). Specific and quantitatively important contributions made by wood to forested ecosystems have been recognized only recently, however.

During the transition from solid to decayed wood, large residues support substantial nitrogen-fixing activity (Larsen and others 1978; Bormann and others 1977; Cornaby and Waide 1973). Once incorporated in the soil, decayed wood continues to support nitrogen-fixing activity (Jurgensen and others 1977). It becomes the primary site for nitrogen fixation during dry periods or on dry sites of the Northern Rocky Mountains (Harvey and others 1978b).

As a component of Northern Rocky Mountain forest soils, decayed wood also provides an important substratum for ectomycorrhizal symbionts. In one mature ecosystem, over 90 percent of the active ectomycorrhizal associations were supported by soil organic matter (Harvey and others 1976). As with nitrogen-fixing activity, decayed wood became the primary substratum for ectomycorrhizal activity during dry periods (Harvey and others 1978a) and on dry sites (Harvey and others 1978b, 1979).

The increasing importance of decayed wood in soils during dry seasons and on relatively dry sites is apparently related to the efficiency of the lignin matrix in highly decayed wood to retain moisture (Harvey and others 1978a, 1979).

Soil wood must be considered a primary factor governing soil quality of many forests. It is critical to moisture relations and, by way of the micro-organisms it supports, to nutrient input and availability. Therefore, how much wood is required on a site to support full growth potential and how long it takes to produce it if it is depleted are major considerations in the management of forests in which these contributions are important.

Requirements of decayed wood for high quality Northern Rocky Mountain soils are currently under study and will be reported separately. Here, we report a preliminary assessment of how long it may take to produce decayed wood in soils of three Northern Rocky Mountain ecosystems.

MATERIALS AND METHODS

This study was conducted on three sites within the boundaries of the Coram Experimental Forest located in Flathead County between Flathead Lake and Glacier National Park of northwestern Montana. The timber type is Douglas-fir larch. Elevations range from 3,340 ft (1 018 m) to 6,370 ft (1 942 m) above sea level. Mean annual precipitation at the lower elevations averages 31 in (78.7 cm) and the mean annual temperature, 42.5° F (5.3° C). Mean annual summer temperatures average 61° F (16.1° C), see Klages and others (1976).

Three sites were chosen to represent a wide range of temperature-moisture conditions typical of Northern Rocky Mountain forests. Each supports a mature ecosystem approximately 250 years of age with no history of disturbance by man and includes at least 1 ha of uniform conditions.

These sites have been characterized in detail elsewhere (Harvey and others 1979). In summary, site 1 is a warm, dry south slope dominated by Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco). Site 2 is a cool, moist east slope dominated by Douglas-fir, western larch (*Larix occidentalis* Nutt.), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), and Engelmann spruce (*Picea englemanni* Parry), and site 3 is a warm, moist north slope dominated by western hemlock (*Tsuga heterophylla* [Raf.] Sarg.). These sites are representative of *Pseudotsuga menziesii Physocarpus malvaceus* (PSME PHMA), *Abies lasiocarpa Clintonia uniflora* (ABLS CLUN), and *Tsuga heterophylla Clintonia uniflora* (TSHE CLUN) habitat types, respectively (Pfister and others 1977).

All major organic materials on these sites were characterized and measured as follows:

1. **Soil organic components:** Samples consisted of 4 x 12 in (10 by 30 cm) soil cores taken randomly from around 10 permanent plot centers evenly dispersed throughout each study site. Each core was divided into litter (0_1 horizon), humus (0_2 horizon), decayed soil wood (0_3 horizon), and charcoal (0_4 horizon) (Harvey and others 1979). The volume of each was determined by measuring its depth in the undisturbed core.

These samples were derived from a series of studies on these sites May to November 1975 and 1976. They represent a total of 1050 cores from site 2 and 160 each from sites 1 and 3.

2. **Down woody residues:** Random line intersect samples from around each of the permanent plot centers were used as a basis for calculating volume as described by Brown (1974). Residues were further characterized with respect to the general stage of decay as sound (no visible deterioration), solid decay (extensively discolored, but resistant to crumbling and breakage), and crumbly decay (easily broken and crumbled).

3. **Standing wood volume:** Site 2 volume measurements were based on a 100 percent inventory (Bensen and Schlieter 1980). Sites 1 and 3 were cruised according to Grosenbaugh (1952), and volume conversion factors were those provided in Faurot (1977).

4. **Radiocarbon dating:** Brown, cubicle decayed wood samples for dating were collected randomly from throughout the study sites. All samples selected were of crumbly decayed logs located on, partially buried in, or completely buried in the soil profile. Duplicate or triplicate samples of each decay type were dated at Washington State University according to procedures described by Sheppard (1975). All three sample types were dated for site 2. Samples from partially buried logs only were dated from sites 1 and 3. All materials of recent origin, such as roots and fungal strands were removed, insofar as possible, as a part of the sample preparation procedure. Each sample consisted of material from throughout a representative cross section and each was microscopically identified as to tree species.

5. **Lignin-carbohydrate analysis:** Samples for lignin and carbohydrate analysis were collected as above for radiocarbon dating. Ten to 15 samples from each sample type and site, as described above, were analyzed for content of lignin (Effland 1977) and carbohydrate, primarily cellulose and associated materials.[1] The species of each sample was also determined.

RESULTS AND DISCUSSION

Table 1 summarizes the results of the radiocarbon dating, lignin, and carbohydrate analyses of decayed wood residue samples from the three sites. The data for samples in various stages of incorporation into the soil show a progression in age from the position of lying on the surface of the soil ($\bar{x}$ 145 yr) to one of being fully incorporated in the soil profile ($\bar{x}$ 370 yr) of site 2 and also from the subalpine fir (site 2 — $\bar{x}$ 145 yr) to the Douglas-fir (site 1 — $\bar{x}$ 247 yr) to the hemlock (site 3 — $\bar{x}$ 473 yr) sites. Measurements derived from cross-section samples provided a maximum age estimate because of the inclusion of wood produced early in the lifespan of the tree. All 12 wood samples were identified as Douglas-fir. Present stands contain other tree species (table 2) and the fire frequency for these sites would not eliminate other species from the previous stands.

Data in table 1 show a significant loss of carbohydrates and persistence of lignin with increasing age (incorporation into the soil profile). Again, species identification of 90 random samples indicated all were Douglas-fir. This suggests Douglas-fir is the most persistent species of wood in these soils. Previous observations (Jurgensen and others 1977) have also suggested that brown, cubicle-decayed Douglas-fir wood is prevalent in these soils.

Table 1.—Radiocarbon age, lignin, and carbohydrate (percent dry weight) content of decayed soil wood from three undisturbed, mature forest stands in western Montana

Position	Species	Radiocarbon age	Lignin	Carbohydrat
		Years		
Site 1				
(PSME/PHMA)[1]				
Partially buried	Douglas-fir	250 ± 100	[2]76.93(5.62)	[2]15.10(5.50)
		280 ± 95		
		210 ± 90		
Site 2				
(ABLA/CLUN)[3]				
Surface	Douglas-fir	130 ± 90	64.9	27.1
		102 ± 90	73.3	18.8
Partially buried		190 ± 90	62.4	30.9
		100 ± 90	84.4	7.6
Buried		450 ± 95	80.9	11.3
		290 ± 90	78.8	11.9
Surface	Douglas-fir		[2]67.45(7.42)	23.87(8.17)
Partially buried			72.56(8.34)	18.57(9.16)
Buried			[4]78.13(3.86)	[5]12.64(4.44)
Site 3				
(TSHE/CLUN)[6]				
Partially buried	Douglas-fir	510 ± 100	[2]75.13(3.35)	[2]16.56(3.38)
		550 ± 120		
		360 ± 90		

[1] *Pseudotsuga menziesii/Physocarpus malvaceus* habitat type.
[2] Mean and standard deviation determined from 10 to 15 random samples.
[3] *Abies lasiocarpa/Clintonia uniflora* habitat type.
[4] Significantly more lignin than surface sample, $\alpha = 0.01$, t-test.
[5] Significantly less carbohydrate than surface sample, $\alpha = 0.01$, t-test.
[6] *Tsuga heterophylla/Clintonia uniflora* habitat type.

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[1] Moore, W.E., and D.B. Johnson. 1967. Procedures for the chemical analysis wood and wood products (as used at the U.S. Forest Products Laboratory). USD For. Serv., Madison, Wis. (unpubl.).

Table 2.—Mean stand volumes (m^3 ha) by tree species of three undisturbed, mature forests in western Montana. includes all stems

Douglas-fir	Western larch	Alpine fir	Engelmann spruce	Western hemlock	Western redcedar	Birch	Lodgepole pine	Total volume
Site 1 (PSME PHMA)[1]								
271.5	6 2							242 7
Site 2 (ABLA CLUN)[2]								
164.7	22.8	66.5	45.3		0 1			299 4
Site 3 (TSHE CLUN)[3]								
152.7				255 3	17.3	9 0	4 6	438 9

[1] *Pseudotsuga menziesii Physocarpus malvaceus* habitat type
[2] *Abies lasiocarpa Clintonia unifloraa* habitat type
[3] *Tsuga heterophylla Clintonia uniflora*

Table 3.—Mean volumes (m^3 ha) of wood residues[1] in three undisturbed, mature forest stands in western Montana

Condition	Douglas-fir	Western larch	Alpine fir	Engelmann spruce	Western hemlock	Western redcedar	Birch	Alder	Total volume
Site 1 (PSME PHMA)[2]									
Sound	22.5	5.2							
Solid decay	45.4	7.2							
Crumbly decay	57.6	16.6							154 6
Site 2 (ABLA CLUN)[3]									
Sound	82.3	42.4	27.10	1 5					
Solid decay	54 2	34 8	21 92	5 1					
Crumbly decay	105.4	46.0	7 46	1 8				0 1	430 3
Site 3 (TSHE CLUN)[4]									
Sound	9.4	36.2			8 8	6 3			
Solid decay	6.6	54 0			43.5	5 4	4 [illegible]		
Crumbly decay	20.3	32.2			25 9	1 5			254 2

[1] Not considered as incorporated in the soil profile
[2] *Pseudotsuga menziesii Physocarpua malvaceus* habitat type
[3] *Abies lasiocarpa Clintonia uniflora* habitat type
[4] *Tsuga heterophylla Clintonia uniflora* habitat type

A complete inventory of all woody materials on these sites is rovided in tables 2, 3, and 4. Table 3 shows the greatest ccumulation of downed woody residues, not incorporated in ie soil profile, on the cool, moist site (site 2, ABLA CLUN). onversely, table 4 shows that the end products of the decay rocess (woody materials incorporated in the soil profile) are ighest on the warm moist site (site 3, TSHE CLUN). The reatest stand volumes occur on the warm moist site (table 2), ut the tendency of the ecosystem to equilibrate with high wood esidue volumes varies with site conditions. The apparent ndency to accumulate undecayed residue on the relatively roductive growing site (site 2) with the coolest temperatures dicates decay is reduced by the cool temperatures.

Selected data from tables 2, 3, and 4 were used to calculate elative rates of wood accumulation and dispersion on these ites (table 5). These calculations show a tendency for the cool moist ecosystem (site 2. ABLA CLUN) to accumulate woody residue at a relatively high rate. The difference between wood production, as reported in Pfister and others (1977) and the soil wood return rate, which is based on the difference[1] between total wood production over the 250-year stand age and total wood reserves measured on each site was used to estimate the approximate time periods required to return wood reserves to the soil. A one-third loss of volume was estimated between the time fresh wood began the process of decay and disintegration and the time it began to function as soil. This estimate is based on field measurements by the authors.

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[1] This figure (column 8, table 5) represents the volume of wood that can no longer be visually accounted for in the sampling as intact wood; that is, it has been incorporated into the humus and mineral soil components or released to the atmosphere as CO$_2$. Microscopic observations by the authors indicate substantial quantities of this material have been incorporated into the humus components of these soils.

APPLICATIONS

Forest management actions should incorporate an awareness that depletion in site reserves of organic material, particularly decayed soil wood, can potentially reduce growth rates by reducing ectomycorrhizal and nitrogen-fixing activities. Replacement of the woody soil components lost due to harvesting or fire activity requires time periods from ca. 100 to 300 years. Therefore, harvesting plans, particularly those for dry sites, should be directed toward maintaining modest levels of organic matter, including large woody materials. Even where excessive depletion of woody residue has occurred (for example, sites that have been subjected to repeated and hot wildfires), the potential for soil improvement is considerable. Forest management should encourage the building of organic reserves and the rapid decay of available wood residues.

Table 4.—Mean volumes (m^3/ha/30 cm depth) of soil organic material in three undisturbed, mature forest stands in western Montana

Type of material				Total soil
0_1 (litter)	0_2 (humus)	0_3 (decayed wood)[1]	0_4 (charcoal)	(wood materials only)
Site 1 (PSME/PHMA)[2]				
60.9	304.8	365.8	7.6	373.4
Site 2 (ABLA/CLUN)[3]				
60.9	335.3	365.8	9.1	374.9
Site 3 (TSHE/CLUN)[4]				
152.4	457.2	426.7	2.9	429.7

[1] Considered incorporated in and functioning as soil.

[2] *Pseudotsuga menziesii Physocarpus malvaceus* habitat type

[3] *Abies lasiocarpa Clintonia uniflora* habitat type.

[4] *Tsuga heterophylla Clintonia uniflora* habitat type.

Table 5.—Derivation of woody residue dispersal rate (calculated by dividing wood production potential by persistent woody reserve three undisturbed forest stands in western Montana (m^3/ha)

Soil wood	Nonsoil wood residue	Stand volume	Wood reserves	Stand age	Yield capacity[1] per year	Wood production potential (250 yr)	Wood dispersed[2] (250 yr)	Dispersion (decay) rate[3] per year	Wood accumulation potential[4] per year	Soil w productio
				Years						*Yea*
Site 1 (PSME/PHMA)[6]										
373.4	154.6	242.7	700.8	250	4.9	1224.5	523	2.1	2.8	19
Site 2 (ABLA/CLUN)[7]										
374.9	430.3	299.4	1104.6	250	6.3	1574.4	469.7	1.9	4.4	27
Site 3 (TSHE/CLUN)[8]										
429.7	254.2	[9]311.2	955.1	250	7.7	1924.2	929.1	3.7	4.0	17

[1] Pfister and others 1977.

[2] Dispersal of wood in soil to a point where it is classified as mixed in mineral soil or lost from the system as CO_2 (production potential minus reserves).

[3] Wood dispersed divided by stand age.

[4] Yield capacity minus dispersion rate.

[5] Wood production potential divided by dispersation rate (column 2) times 0.33.

[6] *Pseudotsuga menziesii Physocarpus malvaceus* habitat type.

[7] *Abies lasiocarpa Clintonia uniflora* habitat type.

[8] *Tsuga heterophylla Clintonia uniflora* habitat type

[9] Includes a 50 percent volume loss to live stem decay in hemlock stems.

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The important properties contributed to forest soils by decayed wood in the Northern Rocky Mountains make it desirable to determine the time required to reconstitute such materials in depleted soils. The ratio of fiber production potential (growth) to total quantity of wood in a steady state ecosystem provides estimates varying from approximately 100 to 300 years, depending on habitat type, for replacement of decayed soil wood. Radiocarbon dating of decayed wood in various stages of incorporation into the soil ranged from 100 to 550 years, depending on site and depth in soil. Species identification of decayed wood indicated that Douglas-fir residue is the most persistent woody material in these Northern Rocky Mountain soils.

KEYWORDS: decay, disintegration, decomposition, recycling, nutrients, fuels, wood residues, soils, ectomycorrhizae, nitrogen fixation, site quality, forest fire, organic reserves

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Crown Width and Foliage Weight of Northern Rocky Mountain Conifers

Melinda Moeur

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MELINDA MOEUR received her master's degree in forestry from the University of Minnesota in 1980. As a research forester at the Forestry Sciences Laboratory, Moscow, Idaho, she has worked on linking vegetation, watershed, and wildlife system models into a decision-support system.

RESEARCH SUMMARY

Equations were derived for predicting crown width of trees from diameter, height, crown length, and basal area per acre, and for predicting foliage weight of trees from diameter, height, crown length, age, relative diameter, and number of trees per acre. Coefficients were estimated for 11 conifer species in northern Idaho and western Montana. Embedding these equations in the prognosis model for stand development will enhance the prediction of vegetation characteristics needed for interfacing insect outbreak, wildlife habitat, and watershed models.

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INTRODUCTION

This paper reports on the development of multiple linear regression models predicting individual tree crown width and foliage weight for 11 conifer species in northern Idaho and western Montana. The equations have been applied in a spruce budworm version[1] of the stand prognosis model (Stage 1973) being currently developed. The crown width and foliage biomass equations, when linked with other relationships in the spruce budworm system, help predict insect damage and dispersal of larvae during simulated outbreaks. The crown width function has also been used to predict percent stand crown cover in the prognosis model (Stage 1973) for linkage with proposed watershed[2] and big game habitat prediction[3] submodels.

The relationship between crown width and tree diameter has been of interest to several researchers in developing crown competition indices (see for example Krajicek and others 1961 or Vezina 1963). This relationship has been expressed as:

$$\text{crown width} = a + b\,(\text{d.b.h.})$$

In some studies, for example Smith (1966), stand density inversely influenced tree crown width. Vezina (1964) used stand basal area to predict stand crown closure. Bonnor (1964), in studying the relationship between diameter at breast height (d.b.h.) and crown width on vertical photography, found no effect from stand density. The current study investigates the contribution of a number of stand and individual tree characteristics in predicting crown width by species.

The second part of this study looks at the relationship between individual tree foliage weight and measured tree and stand characteristics. Kittredge (1944) developed the following logarithmic expression to estimate leaf weight for several conifer and hardwood species:

$$\ln\,(\text{leaf weight}) = b\,(\ln \text{d.b.h.}) + a$$

He noted conflicting site and age effects, possibly confounded by geographical location. The effects of density and crown class as sources of variation were not separated out in his study.

Brown (1978) approached the problem of estimating foliage weight indirectly by first developing total crown weight as a function of tree diameter, height, and crown length, and then estimating the proportion of the total crown in foliage in a separate equation. In addition, Brown presented more than one model form for each species depending on crown class and size class. The current study used Brown's data with the purpose of simplifying the direct estimation of foliage weight by investigating one or two model forms applicable to all tree species considered.

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DATA

The data studied are a subsample of trees used by Brown (1978) in estimating crown weights. Trees deleted from the original data set were those lacking measurements for crown width or foliage weight. Refer to Brown (1978) for a more complete description and listing of the data.

Measurements from dominant and codominant trees were studied for the following 11 species (abbreviations are used in following tables and figures):

DF	Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
ES	Engelmann spruce	*Picea engelmannii* Parry
GF	Grand fir	*Abies grandis* (Dougl.) Lindl.
LP	Lodgepole pine	*Pinus contorta* Dougl.
PP	Ponderosa pine	*Pinus ponderosa* Laws.
AF	Subalpine fir	*Abies lasiocarpa* (Hook.) Nutt.
WH	Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
WL	Western larch	*Larix occidentalis* Nutt.
WC	Western redcedar	*Thuja plicata* Donn
WP	Western white pine	*Pinus monticola* Dougl.
BP	Whitebark pine	*Pinus albicaulis* Engelm.

In addition, trees of intermediate and suppressed crown classes were available only for western redcedar (WC-INT), ponderosa pine (PP-INT), grand fir (GF-INT), and Douglas-fir (DF-INT). Tables 1 and 2 show the distribution of data used in developing the models.

PROCEDURE

The models were developed by means of a regression screening method. First, the relationships between the two dependent variables of crown width and foliage weight, and stand and tree characteristics were studied by screening for the best combinations of the independent variables and their logarithmic transformations. Variable screening and coefficient estimation were done in a multiple linear regression computer program, REX (Grosenbaugh 1967). The following relationships between the dependent and independent variables were examined:

$$Y = \mathrm{f}(D, D^2, H, CL, CR, A, TPA, BA, DREL, SP, SI)$$

$$\ln Y = \mathrm{f}(\ln D, (\ln D)^2, \ln H, \ln CL, \ln CR, \ln A, \ln TPA, \ln BA, \ln DREL, SP, SI)$$

Table 1.—Distribution of sample trees by species and crown class used in estimating crown width

	Number of trees		Range of Measurements			
Species[1]	<3.5 inches	≥3.5 d.b.h.	d.b.h.	Height	Crown length	Stand basal area
			Inches	*--------Feet--------*		*Feet^2 acre*
BP	12	7	0 - 10.6	3 - 44	2 - 36	1 - 181
WP	17	8	0 - 24.7	3 - 126	3 - 88	1 - 299
WC	14	14	0 - 26.6	2 - 127	2 - 98	1 - 300
WC-INT	11	11	0 - 10.6	4 - 64	2 - 42	45 - 335
WL	15	9	0 - 21.8	3 - 129	3 - 75	1 - 271
WH	16	12	0 - 21.4	4 - 126	3 - 111	1 - 320
AF	15	10	0 - 12.7	3 - 93	2 - 70	1 - 260
PP	15	20	0 - 34.0	2 - 144	2 - 89	1 - 325
PP-INT	12	9	0 - 12.1	4 - 70	1 - 44	22 - 280
LP	12	7	0 - 15.6	2 - 84	1 - 60	1 - 271
GF	16	13	0 - 20.4	3 - 137	3 - 108	1 - 432
GF-INT	13	9	0 - 11.8	4 - 72	2 - 60	39 - 296
ES	14	8	0 - 23.2	2 - 128	2 - 105	1 - 240
DF	16	13	0 - 33.9	4 - 143	4 - 86	2 - 238
DF-INT	12	10	0 - 11.2	4 - 83	1 - 47	36 - 360
Total	210	160				

[1] See text page 2 for species list.

Table 2.—Distribution of sample trees by species and crown class used in estimating foliage weight

Species[1]	Number of trees 3.5 inches d.b.h.	Number of trees ·3.5 inches d.b.h.	Range of measurements d.b.h.	Height	Crown length	Number of trees per acre	Age
			Inches	*Feet*	*Feet*		*Years*
BP	12	4	0 - 7.4	3 - 38	2 - 27	461 - 6324	5 - 182
WP	17	2	0 - 7.4	3 - 66	3 - 46	300 - 4500	4 - 55
WC	14	11	0 - 26.6	2 - 127	2 - 98	110 - 7800	3 - 237
WC-INT	11	11	0 - 10.6	4 - 64	2 - 42	169 - 3611	16 - 162
WL	15	3	0 - 6.6	3 - 50	3 - 29	600 - 5100	3 - 55
WH	16	4	0 - 7.0	4 - 38	3 - 38	848 - 7200	4 - 32
AF	15	10	0 - 12.7	3 - 93	2 - 70	87 - 15121	4 - 201
PP	15	20	0 - 34.0	2 - 144	2 - 89	5 - 7200	6 - 217
PP-INT	12	9	0 - 12.1	4 - 70	1 - 44	142 - 3344	11 - 140
LP	12	0	0 - 1.8	2 - 13	1 - 12	300 - 6000	5 - 11
GF	16	8	0 - 15.6	3 - 79	3 - 70	300 - 7079	4 - 124
GF-INT	13	9	0 - 11.8	4 - 72	2 - 60	359 - 5804	15 - 117
ES	14	3	0 - 9.0	2 - 57	2 - 44	600 - 12730	7 - 153
DF	16	10	0 - 33.9	4 - 143	4 - 86	21 - 7200	6 - 262
DF-INT	12	10	0 - 11.2	4 - 83	1 - 47	261 - 4500	12 - 145
Total	210	114					

[1] See text page 2 for species list

here:

D = diameter breast height, inches (cm)
H = height, ft (m)
CL = crown length, ft (m)
CR = crown ratio
A = tree age, years
TPA = number of trees per acre (number per hectare)
BA = stand basal area, ft^2 ac (m^2 ha)
DREL = relative diameter (tree d.b.h quadratic mean stand diameter)

$$SP_i = \begin{cases} 1 \text{ if tree is of species } i, \\ 0 \text{ otherwise} \end{cases}$$

$$SI_j = \begin{cases} 1 \text{ if tree is in site class } j, \\ 0 \text{ otherwise} \end{cases}$$

Y = predicted crown width (*CW*), ft (m) or foliage weight (*WT*), lbs (kg)

RESULTS

Variable selection began with the model chosen in the REX screening process as having the lowest mean square error var(Y). A general model was chosen when coefficients that were not significantly different from zero when tested by the T-statistic at the 0.05 level, were deleted from the parameter set, and all remaining coefficients were significant when the model was refit.

Refinements on the general model were investigated by allowing each parameter to vary by species. Species x parameter interactions that significantly improved the regression sum of squares were then included in the final model form.

In developing the equations, the data were divided into two sets consisting of those trees 3.5 inches (8.9 cm) d.b.h. and larger, and trees less than 3.5 inches (8.9 cm). Each set was then modeled independently. The break in diameter was chosen to correspond to prognosis model methodology that predicts diameter growth for large trees and height growth for smaller trees. For the set of smaller trees, d.b.h. was not included in the list of possible predictor variables. The fundamental reason for modeling the two size classes of trees differently is that for small trees, either diameter at breast height is not available, or is not as meaningful a dimension as it is for larger trees.

Crown Width

For 160 trees 3.5 inches (8.9 cm) d.b.h. and larger, the general model is:

$$\ln(CW) = b_0 + b_1\ln(D) + b_2\ln(H) + b_3\ln(CL)$$

In this and all subsequent models, a log-log model form was chosen in order to linearize the geometric relationships and stabilize the variance structure commonly encountered when working with a wide range of data (for instance, when variance is proportional to tree size). In this and subsequent models, the second assumption is borne out by the uniform random patterns shown in scatterplots of residuals versus predicted values in the log scale.

It is interesting to note that in this model no stand density term is included as a measure of competition. However, if the log model were inversely transformed to the natural scale, the combination of the *CL* term with its positive coefficient, and *H* with its negative coefficient (table 3) could be interpreted as crown ratio. The effect of competition on predicted crown width would be represented by crown ratio instead of stand density. It is assumed that this effect would be positive, that is, crown width would increase with increasing crown ratio.

Table 4 is an analysis of variance showing the improvement in the regression sum of squares when variables in the general model are allowed to vary by species. For example, varying the intercept term by species improves the regression by a significant amount. Then, when either ln(*D*) or ln(*H*) are allowed to vary by species, the fit is further significantly improved. Of these two alternatives, the latter has a slight advantage. Although fitting ln(*CL*) by species, or any more successively complex model also improves the regression, the signs of the coefficients for the *H* and *CL* terms become inconsistent (some species with positive coefficients and some with negative coefficients for a single parameter). The inconsistencies of sign among species could not be logically explained, for example, as a pattern indicating ranking of species by tolerance. Therefore i is assumed that the terms change sign because the model is overfitting the particular data set. Acceptable models were thus constrained to those with consistent coefficients. The final model chosen is that in which the intercept and height terms vary by species (indicated by the subscript *i* on the parameter):

$$\ln(CW) = b_{0_i} + b_1\ln(D) + b_{2_i}\ln(H) + b_3\ln(CL)$$

The coefficients for this model, shown in table 3, gave a mean square error of 0.04898. The equation overpredicts crown width in the natural scale for four species and underpredicts for sever species, as shown in table 5. The mean crown width is underestimated by 5.7 ft (1.7 m).

Negative bias (mean residual deviation from zero), introduced when the inverse logarithmic transformation is used t convert log-normally distributed estimates to the original natura scale, can be approximately corrected by adding one-half the residual variance to the estimate on the log scale (Baskervil 1972). This amounts to multiplying the estimate of crown wid in the natural scale by exp[½MSE]. Thus a factor of $e^{1/2(.04898)}$ 1.025 may be applied to the estimate in the natural scale correct for underprediction. After "bias adjustment," mean crown width is overestimated slightly, 1.2 ft (0.4 m).

Table 3.—Coefficients for estimating ln (crown width) of trees 3.5 inches d.b.h. and larger:
$\ln(CW) = b_{0_i} + b_1\ln(D) + b_{2_i}\ln(H) + b_3\ln(CL)$

Species[1]	Variable coefficients Intercept b_{0_i}	 ln(H) b_{2_i}
BP	−0.91984	−0.07299
WP	4.30800	−1.37265
WC	2.79784	− .89666
WL	2.31359	− .80919
WH	1.32772	− .52554
AF	1.74558	− .73972
LP	1.06804	− .55987
GF	2.20611	− .76936
ES	3.76535	−1.18257
DF	3.02271	−1.00486
PP	1.62365	− .68098

Variables	Variable coefficients
ln(*D*)	$b_1 = 1.08137$
ln(*CL*)	$b_3 = 0.29786$

Regression sum of squares/d.f.	=	33.37909/23
Error sum of squares/d.f.	=	6.66189/136
Mean square error	=	0.04898
R^2	=	0.8336

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[1] See text page 2 for species list.

Table 4.—Analysis of improvement of ln(crown width)[1] regression models attainable by varying parameters by species, trees 3.5 inches d.b.h. and larger

	Model[2]	Source	Remarks	Degrees of freedom	Marginal sum of squares	Mean square reduction	F[3]
(1)	$b_0 + b_1\ln(D) + b_2\ln(H) + b_3\ln(CL)$	Reduction due to model (1)		3	24.09107	8.03036	206.65
(2)	$\underline{b_0} + b_1\ln(D) + b_2\ln(H) + b_3\ln(CL)$	Reduction due to model (2) -reduction due to model (1)		10	7.46691	.74669	19.2[illegible]
(3)	$\underline{b_0} + \underline{b_1}\ln(D) + b_2\ln(H) + b_3\ln(CL)$	Reduction due to model (3) -reduction due to model (2)		10	1.45889	.14589	3.[illegible]
(4)	$\underline{b_0} + b_1\ln(D) + \underline{b_2}\ln(H) + b_3\ln(CL)$	Reduction due to model (4) -reduction due to model (2)		10	1.82111	.18211	4.6[illegible]
(5)	$\underline{b_0} + b_1\ln(D) + b_2\ln(H) + \underline{b_3}\ln(CL)$	Reduction due to model (5) -reduction due to model (2)	inconsistent signs in *CL* terms	10	2.34274	.24327	[illegible]
(6)	$\underline{b_0} + \underline{b_1}\ln(D) + \underline{b_2}\ln(H) + b_3\ln(CL)$	Reduction due to model (6) -reduction due to model (4)	inconsistent signs in *H* terms	10	1.10706	.11071	2.85
(7)	$\underline{b_0} + \underline{b_1}\ln(D) + b_2\ln(H) + \underline{b_3}\ln(CL)$	Reduction due to model (7) -reduction due to model (3)	inconsistent signs in *CL* terms	10	1.36227	.13623	3.51
(8)	$\underline{b_0} + b_1\ln(D) + \underline{b_2}\ln(H) + \underline{b_3}\ln(CL)$	Reduction due to model (8) -reduction due to model (4)	inconsistent signs in *H* and *CL* terms	10	1.35748	.13575	3.49
	complete model $\underline{b_0} + \underline{b_1}\ln(D) + \underline{b_2}\ln(H) + \underline{b_3}\ln(CL)$	Error	inconsistent signs in *H* and *CL* terms	116	4.50798	.03886	

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[1] Mean ln(*CW*) = 2.53253 feet, standard deviation 0.50183.

[2] Terms varying by species are underlined.

[3] Tabulated F values: $F^{10}_{116, .01} = 2.49$

Table 5.—Summary of residuals (natural scale) from prediction equations for crown width of trees. Bias adjustment factors are 1.025 for trees greater than or equal to 3.5 inches d.b.h., and 1.031 for trees less than 3.5 inches

		Trees ≥3.5 inches d.b.h.			Trees <3.5 inches d.b.h.	
		Σ (obs-pred)			Σ (obs-pred)	
Species[1]	No. of trees	without correction	with bias correction	No. of trees	without correction	with bias correction
BP	7	− 0.71	1.93	12	0.61	−0.19
WP	8	1.59	− .36	17	− .03	−2.12
WC	25	−1.25	−11.26	25	1.70	−2.00
WL	9	− .03	−3.08	15	1.25	− .27
WH	12	.15	−5.66	16	2.08	.20
AF	10	− .80	−3.00	15	.58	−1.01
LP	7	5.68	3.73	12	.29	− .08
GF	22	1.80	−6.09	29	1.55	−2.40
ES	8	2.35	− .43	14	.52	− .98
DF	23	9.95	2.07	28	4.19	.78
PP	29	21.02	10.30	27	8.84	5.66
Weighted mean residual (ft/tree)		5.67	−1.18		2.48	−0.07
(m/tree)		(1.73)	(−0.36)		(0.76)	(−0.02)

[1]See text page 2 for species list.

The general model for prediction of crown width for 210 trees less than 3.5 inches (8.9 cm) d.b.h. is:

$$\ln(CW) = b_1\ln(H) + b_2\ln(CL) + b_3\ln(BA)$$

In this model for smaller trees the density effect, as measured by the basal area term, is positive rather than negative as might be expected (table 6). One possible explanation is that there is no competition effect among small trees due to stocking. Instead, the density effect is positive in that small trees in a well-stocked stand expand laterally to utilize all available space. As the stand matures with time, closure of the canopy begins, and individual tree crowns start to compete, stocking may negatively affect crown width. This argument would assume that the measured stands are mainly even-aged, and would not hold for suppressed trees with weak crowns. That more than three-fourths of the data are from dominant or codominant trees helps support this explanation.

Table 6.—Coefficients for estimating ln(crown width) of trees less than 3.5 inches: $\ln(CW) = b_{1_i}\ln(H) + b_2\ln(CL) + b_3\ln(BA)$

	Variable coefficients
Species[1]	$\ln(H)$ b_{1_i}
BP	0.07049
WP	.37031
WC	.46452
WL	.23846
WH	.25622
AF	.33722
LP	.26342
GF	.38503
ES	.33089
DF	.32874
PP	.36380
Variables	Variable coefficients
$\ln(CL)$	b_2 = .28283
$\ln(BA)$	b_3 = .04032

Regression sum of squares/d.f.	= 371.02441/13
Error sum of squares/d.f.	= 11.89093/197
Mean square error	= 0.06036
R^2	= 0.9689

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[1]See text page 2 for species list

Table 7 shows the effects on the general model of varying parameters by species. Since the intercept term in the original model was not significantly different from zero, all subsequent regressions were fitted through the origin. Varying ln(*H*), ln(*CL*) or ln(*BA*) by species significantly improves the fit. However, inconsistency in signs for the ln(*CL*) or ln(*BA*) terms occurs in all except model (2). Thus model (2) was chosen for predicting crown width for trees less than 3.5 inches (8.9 cm) d.b.h.:

$$\ln(CW) = b_{1i}\ln(H) + b_2\ln(CL) + b_3\ln(BA)$$

where the subscript *i* denotes a different coefficient for the ln(*H*) term for every species.

The coefficients in table 6 gave a mean square error of 0.06036. The model underpredicts crown width by an average of 2.5 ft (0.8 m) (table 5). A factor of $e^{[illegible]}$ = 1.031 may be applied to the estimate in the natural scale to correct for negative bias. When this is done, crown width is overpredicted by only 0.07 ft (0.02 m).

Foliage Weight

The general model for predicting needle weight developed from 114 trees 3.5 inches (8.9 cm) d.b.h. and larger is

$$\ln(WT) = b_0 + b_1\ln(D) + b_2\ln(H) + b_3\ln(CL) + b_4\ln(A) + b_5\ln(TPA) + b_6\ln(DREL)$$

The analysis of variance in table 8 is slightly different from that in tables 4 and 7. It was not possible to fit the complete model (species x parameter interactions for seven variables) in the REX regression program because of the dimension of the problem. Instead, the improvement in fit was analyzed between two models at a time by forming an F ratio in which the denominator is the mean square of the model with the most parameters in it. For instance, the general model was fit in (1). Then in (2) the intercept was varied by species, and the reduction in error between (1) and (2) associated with 9 d.f. was measured with an F-test. Since this reduction was significant, the species-intercept term was carried through in each successively more complex model, (3) through (8). Beyond fitting the intercept term

Table 7.—Analysis of improvement of ln(crown width)[1] regression models attainable by varying parameters by species, trees less than 3.5 inches d.b.h.

	Model[2]	Source	Remarks	Degrees of freedom	Marginal sum of squares	Mean square reduction	F[3]
(1)	$b_1\ln(H) + b_2\ln(CL) + b_3\ln(BA)$	Reduction due to model (1)		3	364.13574	121.37858	2063
(2)	$\underline{b_1}\ln(H) + b_2\ln(CL) + b_3\ln(BA)$	Reduction due to model (2) -reduction due to model (1)		10	6.88867	.68887	11.71
(3)	$b_1\ln(H) + \underline{b_2}\ln(CL) + b_3\ln(BA)$	Reduction due to model (3) -reduction due to model (1)	Inconsistent signs in *CL* terms	10	6.89868	.68987	11.73
(4)	$b_1\ln(H) + b_2\ln(CL) + \underline{b_3}\ln(BA)$	Reduction due to model (4) -reduction due to model (1)	Inconsistent signs in *BA* terms	10	6.77222	.67[illegible]	11.51
(5)	$\underline{b_1}\ln(H) + \underline{b_2}\ln(CL) + b_3\ln(BA)$	Reduction due to model (5) -reduction due to model (2)	Inconsistent signs in *CL* terms	10	1.16358	.11636	1.98
(6)	$\underline{b_1}\ln(H) + b_2\ln(CL) + \underline{b_3}\ln(BA)$	Reduction due to model (6) -reduction due to model (2)	Inconsistent signs in *BA* terms	10	.81690	.08169	1.39
(7)	$b_1\ln(H) + \underline{b_2}\ln(CL) + \underline{b_3}\ln(BA)$	Reduction due to model (7) -reduction due to model (3)	Inconsistent signs in *BA* terms	10	1.07251	.10725	1.82
	complete model $\underline{b_1}\ln(H) + \underline{b_2}\ln(CL) + \underline{b_3}\ln(BA)$	Error	Inconsistent signs in *CL* and *BA* terms	177	10.41343	.05883	

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[1] Mean ln(*CW*) = 1.26648 feet, standard deviation = 0.46956.
[2] Terms varying by species are underlined.
[3] Tabulated F values F^{10}_{177} = 1.63.

Table 8.—Analysis of improvement of ln(foliage weight)[1] regression models attainable by varying parameters by species, trees 3.5 inches d.b.h. and larger

Model[2]	Source	Remarks	Degrees of freedom	Marginal sum of squares	Mean square	F[3]
(1) $b_0 + b_1\ln(D) + b_2\ln(H) + b_3\ln(CL)$	Reduction due to model (1)		6	152.41829	25.40305	126.59
$+ b_4\ln(A) + b_5\ln(TPA) + b_6\ln(DREL)$	Residual from model (1)		107	21.47126	.20067	
(2) $\underline{b_0} + b_1\ln(D) + b_2\ln(H) + b_3\ln(CL)$	Reduction due to model (2)-(1)		9	8.43661	.93740	7.05
$+ b_4\ln(A) + b_5\ln(TPA) + b_6\ln(DREL)$	Residual from model (2)		98	13.03464	.13301	
(3) $\underline{b_0} + \underline{b_1}\ln(D) + b_2\ln(H) + b_3\ln(CL)$	Reduction due to models (3)-(2)		9	1.35027	.15003	1.14
$+ b_4\ln(A) + b_5\ln(TPA) + b_6\ln(DREL)$	Residual from model (3)		89	11.68435	.13128	
(4) $\underline{b_0} + b_1\ln(D) + \underline{b_2}\ln(H) + b_3\ln(CL)$	Reduction to models (4)-(2)		9	1.60567	.17841	1.39
$+ b_4\ln(A) + b_5\ln(TPA) + b_6\ln(DREL)$	Residual from model (4)		89	11.42897	.12842	
(5) $\underline{b_0} + b_1\ln(D) + b_2\ln(H) + \underline{b_3}\ln(CL)$	Reduction due to model (5)-(2)		9	2.20900	.24544	2.02
$+ b_4\ln(A) + b_5\ln(TPA) + b_6\ln(DREL)$	Residual from model (5)	inconsistent signs in CL terms	89	10.82565	.12164	
(6) $\underline{b_0} + b_1\ln(D) + b_2\ln(H) + b_3\ln(CL)$	Reduction due to models (6)-(2)		9	.75875	.08431	.61
$+ \underline{b_4}\ln(A) + b_5\ln(TPA) + b_6\ln(DREL)$	Residual due to model (6)	inconsistent signs in A term	89	12.27590	.13793	
(7) $\underline{b_0} + b_1\ln(D) + b_2\ln(H) + b_3\ln(CL)$	Reduction due to models (7)-(2)		9	.81401	.09446	.66
$+ b_4\ln(A) + \underline{b_5}\ln(TPA) + b_6\ln(DREL)$	Residual from model (7)	inconsistent signs in TPA term	89	12.22063	.13731	
(8) $\underline{b_0} + b_1\ln(D) + b_2\ln(H) + b_3\ln(CL)$	Reduction due to models (8)-(2)		9	1.41581	.15731	1.20
$+ b_4\ln(A) + b_5\ln(TPA) + \underline{b_6}\ln(DREL)$	Residual from model (8)	inconsistent signs in DREL terms	89	11.61885	.13055	

---

[1] Mean in(WT) = 3.41782 lb; standard deviation = 1.24050.

[2] Terms varying by species are underlined.

[3] Tabulated F values: $F^{9}_{98,0.01} = 2.59$. $F^{9}_{89,0.05} = 1.98$

by species, there was no significant species interaction with any of the variables in the general model except for ln(CL). However, since the signs of the coefficients for the species x ln(CL) term were inconsistent, this model was rejected as possibly overfitting the data.

Thus, the final model is that in which just the intercept term varies by species:

$$\ln(WT) = b_{0,} + b_1\ln(D) + b_2\ln(H) + b_3\ln(CL) + b_4\ln(A) + b_5\ln(TPA) + b_6\ln(DREL)$$

The coefficients in table 9 gave a residual mean square of 0.13301. Note that since there were no data available for lodgepole pine, no parameters were estimated for this species. Table 10 shows for which species the model overpredicts and underpredicts. The mean prediction underestimates foliage biomass by 86.9 lb (39.4 kg). A correction for bias of $e^{1/2(.13301)} = 1.069$ may be applied, resulting in an overprediction of 5.7 lb (2.6 kg) per tree after adjustment.

In the above model, predicted foliage weight decreases as trees per acre increase, an indication of competitive stress due to stocking. The positive crown length and negative height, which reflect crown ratio in the natural scale, and positive relative diameter terms may all be interpreted as measures of an individual tree's competitive status. In addition, the negative age term coupled with the positive diameter term may be interpreted as an estimator of mean annual diameter increment in the natural scale, which would be expected to vary directly with foliage weight. As tree age is not always a readily available measurement in inventory data, an alternative equation for foliage weight involving a transformation of the diameter and age terms is presented in a later section.

Table 9.—Coefficients for estimating ln(foliage weight) of trees 3.5 inches and larger:
$\ln(WT) = b_{0i} + b_1\ln(D) + b_2\ln(H) + b_3\ln(CL) + b_4\ln(A) + b_5\ln(TPA) + b_6\ln(DREL)$

Species[1]		Variable coefficients Intercept b_{0i}
BP		2.62251
WP		2.66607
WC		3.05935
WL		1.75654
WH		2.65457
AF		3.06017
GF		3.11508
ES		3.30085
DF		2.70587
PP		2.45249
Variables		**Variable coefficients**
ln(D)	b_1	2.08624
ln(H)	b_2	1.07705
ln(CL)	b_3	.69082
ln(A)	b_4	-.30885
ln(TPA)	b_5	-.14210
ln(DREL)	b_6	.39924
Regression sum of squares d.f.		160.85490 15
Error sum of squares d.f.		13.03465 98
Mean square error		0.13301
R^2		0.9250

[1] See text page 2 for species list

In developing an equation for foliage weight prediction for trees less than 3.5 inches (8.9 cm) d.b.h., the general model form is:

$$\ln(WT) = b_0 + b_1\ln(CL) + b_2\ln(A) + b_3\ln(TPA)$$

The analysis of variance of species by parameter interactions for this model is shown in table 11. Varying the intercept and ln(*CL*) by species resulted in significant improvement while maintaining consistency in signs between species. Improvements due to varying other parameters by species were also significant, but integrity of sign was no longer maintained. Therefore, the model chosen for predicting foliage weight of trees less than 3.5 inches (8.9 cm) is:

$$\ln(WT) = b_{0i} + b_{1i}\ln(CL) + b_2\ln(A) + b_3\ln(TPA)$$

where the subscript i denotes a parameter varying by species.

Table 10.—Summary of residuals (natural scale) from prediction equations for foliage weight of trees. Bias adjustment factors are 1.069 for trees greater than or equal to 3.5 inches, and 1.126 for trees less than 3.5 inches

		Trees ≥ 3.5 inches d.b.h.			Trees < 3.5 inches d.b.h.	
		Σ (obs-pred)			Σ (obs-pred)	
Species[1]	No. of trees	without correction	with bias correction	No. of trees	without correction	with bias correction
BP	4	0.44	3.92	12	1.31	0.07
WP	2	2.77	4.65	17	1.85	1.90
WC	22	218.20	330.13	25	5.77	.55
WL	3	.05	.98	15	.16	1.90
WH	4	1.51	5.23	16	1.34	2.96
AF	10	2.22	30.10	15	5.51	.28
LP	0	—	—	12	0.01	1.26
GF	17	48.58	4.29	29	3.88	5.35
ES	3	4.16	5.42	14	1.56	3.13
DF	20	52.94	172.73	28	7.61	1.43
PP	29	515.50	362.32	27	5.15	1.10
Weighted mean						
residual (lbs/tree)		86.89	5.69		3.71	1.12
(kg/tree)		(39.41)	(2.58)		(1.68)	(0.51)

[1] See text page 2 for species list

Table 11.—Analysis of improvement of ln(foliage weight)[1] regression models attainable by varying parameters by species, trees less than 3.5 inches d.b.h.

	Model[2]	Source	Remarks	Degrees of freedom	Marginal sum of squares	Mean square reduction	F[3]
(1)	$b_0 + b_1\ln(CL) + b_2\ln(A) + b_3\ln(TPA)$	Reduction due to model (1)		3	259.86645	86.62215	413.06
(2)	$\underline{b_0} + b_1\ln(CL) + b_2\ln(A) + b_3\ln(TPA)$	Reduction due to model (2) -reduction due to model (1)		10	32.33326	3.23326	15.42
(3)	$\underline{b_0} + \underline{b_1}\ln(CL) + b_2\ln(A) + b_3\ln(TPA)$	Reduction due to model (3) -reduction due to model (2)		10	5.37841	.53784	2.56
(4)	$\underline{b_0} + b_1\ln(CL) + \underline{b_2}\ln(A) + b_3\ln(TPA)$	Reduction due to model (4) -reduction due to model (2)	inconsistent signs in *A* term	10	6.87378	.68738	3.28
(5)	$\underline{b_0} + b_1\ln(CL) + b_2\ln(A) + \underline{b_3}\ln(TPA)$	Reduction due to model (5) -reduction due to model (2)	inconsistent signs in *TPA* term	10	5.20996	.52100	2.48
(6)	$\underline{b_0} + \underline{b_1}\ln(CL) + \underline{b_2}\ln(A) + b_3\ln(TPA)$	Reduction due to model (6) -reduction due to model (3)	inconsistent signs in *A* term	10	5.54004	.55400	2.64
(7)	$\underline{b_0} + \underline{b_1}\ln(CL) + b_2\ln(A) + \underline{b_3}\ln(TPA)$	Reduction due to model (7) -reduction due to model (3)	inconsistent signs in *TPA* terms	10	5.38501	.53850	2.57
(8)	$\underline{b_0} + b_1\ln(CL) + \underline{b_2}\ln(A) + \underline{b_3}\ln(TPA)$	Reduction due to model (8) -reduction due to model (4)	inconsistent signs in *A* and *TPA* terms	10	3.79663	.37966	1.81
	complete model $\underline{b_0} + \underline{b_1}\ln(CL) + \underline{b_2}\ln(A) + \underline{b_3}\ln(TPA)$	Error	inconsistent signs in *A* and *TPA* terms	166	34.81201	.20971	

[1] Mean ln(*WT*) = 0.075104 lb; standard deviation = 1.27874

[2] Terms varying by species are underlined.

[3] Tabulated F values: $F^{10}_{166,0.05} = 1.89$, $F^{10}_{166,0.01} = 2.43$.

Mean square error for the above model is 0.23751, and coefficient values are shown in table 12. Table 10 summarizes the residuals for the model. Foliage weight is underestimated by an average of 3.7 lb (1.7 kg) per tree. Negative bias may be compensated for by multiplying the estimate in the natural scale by $e^{1/2(.23751)} = 1.126$, giving an overprediction of 1.1 lb (0.5 kg) per tree after adjustment.

The present approach for estimating foliage biomass uses two model forms; one for small trees and one for large trees—each of which is applicable to all species. The data used in developing these equations were a subset of Brown's (1978) data. His approach was to fit one or more separate model forms for total crown biomass (foliage and branchwood) for trees greater than 1 inch d.b.h. and for trees less than 2 inches d.b. by species and crown class. He further fitted separate regre sion equations for predicting the proportion of total cro biomass in foliage and branchwood components. Folia weight can be estimated indirectly using Brown's method applying these two equations in succession to the data. T following method was used to compare the present approa with Brown's approach for predicting foliage biomass. The b combination (that yielding lowest mean square error) of Brow crown biomass and foliage proportion equations for a spec was solved for each tree in the data set used to develop t current equations. Residual sums of squares [Σ(observed predicted needle weight)^2] were then compared for the t methods. Results are as follows:

Table 12.—Coefficients for estimating ln (foliage weight) of trees less than 3.5 inches d.b.h.: $\ln(WT) = b_0 + b_1\ln(CL) + b_2\ln(A) + b_3\ln(TPA)$

Species[1]	Intercept b_0	$\ln(CL)$ b_1
BP	2.81317	1.47513
WP	2.15894	1.48969
WC	2.64034	1.69973
WL	5.02156	2.31835
WH	4.22701	2.22534
AF	2.03919	1.64942
LP	3.38394	1.96060
GF	2.78090	1.90272
ES	3.30673	2.27613
DF	2.30430	1.52896
PP	3.02050	1.88712
Variables	Variable coefficients	
$\ln(A)$	b_2 22823	
$\ln(TPA)$	b_3 13550	
Regression sum of squares d.f.	297.57812 23	
Error sum of squares d.f.	44.17596 186	
Mean square error	0.23751	
R^2	0.8707	

[1] See text page 2 for species list

Residual sums of squares for prediction of ln (foliage weight)

	Trees < 3.5 inches d.b.h.	Trees ≥ 3.5 inches d.b.h.	Total
Current models	44.17596	13.0346	57.21056
Brown's models	69.9460	10.08098	80.0269

The current model for trees greater than or equal to 3.5 inches (8.9 cm) d.b.h. had a larger residual sum of squares than that obtained from Brown's methods. For trees less than 3.5 inches (8.9 cm), residual sum of squares obtained by the present method are lower. Overall there appears to be no loss in predictive ability by using a single model form as presented here.

Alternative Models for Foliage Weight Prediction

The prediction models for both large and small trees use the variable ln(age), which is not available in the prognosis system (Stage 1973) in which the equations are to be used. Thus the following alternative models are presented.

For trees 3.5 inches (8.9 cm) and larger the alternative model is a transformation of the general model involving the diameter and age terms. Periodic (diameter)² increment, which is available in the prognosis model, is substituted for mean annual (diameter)² increment in the following transformation:

$$\ln(WT) = b_0 + b_1\ln(D) + b_2\ln(H) + b_3\ln(CL) + b_4\ln(A) + b_5\ln(TPA) + b_6\ln(DREL)$$

(general model in log linear form)

or,

$$WT = e^{b_0} \cdot D^{b_1} \cdot H^{b_2} \cdot (CL)^{b_3} \cdot A^{b_4} \cdot (TPA)^{b_5} \cdot (DREL)^{b_6}$$

(general model in exponential form)

Multiplying by $\dfrac{D^{2b_4}}{D^{2b_4}}$

$$WT = e^{b_0} \cdot D^{(b_1 + 2b_4)} \cdot \left(\frac{D^2}{A}\right)^{-b_4} \cdot H^{b_2} \cdot (CL)^{b_3} \cdot (TPA)^{b_5} \cdot (DREL)^{b_6}$$

which, in logarithmic form, is

$$\ln(WT) = b_0 + (b_1 + 2b_4)\cdot\ln(D) - b_4\ln\left(\frac{D^2}{A}\right) + b_2\ln(H) + b_3\ln(CL) + b_5\ln(TPA) + b_6\ln(DREL)$$

and substituting periodic $[\Delta(D^2)]$ for mean annual $[D^2/A)]$ increment,

$$\ln(WT) = b_0 + (b_1 + 2b_4)\ln(D) - b_4\ln[\Delta(D^2)] + b_2\ln(H) + b_3\ln(CL) + b_5\ln(TPA) + b_6\ln(DREL)$$

(alternative model)

Kittredge (1944) noted that it would be expected that "the amount of foliage could be estimated from the periodic annual growth because the increment of stem wood is determined by the amount of foliage which is carrying on photosynthesis in that period" (p. 906). It is important to note that the alternative model has not been reparameterized with the periodic annual increment (PAI) as an independent variable since PAI was not measured. It is merely a transformation of the original parameters and should be presented with a statement of caution about the relationship between the mean annual increment (MAI) and PAI.

The substitution of periodic (diameter)² increment for mean annual increment in the alternative equation assumes that the relationship between (diameter)² and age is linear over a wide range of ages. The assumption breaks down when PAI and MAI diverge as typically happens over time except at the culmination of MAI. Figure 1 shows the difference in predicted foliage weight between the current and alternative models that can be expected when PAI departs from MAI. When PAI is 100 percent greater than MAI, predicted foliage biomass increases 24 percent. PAI 60 percent of MAI produces a 25 percent negative change in predicted foliage biomass.

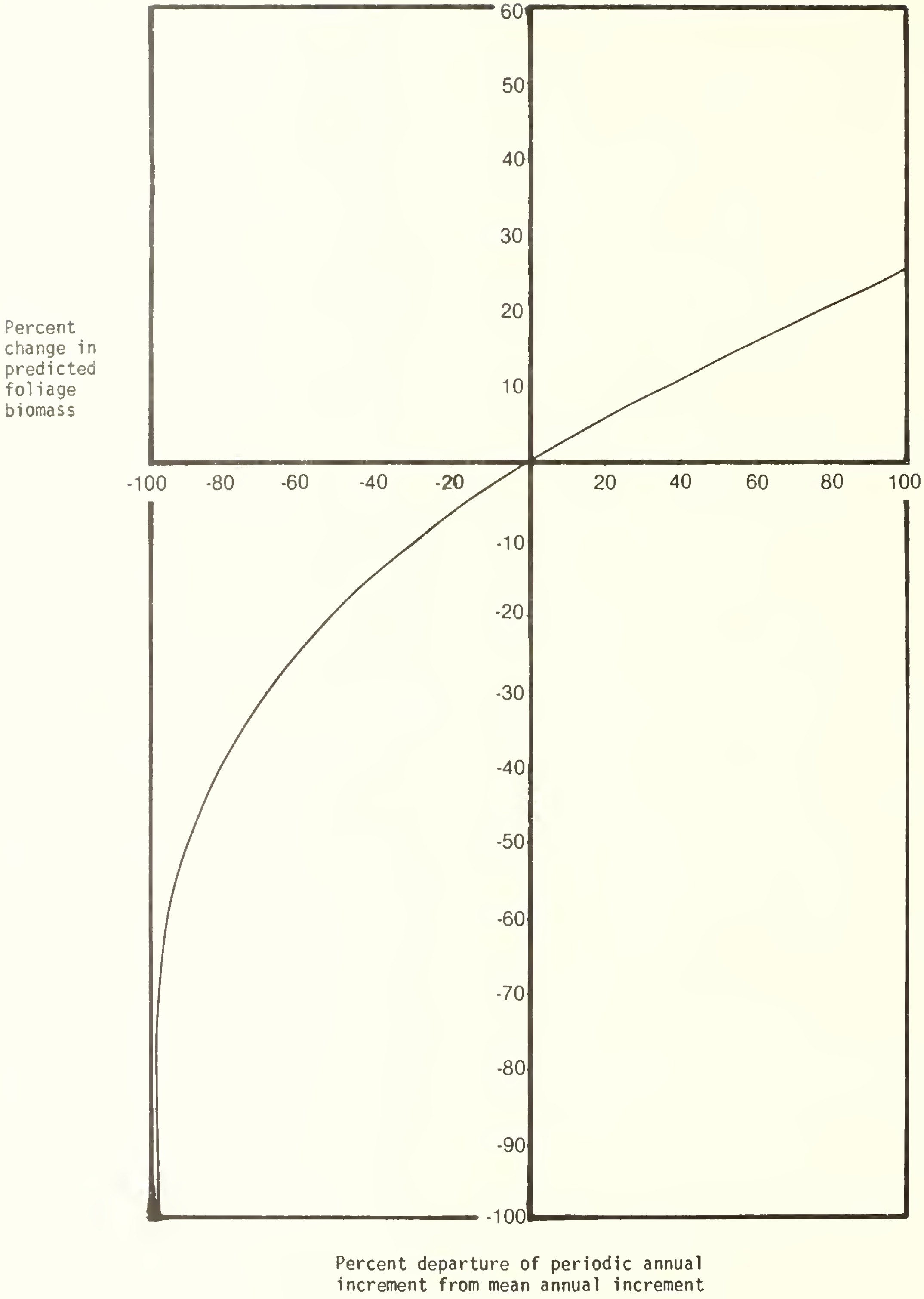

Figure 1.—Change in predicted foliage biomass as periodic annual increment departs from mean annual increment.

To compare whether the alternative model approximates the it obtained by the general model, both models were applied to an independent stand data set[4] in which both periodic and mean annual increments were measured. The tree ages in this stand anged from 2 to 560 years. For 95 trees in the test data set, the chi-square value for the sum of squared differences between needle weight prediction by the alternative model and prediction by the general model was 4.10 compared to the tabulated value of $\chi^2_{95,\ 0.005}$ = 134.24. The alternative model overpredicts needle weight outside of the range of data used to develop the general model (the sum of differences between predictions by he alternative and current models was 741.3 lb [336.2 kg] for he 95 trees). However, with the low chi-square value, the alternative model may be judged adequate, and also uses ndependent variables that are more readily available.

For trees less than 3.5 inches (8.9 cm) d.b.h., the following eparameterized alternative model substituting height for age is resented:

$$\ln(WT) = b_0 + b_1\ln(H) + b_2\ln(CL) + b_3\ln(TPA)$$

lean square error is 0.24759 for the coefficients given in table 3. This model underestimates needle weight for 9 of 11 species (table 14). On the average, it underpredicts needle weight y 3.6 lb (1.6 kg). A correction for underestimation of e[illegible] .132 may be applied giving a mean overprediction of 1.0 lb (0.5 g) after bias adjustment. Residual sum of squares obtained for his alternative equation is 46.0511, which is also lower than hat obtained from Brown's method. Thus, the alternative ormulation is judged acceptable.

Table 13.—Coefficients for estimating ln (foliage weight) of trees less than 3.5 inches d.b.h., alternative model $\ln(WT) = b_0 + b_1\ln(H) + b_2\ln(CL) + b_3\ln(TPA)$

Species[1]	Variable coefficients Intercept b_0	 ln(*CL*) b_2
BP	2 63387	1 35097
WP	1 94351	1 27023
WC	2 24876	1 37600
WL	4 73762	1 98479
WH	4 17456	2 00749
AF	1 60998	1 32649
LP	3 13488	1 62368
GF	2 43200	1 60270
ES	2 93508	1 96125
DF	2 05828	1 25837
PP	2 74410	1 58171

Variables	Variable coefficients	
ln(*H*)	b_1	40350
ln(*TPA*)	b_3	12975

Regression sum of squares d f	295 70288 23
Error sum of squares d f	46 05106 186
Mean square error	0 24759
R^2	0 8653

[1] See text page 2 for species list

Table 14.—Summary of residuals (natural scale) from alternative prediction equation for foliage weight of trees less than 3.5 inches d.b.h. The bias correction factor is 1.132

Species[1]	No. of trees	Σ (obs — pred) without bias correction	 with bias correction
BP	12	1 41	0 11
WP	17	1 85	1 74
WC	25	5 74	74
WL	15	45	2 15
WH	16	1 14	3 00
AF	5	5 83	87
LP	12	09	1 32
GF	29	3 44	5 29
ES	14	1 63	2 85
DF	28	7 39	1 46
PP	27	5 23	1 36
Weighted mean residual			
(lb tree)		3 62	1 03
(kg tree)		(1 64)	(47)

[1] See text page 2 for species list

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Relationships between tree crown width and diameter at breast height, height, crown length, and basal area per acre, and between tree foliage biomass and diameter at breast height, height, crown length, age, relative diameter, and trees per acre are presented for 11 conifer species in the Northern Rocky Mountains

KEYWORDS: crown width, foliage biomass

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Wilderness Campsite Impacts:
Effect of Amount of Use

David N. Cole

THE AUTHOR

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RESEARCH SUMMARY

Campsites that were located near subalpine lakes in the Eagle Cap Wilderness, Oreg., were studied. Research objectives were to determine what ecological changes had occurred on the sites, the extent to which amounts of change increased with increasing use, whether lakeshore sites had been more highly altered than sites set back from lakeshores at least 200 ft (61 m), and the sensitivity of selected indicators of ecological change.

Significant changes on campsites, as compared to adjacent control plots included various types of damage to mature trees; loss of seedlings; loss of undergrowth vegetation; change in the species composition of this undergrowth; an increase in bare mineral soil; decrease in duff depth; a reduction in infiltration rates; an increase in pH and the concentrations of magnesium, calcium, and sodium ions; an increase in soil organic matter; and an increase in soil bulk density. No difference in the concentrations of potassium, phosphate, nitrate, and total nitrogen or in soil texture could be established.

Of the 20 documented types of change, seven were more pronounced on more heavily used sites. Of these seven, loss of seedlings and loss of undergrowth vegetation were almost as pronounced on light-use sites as on moderate- or heavy-use sites, despite the statistical significance of the relationship. The change in species composition of the undergrowth, percent bare mineral soil, percent of trees with exposed roots, and size of the barren campsite core were significantly less on light-use sites than the moderate- or heavy-use sites which had experienced similar amounts of change. Heavy-use sites differ from moderate-use sites primarily in the depth of the duff. This implies that most of the change which is likely to occur on these campsites can result from use of the site just a few times-per-year.

Campsites set back from lakeshores had experienced as much change as lakeshore sites. This implies that lakeshore sites are not inherently more fragile. Where a lakeshore setback policy exists, other justifications for this policy should be given.

The campsite condition class rating developed by S. S. Frissell proved to be the most sensitive indicator of impact tested. Problems with this rating system, along with suggested modifications, are discussed.

CONTENTS

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Wilderness Campsite Impacts:

Effect of Amount of Use

David N. Cole

INTRODUCTION

Along with recent increases in recreational use of wilderness has come an awareness that this use has already modified pristine ecosystems intended for preservation. In many areas, the most severe impacts occur on campsites where use is highly concentrated, both spatially and temporally. Managers are understandably concerned about the highly altered conditions of many campsites, as it is their responsibility, according to the Wilderness Act of 1964, to manage wilderness areas so that "natural conditions" are preserved and "the imprint of man's work (remains) substantially unnoticeable."

It is commonly assumed that campsite impacts are the result of excessive use and that predicted future increases in use will cause increasingly severe degradation. A common response to this situation is an attempt to disperse users from areas of concentrated use to less frequently visited parts of the wilderness. Currently, 53 percent of all designated wilderness units in the Forest Service and Park Service attempt to disperse use.[1] While dispersal may decrease campsite use and visitor encounter frequencies in areas of heavy use, it can also increase the number of areas where one can expect to encounter other parties, and the number of areas which show the effects of recreational use. This reduces the proportion of the wilderness that offers opportunities for solitude and shows no substantial evidence of human impact.

In order to evaluate the appropriateness of use dispersal in various wilderness situations, or to develop any other information-based wilderness campsite management policy, we need a better understanding of the changes occurring on campsites and the extent to which differences in amounts of use affect campsite condition. A study was designed to provide information of this kind for campsites in Eagle Cap Wilderness in northeastern Oregon. Permanent sampling plots were established on campsites so that long-term changes could be evaluated. This report describes results of the first year of study, an assessment of changes which have already occurred, and how these changes are related to the amount of use the site receives.

The study also compares the amount of change which has occurred on lakeshore campsites and campsites located more than 200 ft (61 m) from a lake. There is a common assumption that lakeshores are more fragile than sites set back from lakes. Currently, 34 percent of all designated wilderness units in the Forest Service and Park Service have regulations prohibiting camping within a certain distance of lakes. This is a sizable percentage as only slightly more than half of the areas in the wilderness system contain bodies of water larger than 1 acre (McCurdy 1977). In the case of Eagle Cap Wilderness, a 200-ft (61-m) setback has been established.

The final objective was to test the sensitivity of indicators of impact that could be used to monitor overall site condition. Managers have increasingly recognized the value of monitoring systems for providing baseline information to help them evaluate their management programs and to identify areas where additional management actions need to be taken. Recently, monitoring has been mandated by Congress in the National Forest Mangement Act. In this study, we examined the ability of several individual measures to predict overall site conditions and amount of change.

PREVIOUS STUDIES

Most detailed studies of campsite impact have been conducted on developed campsites which are accessible by car and which receive much heavier use than most wilderness campsites. Backcountry campsites have been studied in northern Minnesota (Frissell and Duncan 1965, Merriam and others 1973), the mountains of the eastern United States (Rechlin 1973, Bratton and others 1978), Washington (Thornburgh 1962, Schreiner and Moorhead 1976), Idaho (Coombs 1976), and Montana (Fichtler 1980). Of these studies, only Coombs (1976) and Fichtler (1980) provide detailed data for a low-use area typical of most of the wilderness in the United States.

Most studies of backcountry campsites have documented a loss of vegetation cover and an increase in bare ground. Changes in species composition have been described in considerable detail (Thornburgh 1962,

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[1] [illegible]

Coombs 1976; Cole 1977), as have mechanical damage to mature trees (Merriam and others 1973, Rechlin 1973, Fichtler 1980) and the almost complete elimination of tree seedlings (Frissell and Duncan 1965, Coombs 1976, Cole 1977, Fichtler 1980). Other noted changes include an increase in soil compaction (Thornburgh 1962, Merriam and others 1973, Cole 1977, Fichtler 1980), a reduction in infiltration rates (Frissell and Duncan 1965), a loss of organic surface horizons (Frissell and Duncan 1965), and erosion resulting in the exposure of tree roots (Merriam and others 1973, Cole 1977, Fichtler 1980.)

In studies on developed campsites, an increase in pH also has been a consistent finding (Young and Gilmore 1976; Dawson and others 1978; Rutherford and Scott 1979). Changes in soil nutrient concentrations have been less consistent. Young and Gilmore (1976) found increases in calcium (Ca), potassium (K), phosphorus (P), sodium (Na), and nitrogen (N), and no change in magnesium (Mg) concentrations on campsites in Illinois. Working in southern Ontario, Rutherford and Scott (1979) found decreases in nitrate (NO_3), increases in chloride (Cl), and no change in phosphate (PO_4), Mg, K, and sulfate (SO_4) concentrations on campsites. Conflicting results have also been found where soil organic matter has been studied. Dotzenko and others (1967), Settergren and Cole (1970), Dawson and others (1978), and Rutherford and Scott (1979) found decreases on campsites, while Young and Gilmore (1976) and Monti and Mackintosh (1979) found increases.

In one of the few studies to relate amount of use to backcountry campsite condition, Frissell and Duncan (1965) found that more heavily used campsites in the Boundary Waters Canoe Area had less ground-cover vegetation and more tree root exposure than lightly used sites. They found no relationship, however, between amount of use and either vegetation loss (a measure based on a campsite-control comparison) or bare ground.

Fichtler (1980) compared impacts on lightly and heavily used sites in Montana. He found no statistically significant differences in amount of change in the understory, overstory, or soil compaction. The only significant difference was in the amount of bare soil exposed.

Merriam and others (1973), working in the Boundary Waters Canoe Area, found a poor relationship between amount of use and a summary measure of campsite impact. When sites were stratified by vegetation type, a more consistent relationship appeared; in each vegetation type, impact increased with use. The functional relationship was hyperbolic rather than linear, however, with the rate of increase in impact decreasing as use increased.

Similar conclusions about the nature of the relationship between use and impact are evident in the data presented by Rechlin (1973) for backcountry campsites in the Adirondacks and by Dotzenko and others (1967), LaPage (1967), Young and Gilmore (1976), Legg and Schneider (1977), Young (1978), and James and others (1979) for developed campsites. Although overall impact generally increases as use increases, changes in many variables, such as infiltration rates (James and others 1979), soil organic matter (Dotzenko and others 1967; Young and Gilmore 1976), and soil pH (Young and Gilmore 1976) are not significantly correlated with amount of use. For those variables in which amount of impact does increase wit use, near-maximum levels of impact are usually achieve even with light use, and further increases in use do littl to aggravate the severity of these impacts (fig. 1).

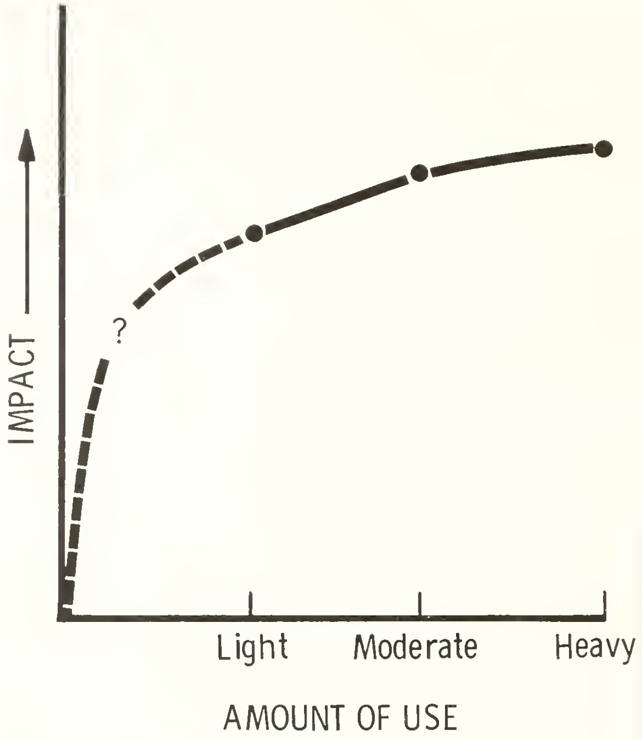

Figure 1.--Typical research results for the relationship between campsite impact variables and amount of use. The response of variables as use increases from no use to light use is poorly understood.

In support of this conclusion, some of the mo pronounced differences between sites which receiv different amounts of use were found in the lightly use Idaho Primitive Area (Coombs 1976). In comparison t light-use sites, heavy-use sites had considerably les vegetation cover and considerably more erosion pavemen

This study in Eagle Cap Wilderness differentiate between impact on lightly, moderately, and heavily use sites which would all have been considered lightly use sites in all of the studies other than those of Coomb (1976) and Fichtler (1980). This focuses attention that part of the use spectrum which is most poorly unde stood (where use differences have the most pronounce influence on amount of impact) and which is mo applicable to the wilderness situation.

STUDY AREA

The Eagle Cap Wilderness was selected for stu because it contained numerous examples of campsit which receive light, moderate, and heavy use, in locatio where at least ordinal estimates of use could be obtaine

Furthermore, in terms of both use and environment, the area seemed to be representative of many heavily glaciated, mountainous wilderness areas in the National Forest System.

The Eagle Cap Wilderness encompasses 293 735 acres (118 870 ha) of the Wallowa Mountains in northeastern Oregon (fig 2). Jagged ridges tower more than 3,280 ft (1 000 m) above deep glacial valleys which radiate from the granitic central core of the range. Several peaks approach 10,000 ft (3 000 m) in elevation, while the lowest elevations in the area are under 3,600 ft (1 100 m).

Over 13,000 visitors entered the Wilderness in 1978 and accounted for about 83,000 visitor-days of use. The distribution of use was highly concentrated, with most visitors attracted to the more than 50 lakes scattered through the subalpine zone (fig 3). One area of about 2,500 acres (1 000 ha), the Lake Basin, contains 10 major lakes and was visited by [illegible] of [illegible] visitors to the Wilderness in 1978. Other lakes are more isolated and reached by less frequently traveled trails. A few lakes are still trailless. Twenty-two of the 26 campsites selected for study were located at subalpine lakes where it was possible to obtain an ordinal estimate of amount of use. The forest overstory at all sites was dominated by *Abies lasiocarpa* (subalpine fir) in conjunction with *Picea engelmannii* (Engelmann spruce), *Pinus contorta* (lodgepole pine), and *Pinus albicaulis* (whitebark pine); the understory was usually dominated by *Vaccinium scoparium* (grouse whortleberry). By confining the sample to campsites near lakes located between 7,050 and 7,800 ft (2 150 and 2 400 m) in an *Abies lasiocarpa*/*Vaccinium scoparium* forest type on soils derived from granitic bedrock, environmental differences were kept to a minimum. Controlling environment in this manner permits the effects of differences in amount of use to be more precisely delineated. Four additional campsites, two in sedge meadows above 7,800 ft (2 400 m) in elevation and two in forests below 6,500 ft (1 981 m) in elevation, were studied for comparative purposes.

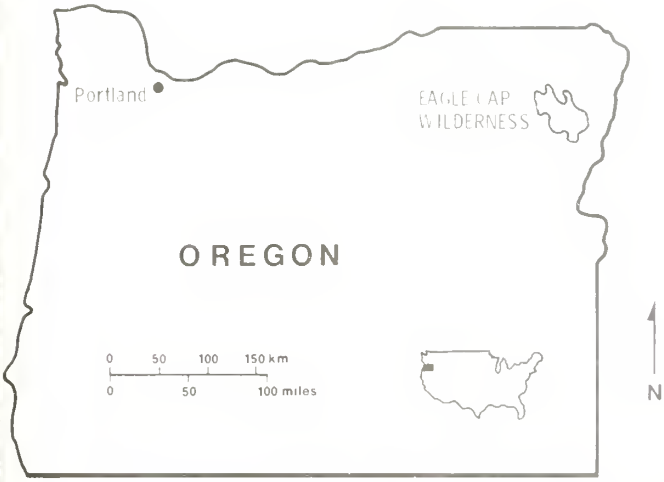

Figure 2.--The Eagle Cap Wilderness is in northeastern Oregon.

Figure 3.--Subalpine lakes are the primary destination of most visitors to the Eagle Cap Wilderness.

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[2] [illegible]

The amount of use each site receives had to be estimated because no campsite-specific use data existed. This was accomplished by assigning each lake to either a heavy-, moderate-, or light-use category on the bases of observations and travel zone use data. The most prominent[3] forested site at each lake, usually located close to where the main trail first reaches the lake, was chosen as the site most representative of the amount of use the lake receives. The study sites consisted of six light-use sites, six moderate-use sites, and 10 heavy-use sites, five within 200 ft (61 m) of a lake and five more than 200 ft (61 m) from a lake (fig. 4-7). Sites within 200 ft (61 m) of a lake have traditionally been the most popular and are st frequently used, despite their having been officially close to camping for the last few years.

Although all analyses treated these use differences a merely ordinal estimates, an estimate of actual amou of use is valuable for comparative purposes. Observatio suggest that most of the light-use sites are used les than five nights per year, with some of them receiving n use during some years. Most moderate-use sites probab are used 10 to 20 nights per year, while most heavy-us sites are used 25 to 50 nights per year.

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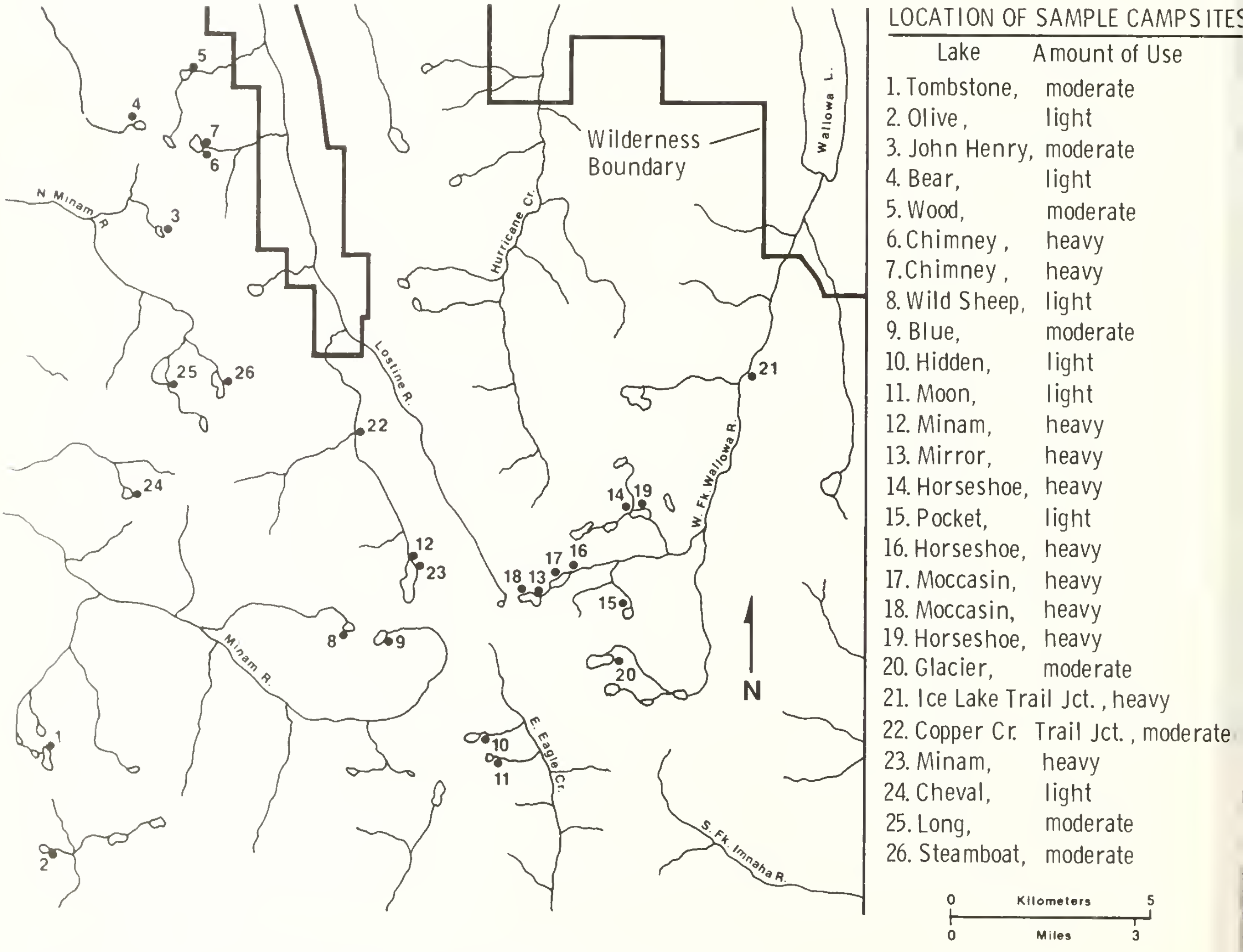
[3] Prominence was defined primarily in terms of location. We chose the site we subjectively determined to be the site most arriving parties would choose. We avoided automatically choosing the most heavily impacted site on the lake to avoid the common circular argument in which heavily impacted sites are subjectively assigned to the heavy-use category and then heavy-use sites are found to be heavily impacted.



LOCATION OF SAMPLE CAMPSITES

Lake	Amount of Use
1. Tombstone,	moderate
2. Olive,	light
3. John Henry,	moderate
4. Bear,	light
5. Wood,	moderate
6. Chimney,	heavy
7. Chimney,	heavy
8. Wild Sheep,	light
9. Blue,	moderate
10. Hidden,	light
11. Moon,	light
12. Minam,	heavy
13. Mirror,	heavy
14. Horseshoe,	heavy
15. Pocket,	light
16. Horseshoe,	heavy
17. Moccasin,	heavy
18. Moccasin,	heavy
19. Horseshoe,	heavy
20. Glacier,	moderate
21. Ice Lake Trail Jct.,	heavy
22. Copper Cr. Trail Jct.,	moderate
23. Minam,	heavy
24. Cheval,	light
25. Long,	moderate
26. Steamboat,	moderate

Figure 4 --Location of sample campsites and their level of use.

Figure 5.--Light-use site number 8, located at Wild Sheep Lake

Figure 6.--Moderate-use site number 1, located at Tombstone Lake

Figure 7.--Heavy-use site number 7, located at Chimney Lake

FIELD METHODS

To a great extent, study methods were determined by the need to establish permanent sampling points. This reflected the primary goal of the study--to measure change in campsite conditions on permanently located sites over a 5-year period. The results presented here, relating current conditions to amount of use, were an additional product of the study.

Each sample site consisted of both a campsite and a similar undisturbed site in the vicinity which could serve as a control. In each campsite, 16 linear transects were established, radiating from a central point in 16 cardinal directions. The distances to the edges of the campsite and the first significant amount of vegetation were recorded for each transect (fig. 8). The amount of vegetation was considered significant when cover exceeded 15 percent in a 1.09- by 3.28-ft (0.67-by 1.00-m) quadrat, oriented perpendicular to and bisected by the tape.

Within the camp area (the polygon enclosed by straight lines connecting transect end points), all trees greater than 55 inches (140 cm) tall were recorded. If damaged by recreational use, the type of damage was recorded. Seedlings between 6 and 55 inches (15 and 140 cm) tall were counted within the camp polygons, exclusive of any "islands" of undisturbed vegetation (fig. 8).

Four additional transects were established, originating at each center point. The first transect was randomly oriented, with each subsequent transect oriente perpendicular to the preceding one. Approximatel 15 quadrats, 3.28 by 3.28 ft (1 by 1 m) were located alon these transects (fig. 9). The exact location of thes quadrats was taken from a table prepared prior to fiel work, and was designed to maximize the probability tha all distances from the central point would be sampled wit equal intensity (that is, the distance between successiv quadrats on a transect decreased with distance from th central point). This assured that (1) the entire disturbanc gradient, from central point to the undisturbed periphery would be equitably sampled; and (2) there was a chanc that all parts of the campsite, except the central poin would be sampled.

In each quadrat, the coverage of each of the followin variables was estimated: rock, firepit, tree trunk and roo exposed mineral soil, organic litter, and vegetation. Th cover of each vascular plant species and that of mosses a a group were also estimated. Coverages were estimate to the nearest percent if under 10 percent and in 10 percen coverage classes where cover exceeded 10 percent. I the latter case, the midpoints of each class were used t estimate mean cover on the campsite.

Soil information was collected at four places on eac campsite between 3.28 and 6.56 ft (1 and 2 m) from th central point (fig. 10). In contrast to the ground-cove information, this concentrates the sampling in the mos highly disturbed parts of the campsite.

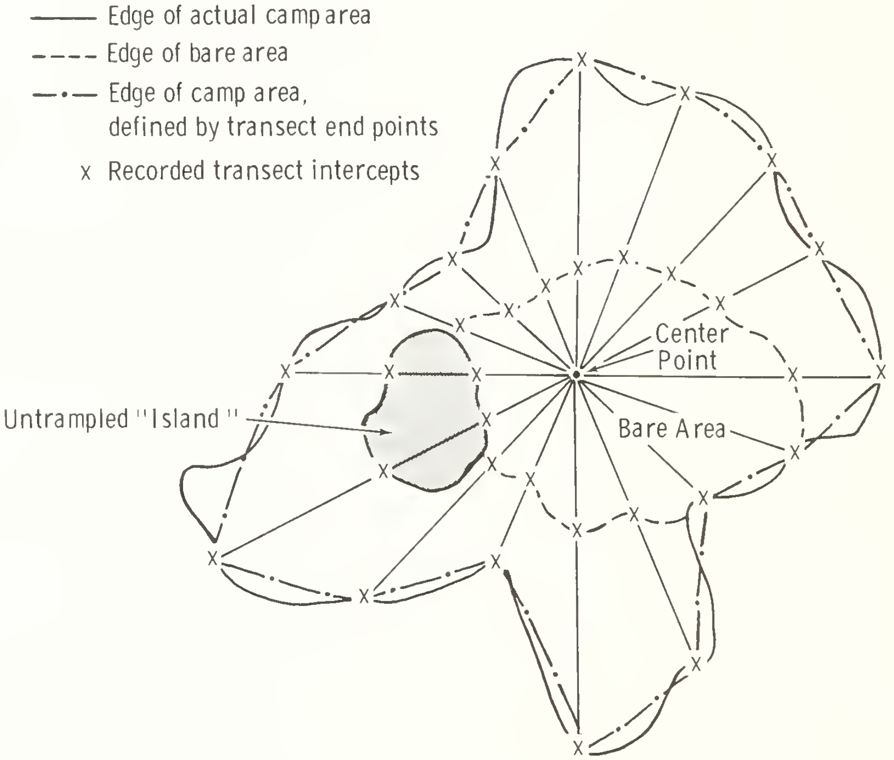


Figure 8.--Hypothetical example of transect layout for determining camp area and radius and bare area and radius. Seedlings were recorded on the camp area defined by transect end points, exclusive of the untrampled "island;" mature trees were recorded on the entire camp area.

Figure 9.--Coverages of rock, firepit, tree trunk and root, exposed mineral soil, organic litter, and vegetation were estimated in approximately 15 quadrats on each campsite

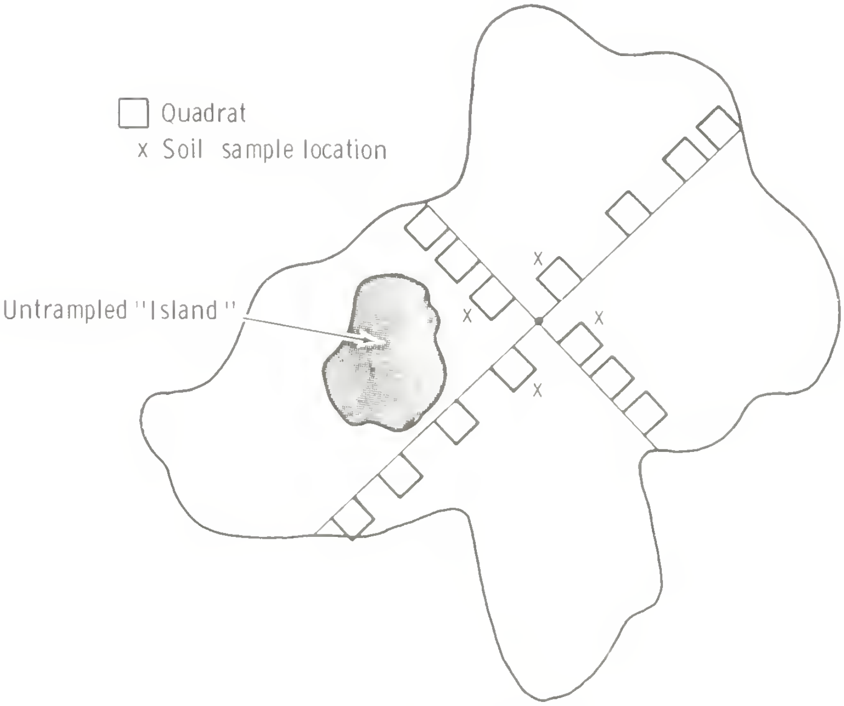


Figure 10.--Quadrat layout and location of soil samples on hypothetical campsite

At each of the four locations, duff depth, bulk density, pH, and infiltration rates were measured and soil samples collected. Duff depth was a measure of the depth of the organic litter and fermentation (0) horizons. The colorimetric method was used to determine pH in the field. Infiltration rates were measured with a double-ring infiltrometer. The rate at which the first 0.39 inch (1 cm) entered the soil was called the instantaneous infiltration rate, while the rate for the first 2 inches (5 cm) was called the saturated rate. Sample points were not presoaked. Volumes for bulk density calculations were determined by measuring the amount of water required to fill a hand-excavated, cellophane-lined hole, 2 inches (5 cm) deep by about 3.5 inches (9 cm) in diameter. The excavated soil was removed in plastic bags for weight determination (fig. 11). Use of the hand-excavation method made precise volume measurements difficult, but this method was judged to be more accurate than the use of soil corers in these rocky soils. As with pH, bulk density measurements were taken in the uppermost portion of the mineral soil after the organic horizons had been removed.

Finally, each campsite was assigned a condition class rating, a visual estimate of campsite condition developed by Frissell (1978).

Figure 11.--Infiltration rates were measured with a double-ring infiltrometer. Soil samples were collected and the volume of the excavated hole was determined for use in calculating bulk density.

Control plots were located in the vicinity in order to get some measure of undisturbed conditions. The size of controls varied between 980 and 2,164 ft^2 (91 and 201 m^2). Percent coverage was estimated for rock, tree trunk and root, exposed mineral soil, organic litter, vegetation, and plant species for the entire control plot. Seedlings were counted on a 538-ft^2 (50-m^2) circular subplot. Four sets of soil measurements and samples, identical to those taken on campsites, were taken on control plots.

DATA ANALYSIS

Distances to the edges of the campsite and the edges of the bare area were averaged to obtain mean radius of camp and bare area measures. They were also plotted on scaled maps, and a polar planimeter was used to determine the camp and bare area. "Islands" of undisturbed vegetation intercepted by more than one transect were subtracted from the total area.

A single mean value was calculated for duff depth, bulk density, pH, instantaneous infiltration rate, and saturated infiltration rate for each campsite and each control. Infiltration rates were expressed in centimeters-per-minute for both the 1-cm and 5-cm applications. The pH values were converted to H^+ concentrations, averaged, and reconverted to pH values.

Soil samples were analyzed at the Montana Forest and Conservation Experiment Station, Missoula, Mont. Each sample was ovendried and weighed to determine bulk density. Nitrate content was determined before drying, using the Specific Ion Analyzer. The four soil samples from each campsite were then passed through a 2-mm screen and composited. Calcium, potassium, magnesium, and sodium concentrations were determined by extraction in 1N ammonium acetate and analysis with the Atomic Absorption Spectrophotometer. Phosphate was extracted with dilute acid fluoride and its concentration determined by molybdenum blue stannous chloride color reaction; total nitrogen was determined by using the modified micro-Kjeldahl procedure (Hesse 1972). Texture was analyzed by buoyucous hydrometer method and organic matter content was determined by combustion at 525° C.

For statistical analysis, standard parametric tests could not be used because the assumption of a normally distributed population could not be made and the sample size was small. Therefore, nonparametric tests were used and the tabular data presented include medians (probably the best measure of central tendency), as well as means and their 95 percent confidence interval.

The significance of differences between campsites and controls was examined with the Wilcoxon matched-pairs, signed-ranks test (Siegel 1956). Those variables that differed were examined further in order to see if the differences were correlated with difference in amount of use.

The relationship between campsite impact and amount of use can be examined in several ways. Most studies have compared existing conditions on campsites that receive different amounts of use. This approach has the serious drawback of assuming that all sites were originally identical and, therefore, that differences in the existing conditions on lightly and heavily used campsites reflect differences in the amount of change which has occurred rather than differences in original conditions.

This drawback can be alleviated to some extent by establishing campsite control pairs and comparing the differences between campsites and controls, an estimate of amount of change on sites which receive different amounts of use. The problem with this approach, which has only been tried by Frissell and Duncan (1965) and Fichtler (1980), is that results will be misleading if control sites are not truly similar to original campsite conditions. Both approaches have opposing strengths and weaknesses. One uses no information about original conditions (control samples), while the other uses so much information that results may be distorted by too much faith in control samples. Both approaches have been taken in this study in order to profit from the unique perspective each provides.

In this second type of analysis, both absolute and relative measures of change are presented. Absolute change is simply the difference between the measure on the control site and the measure on the campsite. For example, if vegetation cover was 10 percent on the control-site and 1 percent on the campsite, the absolute change would be 9 percent. Because absolute change is highly dependent on original conditions (in the example above, 10 percent is the maximum change possible), relative values were also calculated. Relative change is the absolute change expressed as a percentage of the measure on the control site. In the example above, relative change measures show that 90 percent of the vegetation has been lost. Again, both of these change measures are provided to give as complete an interpretation of the data as possible. Negative change values, in both cases, indicate higher values on the campsite.

Change in species composition was measured with the following coefficient of floristic dissimilarity:

$$FD = 0.5\Sigma|p_1 - p_2|$$

where p_1 is the relative cover of a given species on the control plot, and p_2 is the relative cover of the same species on the campsite (Cole 1978). Additional methods of species composition analysis are discussed in the results section.

Finally, a summary impact rating was calculated for each campsite in a manner similar to that employed by Merriam and others (1973). Impact indicators included camp area, relative vegetation loss, absolute increase in bare ground, floristic dissimilarity, relative seedling loss, percent of trees with trunk scars, relative decrease in duff depth, and relative decrease in instantaneous infiltration rate (table 1). For each of these indicators the range in amount of change was divided into three classes with approximately the same number of campsites in each class. Each campsite was assigned to one of these classes and given an impact value of 1 to 3 (low to high amount of change) for each indicator. The mean of all impact values that apply to each campsite[4] determines the index of impact or impact rating.

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[4] [illegible]

Table 1.--Values used to calculate the impact rating for each campsite[1]

Impact value	Camp area	Relative vegetation loss	Absolute increase in bare ground	Floristic dissimilarity	Relative seeding loss	Trees with trunk scars	Relative decrease in duff depth	Relative d crease in i stantaneou infiltration r
		Indicators of impact						
	m²	Percent						
1	<100	< 75	< 10	< 50	< 76	< 15	< 45	< 20
2	100-220	75-95	10-40	50-65	76-95	15-45	45-75	20-70
3	>220	> 95	> 40	> 65	> 95	> 45	> 75	> 70

[1] The impact rating is the mean impact value for all impact indicators used.

All correlations used Kendall's tau as a statistic (Siegel 1956). Kolmogorov-Smirnov tests (Siegel 1956) were used to compare the amount of change which had occurred on heavily used sites located within 200 feet (61 m) of lakeshores to that on heavily used sites more than 200 feet (61 m) from lakeshores.

RESULTS AND DISCUSSION

How Much Change Has Occurred on the Campsites?

Campsite area varied between 387 and 6,060 ft² (36 and 563 m²), with the median site being 2,077 ft² (193 m²) (table 2). The largely barren central core comprised about 45 percent of a "typical" campsite, although this percentage varied between 15 and almost 100 percent.

Essentially all of the trees growing on those sites had been "damaged" by recreationists (fig. 12). Damage to many of these trees was relatively minor--lower branches had been broken or nails had been driven into the trunks. Twenty-seven percent of these trees, however, bore trunk scars from chopping. Of these scars, 22 percent were larger than 1 ft² (0.99 m²) and 67 percent were located below breast height, conditions under which the probability of decay in spruce and true fir is particularly high (Wright and Isaac 1956).

Another 33 percent of the trees on the campsites had been cut down. Observations in the field suggested that, as a damage estimate, this value should have been even higher because more felled trees were found just beyond the campsite periphery than on the campsite itself. Most these felled trees were less than 2 inches (5 cm) in diamet at breast height, so the loss of saplings available eventually replace the overstory trees is also mc dramatic than these figures suggest.

This frequency of mechanical damage to trees is high than that reported elsewhere. McCool and others (196 report that 60 to 65 percent of the sites they studied the Boundary Waters Canoe Area had damaged trees; the Eagle Cap essentially all sites with trees had damag In two Montana backcountry areas, only 68 percent of t trees on all campsites had been damaged (Ficht 1980).

Despite this damage to the overstory, there was lit evidence of recreation-related tree mortality or even lo of vigor except where trees had been felled outright. T fact that more than six decades of recreational use ha had little noticeable effect suggests that premat mortality may never by a serious problem. Other stud have also noted a lack of tree mortality despite extens mechanical damage (for example, James and others 19 except where the tree species is particularly suscepti to decay (Hinds 1976) or where severe edaphic limitati occur (Settergren and Cole 1970). This has led to conclusion that mature trees are the growth form le sensitive to recreational impact (Leeson 1979). It possible, however, that premature windthrow may be recognized as recreation-caused or that disease eventually become a problem.

Table 2.--General characteristics of the campsites

Statistic	Camp area (N = 22)	Bare area (N = 22)	Mutilated trees (N = 19)	Trees with exposed roots (N = 19)	Felled trees (N = 19)	Scarred trees (N = 19)	Floristic dissimilarity[1] (N = 22)	Condit class[2] (N = 2
	m²		Percent					
Median	193	87	96	32	28	25	59	4.0
Mean[3]	197 ± 57	97 ± 27	91 ± 5	34 ± 12	33 ± 11	27 ± 9	55 ± 8	3.7 ± 1

[1] A measure of the percent change in species composition on the campsite.

[2] A visual estimate of impact proposed by Frissell (1978) which varies between 1 (low impact) and 5 (high impact).

[3] Includes a 95 percent confidence interval.

Figure 12.--Over 90 percent of the mature trees on the sample campsites had been scarred, felled, or had limbs cut.

Of the 19 campsites with trees on the site, 17 had trees with exposed roots. On a typical campsite, approximately 30 percent of the trees had exposed roots. Frissell and Duncan (1965) found trees with exposed roots on 60 percent of the campsites they examined, while James and others (1979) found 7 to 14 exposed roots per sample tree on their campsites.

Seedling densities on control sites were almost 10 times higher than on campsites (table 3). This amounts to a 92 percent loss of seedlings on the median campsite, with no campsite having more than 50 percent of the seedlings found on undisturbed sites. The few seedlings that do survive on campsites (four seedlings per site was the median) inevitably occur in protected areas behind

Table 3.--Ground coverages and seedling densities for campsites and controls and estimates of amount of change[1]

Statistic	Seedlings (N = 22)	Vegetation (N = 22)	Bare ground (N = 22)	Litter (N = 22)	Stone (N = 22)	Tree trunk and root (N = 22)
	Stems/ha	*Percent*				
Campsite						
Median	329	6	31	59	2.4	
Mean[2]	507 ± 236	8 ± 4	33 ± 10	51 ± 10	4.6 ± 2.4	1.5 ± 0.6
Control						
Median	2,647	61	1	27	5.0	
Mean	5,020 ± 2,362	55 ± 10	6 ± 5	28 ± 7	10.7 ± 5.4	0.8 ± 0.4
Median absolute change	2,266	47	-25	-30	3.0	-0.6
Median relative change (percent)	92	87	-1,598	-116	58	10
Significance level	[3]<0.001	[3]<0.001	[3]<0.001	0.002	0.005	

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[1] Absolute change is the control value minus the campsite value, relative change is the absolute change divided by the control value. Positive values indicate that campsite values are lower than control values, negative values indicate higher campsite values than control. Significance was tested with the Wilcoxon matched-pairs, signed-ranks test. Differences were considered significant if the level of significance was less than 0.05. Not significant differences are left blank.

[2] Includes a 95 percent confidence interval.

[3] One-tailed tests were used because the direction of change was predicted prior to testing.

boulders or in dense clumps of saplings. There was no evidence that any of the tree species were particularly resistant to trampling. This near-elimination of seedlings has been reported wherever campsite seedling densities have been studied (Frissell and Duncan 1965; Magill and Nord 1963; Brown and others 1977; Fichtler 1980). Along with the loss of saplings to felling, this forecasts a future lack of trees to replace the overstory trees when they eventually die. Continued recruitment of trees will probably be one of the major challenges to long-term site maintenance.

Ground-cover changes have also been dramatic. As vegetation cover has disappeared, increasing amounts of bare mineral soil and organic litter have been exposed. A small, but statistically significant, decrease in stone cover is also evident. This may result from removal of rocks on campsites to make fire rings or to smooth sleeping areas, but probably also reflects a tendency for campsites to be located on exceptionally stone-free sites.

In comparison to controls, the median campsite had one-tenth the vegetative cover, 30 times as much bare ground, and twice the exposed litter cover. Eighty-seven percent of the original vegetation had been lost, leaving only 6 percent scattered about the site. These results are comparable to those of Frissell and Duncan (1965) in the Boundary Waters Canoe Area, and to Coombs' (1976) measures on heavy-use sites in the Idaho Primitive Area. Cover loss was much less extreme on developed sites in Rhode Island (Brown and others 1977) and Pennsylvania (LaPage 1967), where trampling-resistant species, usually exotic grasses, maintain some vegetative cover.

The median floristic dissimilarity between campsites and controls, 59 percent, indicates that a pronounced shift in species composition of the undergrowth has occurred. Inherent variability in species composition between undisturbed stands of this vegetation type accounts for about 25 percent of this dissimilarity (Cole 1978). Differences in excess of 25 percent can be attributed to changes resulting from recreational use. Previous estimates of floristic dissimilarity on similar campsites in the Eagle Cap Wilderness were about 80 percent (Cole 1981a), but these campsite measurements were concentrated close to the heavily used central core of the site. Apparently, and not unexpectedly, the change in species composition on each campsite decreases from campsite center to campsite periphery.

Every species experiences a decrease in cover on the campsites, with the exception of three introduced species--*Poa annua* (annual bluegrass), *Sagina saginoides* (alpine pearlwort), and *Spergularia rubra* (red sand-spurry), and six natives that are only found in small quantities on one or two of the campsites.[5] Therefore, there is no widespread "invasion" of species that increase in abundance in response to recreational use. This contrasts with lower elevation campsites where weedy invaders such as *Taraxacum officinale* (common dandelion) and *Poa pratensis* (Kentucky bluegrass) are usually the most abundant species on campsites (Cole 1977).

Some species increase in relative importance on campsites, however. Table 4 provides two indexes of change in importance for the most common vascular plant species in the area. The major species that increase in importance on campsites are *Carex microptera* (small-winged sedge), *Carex rossii* (Ross sedge), *Juncus parryi* (Parry's rush) *Muhlenbergia filiformis* (pullup muhly), and *Sibbaldia procumbens* (creeping sibbaldia), four graminoids, and a rhizomatous, mat-forming forb with creeping stems. A number of other studies have also found that *Carex* sp. *Juncus parryi,* and *Sibbaldia procumbens* are resistant to trampling (for example, Landals and Scotter 1973; Holmes and Dobson 1976).

The major species that decrease in importance on campsites are *Antennaria alpina* (alpine pussytoes, *Festuca viridula* (green fescue), *Hieracium gracile* (slender hawkweed), *Phyllodoce empetriformis* (red mountain-heath), *Potentilla flabellifolia* (fan-leaf cinquefoil), *Vaccinium scoparium,* and *Veronica cusickii* (Cusick's speedwell). The sensitivity of the brittle shrubs *Phyllodoce* and *Vaccinium* has been a consistent finding (for example, Dale and Weaver 1974; Hartley 1976), but results for the other species have been inconsistent. For example, *Hieracium gracille* has been judged to be resistant by Coombs (1976) and sensitive by Schreiner (1974), Hartley (1976), and this stud Apparently, the response of many species varies with such factors as season, type of impact, associated plants, and perhaps, phenotypic variability within the species.

The three most prominent understory species on controls--*Vaccinium scoparium, Phyllodoce empetriformis,* and *Juncus parryi*--undergo pronounced shifts in importance on campsites (table 5). The median combined, relative cover of *Vaccinium* and *Phyllodoce* drops from 39 percent on controls to 6 percent on campsites, while the median, combined, relative cover of *Juncus* and *Carex rossii* increases from 8 percent on controls to 28 percent on campsites. All differences are statistically significant.

When the response of major growth forms to camping is compared, graminoids increase in importance, wh shrubs and bryophytes decrease, and forbs are essentially unaffected (table 5). Shrubs make up 41 percent of the cover on controls, but only 9 percent on the median campsite. Median graminoid values increase from 2 percent on controls to 56 percent on campsites. Similar responses have been noted in other subalpine campsite impact studies (Cole 1979; Leeson 1979; Weaver and others 1979).

As vegetation cover is removed, litter cover values increase. This increase, apparent in table 3, is not a r increase in litter; more litter is exposed because the overlying vegetation cover has been removed. Failure to recognize this has caused confusion about litter response to camping in some studies (for example, Coombs 1973 Increased litter cover values on campsites indicate t vegetation cover is removed more rapidly, exposing underlying litter, than litter is removed, exposing b ground. Nevertheless, litter is being removed, as increases in bare ground indicate. Table 3 shows that the median campsite, litter cover increases about percent as a result of vegetation destruction, but ab 25 to 30 percent of the litter cover is eroded, expos bare ground.

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[5] Appendix 1 contains frequency and cover data for all spe encountered on campsites or controls.

Table 4.--Relative importance of the most common vascular plant species[1] on campsites and controls

Species	A[2]	B[2]
Antennaria alpina	0.3	0.9
Antennaria lanata	2.4	7
Carex microptera	1.5	1.5
Carex rossii	9.0	4.5
Erigeron peregrinus	.6	1.9
Festuca viridula	2	9
Hieracium gracile	.1	4
Juncus parryi	3.2	1.7
Luzula hitchcockii	.8	1.6
Muhlenbergia filiformis	1.5	3.6
Phyllodoce empetriformis	.5	.4
Potentilla flabellifolia	.5	5
Sibbaldia procumbens	1.3	3.5
Vaccinium scoparium	.2	.5
Veronica cusickii	.6	.7

[1] All species with a mean cover greater than 1 percent or which occur on more than one-third of the control sites.

[2] Column A is the ratio between the number of cases in which relative cover is higher on campsites than controls, and the number of cases in which the reverse is true. Column B is the ratio between mean relative cover on campsites and mean relative cover on controls. A number greater than 1 indicates that the species increases in relative importance on campsites.

Table 5.--Relative cover of growth forms and selected species on campsites and controls

Growth forms and selected species	Control sites (N = 21)		Campsites (N = 21)		Significance level[1]
	Median	Mean	Median	Mean	
Graminoids	28	27 ± 7	56	55 ± 7	0.002
Shrubs	41	42 ± 10	9	19 ± 8	002
Forbs	18	19 ± 5	21	21 ± 8	
Bryophytes	10	12 ± 4	1	5 ± 3	005
Carex rossii	2	2 ± 1	8	14 ± 7	001
Juncus parryi	6	12 ± 5	20	22 ± 7	005
Vaccinium scoparium	30	28 ± 9	5	13 ± 7	005
Phyllodoce empetriformis	9	11 ± 4	1	5 ± 3	004

[1] Significance was tested with the Wilcoxon matched-pairs, signed-ranks test. Differences were considered significant if the significance level was less than 0.05. Nonsignificant differences are left blank.

This increase in bare ground is much more severe than that reported by Young (1978) on developed sites in Illinois, or by Frissell and Duncan (1965) and Fichtler (1980) on backcountry sites in Minnesota and Montana, respectively. It is comparable to the results of Brown and others (1977) for developed sites in Rhode Island and of Coombs (1976) for bare soil and erosion pavement on heavy-use, backcountry sites in Idaho.

The loss of organic litter is more evident in the decrease in duff depth presented in table 6. The depth of the soil organic horizons on campsites was less than one-half what it was on controls. On the other hand, the organic matter content of the upper A horizon was about 20 percent higher on campsites than on controls, suggesting that, although some of the surface organic litter pulverized by recreational use is probably removed by erosion, some of it moves down into the uppermost mineral horizons where it accumulates. Monti and Mackintosh (1979) present photomicrographs which clearly show bands of "humus" particles which have accumulated in the upper 2.54 to 7.62 inches (1 to 3 cm) of mineral soil on campsites in Ontario. About 55 percent of the O horizon was lost on these campsites, a figure close to the 51 percent lost on Eagle Cap campsites, despite much heavier use in Ontario. Similar measures of reduction in duff depth--60 to 65 percent--have been reported on campsites in the Boundary Waters Canoe Area (Frissell and Duncan 1965; McCool and others 1969).

Measures of the magnitude and even direction of change in soil organic matter content have been less consistent. We found a 20 percent increase on campsites. Monti and Mackintosh (1979) and Legg and Schneider (1977), working in northern forest types in Ontario and Michigan, respectively, also report accumulations of organic matter in the surface mineral horizons on campsites, but they did not compare this to conditions on control sites. Young and Gilmore (1976) found a 28 percent increase in soil organic matter on forested campsites in Illinois. Studies in Colorado, Iowa, and Ontario, however, have found decreases in soil organic matter on campsites (Dotzenko and others 1967; Dawson and others 1978; Rutherford and Scott 1979). At this time, there is no apparent explanation for this difference in results, as the direction of change is not correlated with vegetation type, soil type, climatic regimen, campsite age, amount of use, or measurement technique.

Bulk density increased on campsites, but this increase was not as great as expected (15 percent). Bulk densities were unusually low, both on campsites and controls reflecting the high organic matter content of the soil and the influence of volcanic ash. These characteristics make the soil less compactible and prevent the more sizable increases of 72 percent, 46 percent, 34 percent, 30 percent 23 percent, and 21 percent reported on campsites in Rhode Island (Brown and others 1977), Colorado (Dotzenko and others 1967), Ontario (Monti and Mackintosh 1979), Iowa (Dawson and others 1978), Missouri (Settergren and Cole 1970), and Michigan (Legg and Schneider 1977), respectively.

Although the effects of changes in bulk density on vegetative growth are highly variable, most studies have shown no harmful effects until bulk densities exceed 1. g/cm³ or more (Barton and others 1966; Minore and others 1969). In fact, in some sandy soils, low levels of compaction improve the growth of certain species by increasing the water-holding capacity of the soil (Blom 1976). This suggests that, particularly on the Eagle Cap campsites where bulk densities are universally low, increases in bulk density may not be a significant impact. Other manifestations of compaction, such as decreased infiltration rates or loss of microsites suitable for seed germination (Harper and others 1965), may be more significant.

Table 6.--Soil conditions on campsites and controls and estimates of amount of change[1]

Statistic	Duff depth (N = 22)	pH (N = 20)	Instantaneous infiltration rate (N = 20)	Saturated infiltration rate (N = 22)	NO_3 (N = 20)	K (N = 20)	Mg (N = 20)	Ca (N = 20)	Na (N = 20)	PO_4 (N = 20)	Total N (N = 20)	Organic matter (N = 20)	B de (N
	cm		*cm/min*		*Parts per million*							*Percent*	*g/*
Campsite													
Median	0.25	5.48	0.33	0.16	7.6	195	61	528	53	14	3,193	18	0
Mean[2]	0.32 ± 0.18	5.44 ± 0.16	0.38 ± 0.10	0.16 ± 0.04	7.9 ± 2.5	211 ± 39	80 ± 33	666 ± 222	55 ± 5	20 ± 9	3,493 ± 780	19 ± 4	0.96 ±
Control													
Median	0.53	5.13	0.59	0.25	3.6	167	39	287	45	11	2,342	15	(
Mean	0.74 ± 0.30	5.13 ± 0.09	0.66 ± 0.17	0.26 ± 0.05	7.4 ± 2.9	183 ± 37	42 ± 8	362 ± 89	47 ± 3	21 ± 9	2,868 ± 626	15 ± 2	0.8 ±
Median Absolute Change	0.30	-0.50	0.19	0.09	-4.1	-40	-23	-300	-6	0.8	-165	-2	-(
Median Relative change (percent)	51	-9	29	33	-68	-28	-107	-101	-13	2	-5	-20	-1
Significance	[3]<.001	.003	[3].003	[3]<.001			.001	.002	.014			.027	[illegible]

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[1] Absolute change is the control value minus the campsite value, relative change is the absolute change divided by the control value. Positive values indicate that campsite va are lower than control values; negative values indicate higher campsite values than controls. Significance was tested with the Wilcoxon matched-pairs, signed-ranks test. Differences w considered significant if the level of significance was less than 0.05. Nonsignificant differences are left blank.

[2] Includes a 95 percent confidence interval.

[3] One-tailed test

The decreases in infiltration rates on Eagle Cap campsites, while statistically significant, are also much less pronounced than decreases found elsewhere. The rate at which the first 0.39 inch (1 cm) of water percolates into the soil is 28 percent slower on campsites than on controls; the decrease on campsites when 2 inches (5 cm) of water were applied was about the same--33 percent. In contrast, other studies have found infiltration rates on controls to be 20 to 60 times higher than on campsites (Brown and others 1977, James and others 1979, Monti and Mackintosh 1979).

Most of this difference in magnitude of change is a result of extremely low infiltration rates on Eagle Cap controls. Infiltration rates on the campsites are comparable to those on campsites in other studies; rates on controls are an order of magnitude lower. Soils were notably hydrophobic and were not presoaked. Hydrophobicity, which can cause dramatic reductions in infiltration rates, is particularly pronounced in highly organic and sandy soils, like those in this study (Singer and Ugolini 1976). Studies have also found soils under ericaceous shrubs and conifers to be particularly water-repellant (Richardson and Hole 1978).

Finally, several statistically significant changes in soil chemistry were found. From a median value of 5.13 on controls, pH increased to 5.48 on campsites. Concentrations of Mg, Ca, and Na were also significantly higher on campsites. Mg increased 107 percent, and Ca and Na increased 101 percent and 13 percent, respectively. Concentrations of NO_3, K, and total N increased on campsites, but the results were so variable that a significant difference could not be established. Phosphate content, like particle-size distribution,[5] did not differ. These results contrast somewhat with those of Young and Gilmore (1976). They found similar increases in Ca (116 percent) and Na (57 percent) on campsites, in addition to increases in P (50 percent) and N (26 percent), and no change in Mg, the nutrient which increased the most on the Eagle Cap campsites. Rutherford and Scott (1979) found no change in Mg, K, or PO_4, and a decrease in NO_3. Obviously, the effects of camping on soil chemistry are highly variable, depending upon the extent to which campfire ashes are scattered about the site, the nutrient inputs in excess food, soap, and so forth, the degree to which leaching is reduced by decreased infiltration rates (Young and Gilmore 1976); and the innate character of the undisturbed soil.

It is doubtful, however, that any of these changes are significant in an ecological sense. For example, in a Montana study which included *Abies lasiocarpa-Pinus contorta-Carex geyeri-Vaccinium scoparium* (subalpine fir-lodgepole pine-elk sedge-grouse whortleberry) forests, seasonal variations in soil pH and Na content were greater than the differences between campsites and controls found in this study (Weaver and Forcella 1979). Although changes in Mg and Ca concentrations on campsites were greater than their seasonal variability, the differences were not sufficiently dramatic to suggest any basic ecological change.

It is interesting to note that those ions which increased the most on the Eagle Cap campsites are highly mobile ions particularly susceptible to leaching. Their presence in high concentrations on campsites supports the hypothesis of Young and Gilmore (1976) that campsite increases are a result of reduced leaching.

To What Extent Do Impacts Vary with Differences in Amount of Use?

Despite these sizable differences between campsites and controls, the amount of change that has occurred on campsites is extremely variable. This is reflected in the large confidence intervals around the means in tables 2, 3, 5, and 6. It has often been assumed that most of this variability in campsite conditions and impacts can be attributed to differences in the amount of use the site receives. I (Cole 1981b) have suggested that environmental differences usually contribute more to variability than use differences. In this study, environmental variability was reduced by only examining campsites in *Abies lasiocarpa Vaccinium scoparium* forests, close to lakes, and between elevations of 7,050 and 7,800 ft (2 150 and 2 400 m). This allowed a clearer view of the relationship between amount of use and campsite impact.

The relationship between amount of use and impact, for parameters which exhibit significant differences between campsites and controls, are presented in tables 7, 8, and 9. Amount of use is compared to existing site conditions (table 7), the absolute amount of change which has occurred on the site (table 8), and the relative amount of change which has occurred on the site (table 9).

From these tables, there is no significant correlation between the amount of use a site receives and the following variables: camp area, mutilated, felled, or scarred trees, litter cover, soil pH, instantaneous or saturated infiltration rates, Mg, Ca, or Na concentrations, soil organic matter, or bulk density.

Although light-use sites are generally smaller than moderate- and heavy use sites (table 7), campsite area is highly variable and there is substantial overlap in size between use classes. For example, the low-use site at Hidden Lake is 2,906 ft² (270 m²), while a heavy-use site at Minam Lake is only 850 ft² (79 m²). This variability explains the nonsignificant Kendall correlation coefficient and also the nonsignificant Kolmogorov-Smirnov contrast between light- and moderate- use sites, despite the difference in median and mean values. With a larger sample size, it would probably have been possible to conclude that light-use sites are generally smaller than more heavily used sites (significance level was 0.064). There is little difference in the size of moderate- and heavy-use sites, however. Most increases in campsite size can probably be attributed to occasional use by abnormally large parties, or parties with packstock, a process largely independent of frequency of use by more typical, small, backpacking parties.

Tree mutilations also appear to increase in abundance with increasing use, but, again, differences are dwarfed by variability. Differences in the frequency of felled and

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[5] Data are not presented because no differences between campsites and controls were noted.

scarred trees are not related in any consistent manner to the amount of use a site receives. This is not surprising as most tree damage can probably be ascribed to a few atypically destructive groups, again making the frequency of use by undestructive parties irrelevant. Fichtler (1980) also found no relationship between use and tree injury. James and others (1979), however, did find an increase in the number of trunk scars per stem from 1.9 on recently built, light-use sites to 4.3 on the older, heavy-use sites. This damage, which is cumulative, is probably more strongly related to campsite age than to use frequency.

Litter cover, as noted previously, is dependent on changes in vegetation cover and bare ground. Consequently, interpretation of these values is difficult. Coombs (1976) and Fichtler (1980) reported no difference in litter cover between light- and heavy-use sites, but they failed to note that vegetation loss causes an apparent, but not a real, increase in litter values. Thus, their results, similar to these in showing no significant differences between use levels, probably disguise a real loss in litter cover with increasing use, coincident with an increase in bare ground, which will be discussed. Legg and Schneider (1977) reported a significant decrease in litter cover on more heavily used sites, and Young (1978) reported a reduction in litter with increased use, although differences were not statistically significant.

Soil pH generally increases with increasing use. A large sample size might have allowed a statistically significant relationship to be established, but, again, differences between use levels are minor in comparison to site-to-site variability (table 7). The same conclusion can be drawn from measures of the amount of change in pH on the campsites (tables 8 and 9). Young and Gilmore (1976) found that the pH on sites used 34 to 66 days per year (6.1) was significantly higher than the pH on sites used 0 to 33 days per year (5.7), but that a further increase in use caused no further change. These increases, even if they can be attributed to increased use of the campsites, are so slight that they are not ecologically meaningful.

Table 7.--Relationship between campsite conditions and the amount of use the site receives[1]

	Light-use sites (N = 6)		Moderate-use sites (N = 6)		Heavy-use sites (N = 10)		
Impact parameter	Median	Mean	Median	Mean	Median	Mean	Kendall tau
Camp area (m^2)	48	109 ± 99	224	275 ± 196	205	204 ± 51	
Bare area (m^2)	19	51 ± 53	122	112 ± 66	93	116 ± 40	0.30
Mutilated trees (percent)	74	60 ± 49	85	73 ± 40	97	93 ± 7	
Trees with exposed roots (percent)	3	7 ± 8	33	34 ± 26	39	39 ± 22	.41
Felled trees (percent)	43	41 ± 40	12	21 ± 26	34	34 ± 12	
Scarred trees (percent)	3	13 ± 17	37	36 ± 22	11	21 ± 26	
Floristic dissimilarity (percent)	31	42 ± 18	60	59 ± 25	64	61 ± 11	.33
Seedlings (number/ha)	174	314 ± 366	299	404 ± 352	335	686 ± 488	
Vegetation cover (percent)	9	12 ± 11	6	10 ± 12	4	5 ± 2	-.41
Bare ground (percent)	14	30 ± 28	20	26 ± 19	35	40 ± 16	
Litter (percent)	40	50 ± 28	62	56 ± 25	51	49 ± 17	
Duff depth (cm)	0.15	0.22 ± 0.18	0.45	0.67 ± 0.72	0.15	0.18 ± 0.09	-.35
pH	5.25	5.32 ± 0.41	5.25	5.37 ± 0.43	5.55	5.58 ± 0.16	
Instantaneous infiltration rate (cm/min)	0.54	0.60 ± 0.19	0.19	0.28 ± 0.22	0.28	0.32 ± 0.13	
Saturated infiltration rate (cm/min)	0.23	0.24 ± 0.17	0.12	0.15 ± 0.07	0.14	0.13 ± 0.04	
Mg (p/m)	34	50 ± 26	67	132 ± 237	61	77 ± 26	
Ca (p/m)	280	425 ± 265	755	1,070 ± 1,345	528	650 ± 263	
Na (p/m)	54	52 ± 10	53	62 ± 16	51	55 ± 8	
Organic matter (percent)	12	18 ± 11	14	17 ± 13	18	20 ± 5	
Bulk density (g/cm^3)	0.95	1.04 ± 0.29	0.90	0.90 ± 0.19	0.95	0.94 ± 0.11	
Impact rating	1.5	1.6 ± 0.4	2.0	2.0 ± 0.4	2.2	2.1 ± 0.2	.41

[1] Significance level was 0.05. Nonsignificant relationships are left blank.

Table 8.--Relationship between the absolute amount of change which has occurred on a campsite and the amount of use the site receives[1]

Impact parameter	Light-use sites (N = 6) Median	Light-use sites (N = 6) Mean	Moderate-use sites (N = 6) Median	Moderate-use sites (N = 6) Mean	Heavy-use sites (N = 10) Median	Heavy-use sites (N = 10) Mean	Kendall tau
Seedlings (number/ha)	1 113	1 245 ± 667	1,825	3 742 ± 3,241	3 727	6 936 ± 5 210	0 57
Vegetation cover (percent)	37	38 ± 15	30	40 ± 34	60	56 ± 15	.29
Bare ground (percent)	-5	-15 ± 26	26	24 ± 19	32	37 ± 17	34
Litter (percent)	-26	22 ± 24	26	23 ± 30	35	25 ± 20	
Duff depth (cm)	0 06	0 13 ± 0 26	0 15	0 58 ± 1 21	0 35	0 49 ± 0 20	40
pH	0 15	-0 15 ± 0 39	-0 25	0 27 ± 0 40	0 60	0 36 ± 0 24	
Instantaneous infiltration rate (cm/min)	0 07	0 21 ± 0 47	0 46	0 41 ± 0 37	0 05	0 20 ± 0 23	
Saturated infiltration rate (cm/min)	0 01	0 03 ± 0 12	0 12	0 16 ± 0 18	0 09	0 08 ± 0 06	
Mg (p/m)	-18	-19 ± 22	-28	-86 ± 136	35	-30 ± 32	
Ca (p/m)	-216	-221 ± 236	-483	-677 ± 790	-300	-206 ± 176	
Na (p/m)	-8	-4 ± 11	-15	-19 ± 16	-5	-6 ± 10	
Organic matter (percent)	-5	-5 ± 6	-4	0 ± 6	-2	5 ± 5	
Bulk density (g/cm^3)	-0 13	-0.09 ± 0 15	-0 08	-0 05 ± 0 15	-0 14	-0 09 ± 0 14	

[1] The absolute amount of change is the difference between conditions on the campsite and control. A positive change represents a decrease in that measure on the campsite. Significance level was 0 05. Nonsignificant relationships are left blank.

Table 9.--Relationship between the relative amount of change which has occurred on a campsite and the amount of use the site receives[1]

Impact parameter	Light-use sites (N = 6) Median	Light-use sites (N = 6) Mean	Moderate-use sites (N = 6) Median	Moderate-use sites (N = 6) Mean	Heavy-use sites (N = 10) Median	Heavy-use sites (N = 10) Mean	Kendall tau
Seedlings (percent)	73	82 ± 17	92	90 ± 11	89	86 ± 11	
Vegetation cover (percent)	71	78 ± 17	71	70 ± 30	94	91 ± 6	0 29
Bare ground (percent)	-529	-504 ± 638	-1,595	-2,110 ± 1,967	3,293	-3,136 ± 1,726	43
Litter (percent)	-118	-91 ± 115	-49	-233 ± 461	277	240 ± 207	
Duff depth (percent)	3	2 ± 109	21	34 ± 52	68	72 ± 12	36
pH (percent)	3	3 ± 8	-5	-5 ± 8	-11	7 ± 5	
Instantaneous infiltration rate (percent)	8	40 ± 147	57	59 ± 20	12	12 ± 53	
Saturated infiltration rate (percent)	-2	0 ± 39	39	43 ± 22	42	30 ± 30	
Mg (percent)	-41	-67 ± 78	-109	-158 ± 213	108	78 ± 50	
Ca (percent)	-105	-99 ± 97	-160	178 ± 176	30	-69 ± 63	
Na (percent)	-25	-11 ± 23	-33	45 ± 43	10	14 ± 21	
Organic matter (percent)	-19	-43 ± 61	26	2 ± 32	20	35 ± 35	
Bulk density (percent)	-16	-11 ± 14	11	-8 ± 17	16	13 ± 16	

[1] The relative amount of change is the difference between campsite and control conditions expressed as a percent [illegible] change as a percentage of original conditions). A positive change represents a decrease in that measure on the campsite. [illegible] Nonsignificant relationships are left blank.

Differences in the amount of change in other soil properties are even more erratic and variable. For example, instantaneous infiltration rates are reduced, on the average, 40 percent on light-use sites, 59 percent on moderate-use sites, and 12 percent on heavy-use sites; standard deviations are usually greater than the differences between use categories (table 9). The lack of relationship between amount of use and infiltration rates, Mg concentrations, and soil organic matter supports earlier studies. James and others (1979) found mean infiltration rates of 0.27 cm/min on recently built, light-use sites, and 0.29 cm/min on older, heavy-use sites. As reduced infiltration rates are probably one of the more detrimental consequences of soil compaction, these findings--that rates are reduced as much on light-use sites as on heavy-use sites--seem very important.

Young and Gilmore (1976) found similar Mg concentrations and organic matter content on campsites receiving different amounts of use. Organic matter content on their sites was 3 to 4 percent, in contrast to 17 to 20 percent on Eagle Cap campsites, suggesting that the lack of relationship between use and organic matter content applies to a broad range of soil types.

The lack of relationship between use and bulk density, Ca, and Na concentrations is inconsistent with earlier studies. Young and Gilmore (1976) report significant differences in Ca content between light- and moderate-use sites; concentrations on light- and heavy-use sites, however, were not significantly different, and differences between soil types were more pronounced than differences between use categories. They also report significant differences in Na content between light- and heavy-use sites, but differences between light-and moderate-use sites or moderate- and heavy-use sites were not significant. Apparently, the relationship between soil chemistry change and amount of recreational use can be highly variable. The differences involved, however, appear to almost always be so slight that differences in availability of nutrients to plants should be negligible. This makes the question of statistical significance moot.

The lack of relationship between amount of use and bulk density is more difficult to dismiss, as increased bulk density is commonly considered to be an ecologically significant campsite impact, and both Dotzenko and others (1967) and Legg and Schneider (1977) report increases in bulk density associated with increased use. Perhaps our lack of relationship is a result of measurement error with the hand-excavation technique, or perhaps the relative noncompactibility of the Eagle Cap soils makes differences in amount of use less important. Both Dotzenko and others (1967) and Legg and Schneider (1977) found more pronounced differences between controls and their light-use sites than between light- and heavy-use sites. Increases in soil penetration resistance on campsites, another measure of compaction, were not correlated with amount of use in Fichtler's (1980) study.

For the remaining parameters, there is some evidence that impact may be related to amount of use. These parameters will be analyzed in more detail.

SEEDLINGS

Seedling densities are actually higher on heavy-use sites than on moderate- or light-use sites (table 7). This would suggest that impact has been greater on light-use sites. An opposing interpretation emerges when absolute seedling loss is examined; the difference between the density of seedlings on controls and campsites increases from light- to heavy-use sites (table 8). Relative seedling loss is relatively constant across the use categories.

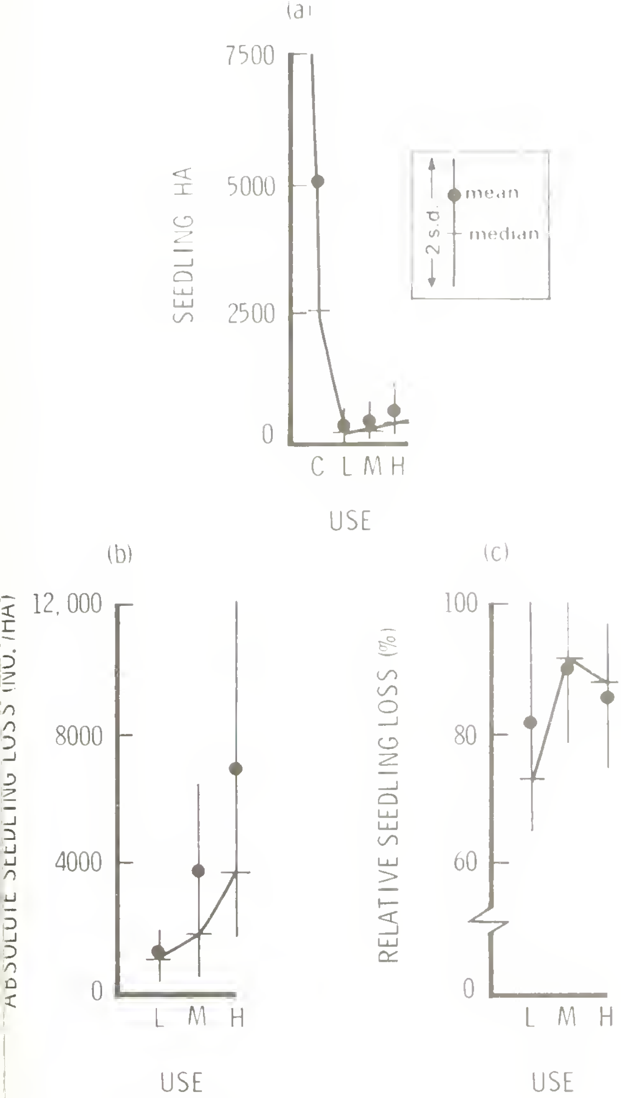
In order to facilitate interpretation, these results have been graphically portrayed in figure 13. Seedling densities on controls are extremely variable, but always an order of magnitude greater than the less variable campsite densities (fig. 13a). The great variability in seedling densities on control sites makes comparisons of absolute loss (fig. 13b) misleading and favors the use of relative loss (fig. 13c) as a measure of impact. Clearly, seedlings are almost completely eliminated on all campsites, regardless of the amount of use they receive. Being highly susceptible to trampling, any consistent use is sufficient to kill most of the seedlings. The number of seedlings surviving on a campsite is probably more a function of the number of protected suitable germination sites than the amount of use the site receives. Fichtler (1980) also found no difference in relative seedling loss between light- and heavy-use sites.

VEGETATION COVER

In comparison to more lightly used campsites, heavy-use sites have less vegetation (table 7), and the amount of change, whether expressed in absolute values (table 8) or relative values (table 9), has been greater. As shown in figure 14, however, differences between use levels are minor in comparison to the differences between campsites and controls. The median cover on the light-use sites is 9 percent; 71 percent of the original cover has been lost. The median cover on heavy-use sites is 4 percent, a 94-percent loss. In this case, there is a statistically significant increase in vegetation impact associated with increased use, but the differences are not pronounced.

These results are similar to those of Frissell and Duncan (1965), who found 12-percent vegetation cover on light-use sites; 81 percent of the original cover had been lost. Heavy-use sites retained a 5-percent cover, a 91 percent loss. In their case, the difference in existing cover on campsites was statistically significant, but the difference in amoun of change was not. Therefore, at these use levels (highe than those found in the Eagle Cap), in the northern Minnesota environment, differences in amount o vegetation change were not related to amount of use Similarly, Fichtler (1980) found no difference in relative cover loss between light- and heavy-use sites in Montana Young (1978) found no relationship between vegetation cover and amount of use on Illinois campsites, and LaPage (1967) found no relationship between use and change in cover after campsites in Pennsylvania were more than 1 year old.

The only study to show any sizable difference in cove between light- and heavy-use sites was Coombs' (1976 study in the Idaho Primitive Area, where use was extremely low. She found about 30 percent cover on light-use sites (a relative loss of 30 percent) and 8 percent on heavy use sites (a relative loss of 81 percent). Apparently vegetation change is considerably less pronounced a very low use levels, but even a few nights of use per yea in the Eagle Cap appears to be enough to eliminate most c the vegetation.



igure 13.--Seedling loss in relation to mount of use. Median, mean, and two tandard deviations for (a) seedlings er hectare on controls, light-, noderate-, and heavy-use campsites, b) the absolute reduction in seedling lensity that has occurred on light- noderate-, and heavy-use campsites, nd (c) the relative reduction in seedling lensity that has occurred on light-, noderate-, and heavy-use campsites. he medians in each use category have een connected by a line.

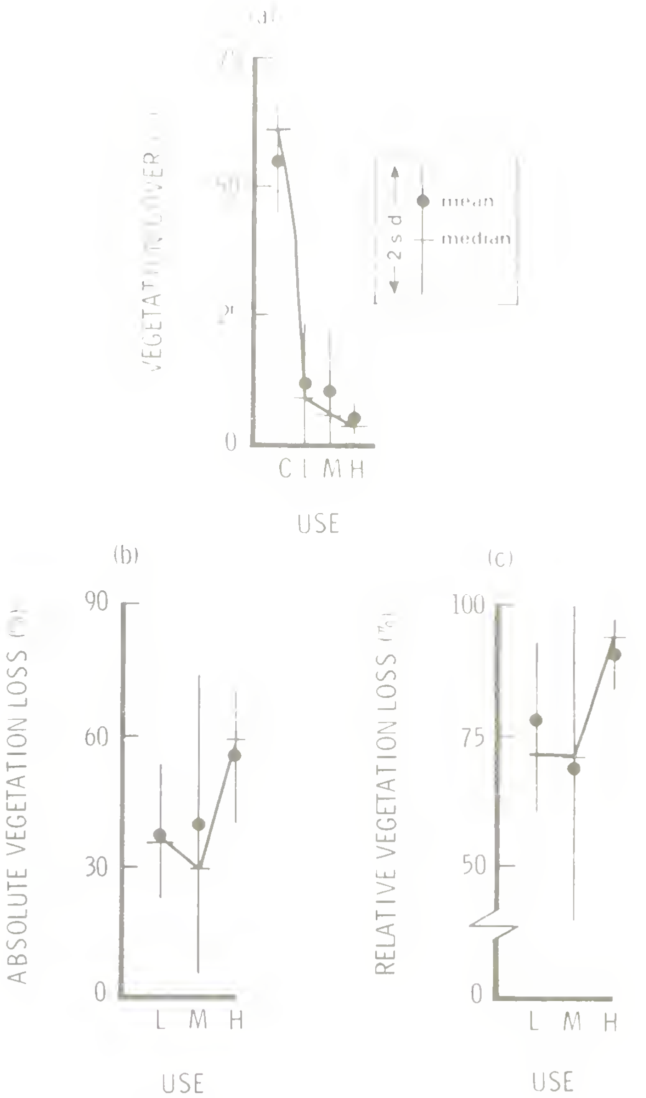


Figure 14.--Loss of vegetation cover in relation to amount of use. Median, mean, and two standard deviations for (a) vegetation cover on controls, light-, moderate-, and heavy-use campsites, (b) absolute reduction in vegetation cover on light-, moderate-, and heavy-use campsites, and (c) relative reduction in vegetation cover on light-, moderate-, and heavy-use campsites. The medians in each use category have been connected by a line.

Species diversity does not vary substantially with ifferences in amount of use. The median species richess--the number of species per 161 ft² (15 m²)-- was 12, 0.5, and 11.5, on light-, moderate-, and heavy-use sites, espectively. The reciprocal of Simpson's index, a measure f species heterogeneity which is most sensitive to hanges in dominant species (Peet 1974), was 4.76, 4.37, nd 4.48, on light-, moderate-, and heavy-use sites, espectively. Young (1978) reported a decrease in species richness at high-use levels, but the short-use season at Eagle Cap precludes such heavy use. At the lower use levels typical of high-elevation wilderness areas, species diversity does not appear to be highly influenced by amount of use. In fact Coombs (1976) found more species on light-use sites than on controls, a finding that supports the observation that species diversity increases at low levels of trampling stress and decreases at high levels of stress (Slatter 1978).

Change in species composition, reflected in the index of floristic dissimilarity, does appear to increase with increasing use, however, from a median value of 31 percent on light-use sites to 64 percent on heavy-use sites (table 7). This suggests that, although heavy-use sites retain as many species and almost as much cover as light-use sites, heavy-use sites experience a more pronounced shift in species compostion. This contrasts with the results of Fichtler (1980), who found no relationship between floristic dissimilarity and amount of use.

Although species composition has been more highly altered on heavy-use campsites, there are no significant differences in the relative importance of growth forms or major species associated with differences in amount of use (table 10). James and others (1979) also found no relationship between use intensity and understory species composition on campsites in coniferous forests, despite pronounced shifts in species composition on campsites. Apparently, species compositional changes may become more pronounced as use intensity increases, but so many other factors influence the surviving populations that the importance of individual species and growth forms does not vary consistently in relation to amount of use.

The more heavily used sites also have a larger central core devoid of vegetation. This bare area increases from a median value of 205 ft^2 (19 m^2) on light-use sites to 1,313 ft^2 (122 m^2) and 1,001 ft^2 (93 m^2) on moderate- and heavy-use sites, respectively (table 7). The proportion of a site that is denuded, however, is similar on light-, moderate-, and heavy-use sites. The barren central core is 40 percent of the area of the median light-use campsite and 45 percent of the heavy-use campsite area.

This finding contrasts with the results of Moorhead and Schreiner (1979). Working in Olympic National Park, they found no consistent relationship between a similar measure of bare area and amount of use, despite significant differences in bare area between different vegetation types. This is one case where it has been clearly shown that environmental differences influence the amount of impact more highly than differences in amount of use.

BARE GROUND

Although median bare ground increases from light- to heavy-use sites, these differences are not statistically significant (table 7). When campsites and controls are compared to give an estimate of amount of change, differences are significant (tables 8 and 9). The median light-use site has 5 percent more bare soil exposed than its associated control (absolute change); this represents a 529 percent increase (relative change). On moderate-use sites, 26 percent more bare soil is exposed, a 1,595-percent increase; and on heavy-use sites, these measures of change increase to 32 percent and 3,292 percent respectively (tables 8 and 9). Graphically portrayed in figure 15, this suggests that the increase in bare ground which occurs on a campsite is controlled to a significant extent by the amount of use the site receives.

Similar results have been found by Young (1978) on campsites in Illinois. He found that bare ground increased from negligible amounts on controls to 30 percent on light-use sites (0 to 33 days per year) and 56 percent on moderate-use sites (33 to 66 days per year), but as use exceeded 66 days per year, no significant increase in bare ground occurred. Coombs (1976) found that bare ground and erosion pavement increased from 2 percent on controls to 15 percent on light-use sites and 26 percent on heavy-use sites in the Idaho Primitive Area. Fichtle (1980) found that bare ground increased sevenfold on light-use sites and seventeenfold on heavy-use sites. This was the only impact parameter that increased significantly with increased use. These results suggest strongly that heavy-use sites experience significantly greater increase in bare ground exposure than light-use sites.

Table 10.--Relative cover of growth forms and selected species in relation to amount of use

Growth forms and selected species	Light-use sites (N = 6)		Moderate-use sites (N = 6)		Heavy-use sites (N = 10)		Kendall tau[1]
	Median	Mean	Median	Mean	Median	Mean	
	Percent						
Graminoids	66	65 ± 18	53	51 ± 15	52	51 ± 8	
Shrubs	17	16 ± 11	9	16 ± 15	6	21 ± 14	
Forbs	5	13 ± 12	35	29 ± 21	17	21 ± 12	
Bryophytes	0.3	6 ± 10	1	3 ± 3	2	6 ± 5	
Carex rossii	5	5 ± 3	9	20 ± 20	9	15 ± 9	
Juncus parryi	20	29 ± 17	12	14 ± 8	27	24 ± 10	
Vaccinium scoparium	3	8 ± 10	6	14 ± 15	6	15 ± 12	
Phyllodoce empetriformis	2	6 ± 5	0.5	1 ± 1	0.3	6 ± 7	

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[1] None of the relationships were significant at the 0.05 level.

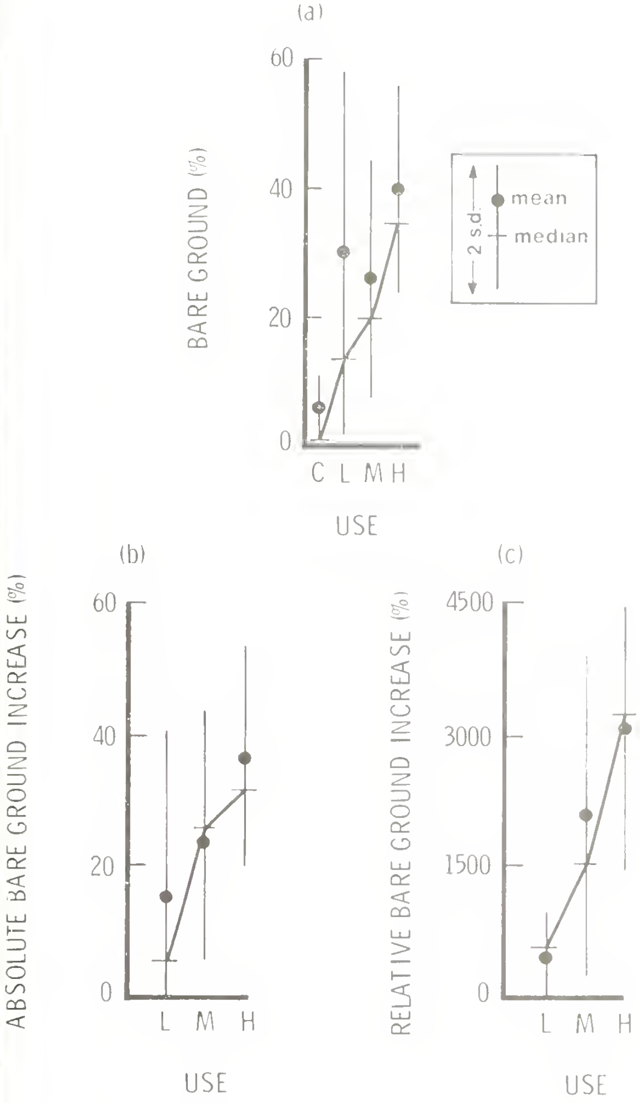


Figure 15.--Increase in bare ground in relation to amount of use. Median, mean, and two standard deviations for: (a) bare ground cover on controls, light-, moderate-, and heavy-use campsites; (b) absolute increase in bare ground cover on light-, moderate-, and heavy-use campsites; and (c) relative increase in bare ground cover on light-, moderate-, and heavy-use campsites. The medians in each use category have been connected by a line.

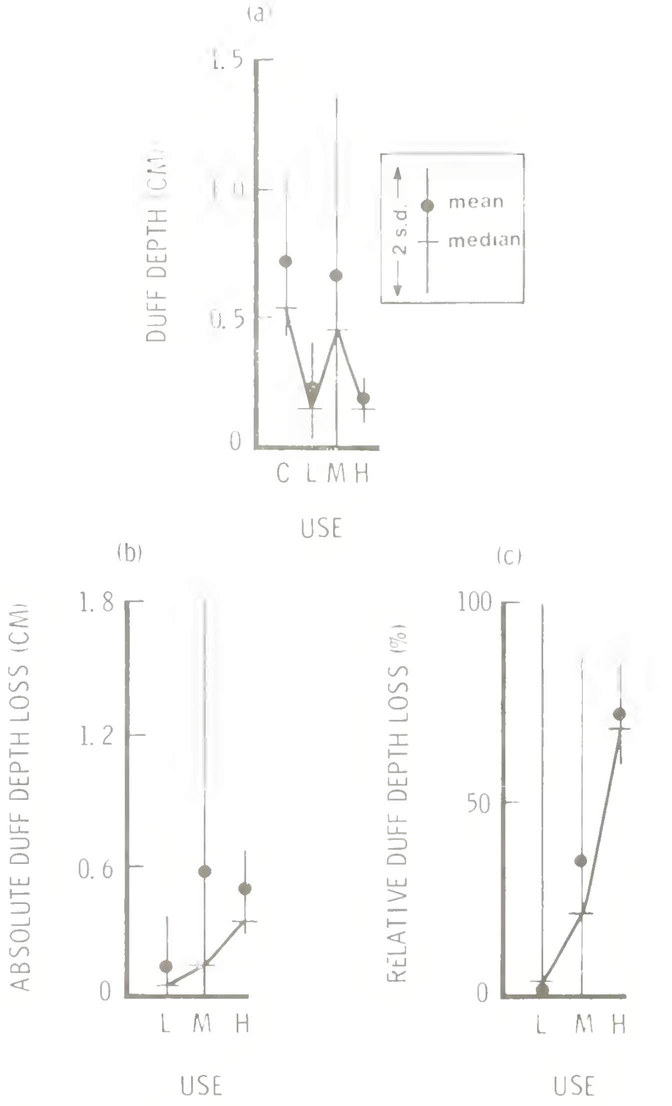


Figure 16.--Decrease in duff depth in relation to amount of use. Median, mean, and two standard deviations for: (a) duff depth on controls, light-, moderate-, and heavy-use campsites, (b) absolute reduction in duff depth on light-, moderate-, and heavy-use campsites, and (c) relative reduction in duff depth on light-, moderate-, and heavy-use campsites. The medians in each use category have been connected by a line.

DUFF DEPTH

Table 7 shows a statistically significant decrease in duff depth associated with increased use, although light-use sites actually have thinner organic horizons than moderate-use sites. Measures of reduction in duff depth, whether absolute (table 8) or relative (table 9) show sizable increases in impact associated with increased use. All of these measures indicate that removal of organic horizons increases as use intensity increases, despite highly variable campsite measurements (fig. 16). The median relative loss of duff increases from 3 percent on light-use sites to 21 percent and 68 percent on moderate- and heavy-use sites, respectively. James and others (1979) found no relationship between use intensity and duff depth, despite pronounced reductions on campsites in general. They did not attempt to pair campsites and controls, however, so site-to-site variability may have disguised any relationship. A second paper on the same study area (Monti and Mackintosh 1979) showed more pronounced reductions in duff depth on high-use sites than on medium- or low-use sites.

TREE ROOT EXPOSURE

The percentage of trees with exposed roots is also significantly lower on light-use sites--3 percent compared to median values of 33 percent and 39 percent on moderate- and heavy-use sites (table 7). Along with the relatively small decrease in duff depth on light-use sites, this suggests that loss of the surface horizons usually does not occur until campsites are used more than about five times per year. Conditions are highly variable, however, some light-use campsites have numerous trees with exposed roots and have lost most of their organic horizons. James and others (1979) found that the mean number of exposed roots within 3.28 ft (1 m) of each sample tree increased from 7.1 on recently built, light-use sites to 13.8 on older, heavy-use sites. Fichtler (1980), however, found no relationship between use and linear feet of exposed roots.

IMPACT RATING

The overall summary measure of impact, which could vary between 1 and 3, had median values of 1.5, 2.0, and 2.2 for light-, moderate-, and heavy-use sites, respectively (table 7). This general increase in impact in response to increased use is statistically significant, however, there is a considerable amount of overlap between use classes. For example, 90 percent of the heavy-use sites have ratings as low or lower than the rating of the most highly impacted low-use site. In other words, heavy-use sites are usually more highly impacted than light-use sites, but differences are slight, and light-use sites can be more highly impacted than heavy-use sites. Moreover, differences between light- and moderate-use sites are much more pronounced than differences between moderate- and heavy-use sites.

How Much Change Occurs in Other Environmental Situations?

It has been suggested that campsite impacts could be reduced by locating campsites on durable sites (Cole 1981b). Trails illustrate the importance of location where poorly located trail segments are badly eroded, while adjacent segments, receiving the same amount of use, are often in good shape.

Experimental trampling studies have found that trampling impact usually varies more between vegetation types than between use levels. For example, in a study at Waterton Lakes National Park, 800 tramples reduced the vegetation of a lodgepole pine stand to 1.1 percent of its original cover. A similar number of tramples in a prairie grassland only reduced cover to 22.1 percent. To maintain this percentage of original cover in the lodgepole stands would require a reduction in the number of tramples to 40 (Nagy and Scotter 1974). In other words, shifting the trampling from lodgepole to grassland sites would accomplish as much, in terms of maintaining original cover, as a twentyfold reduction in use of the lodgepole sites. Moorhead and Schreiner (1979) arrived at similar conclusions in a study of the bare area on campsites in Olympic National Park.

In order to examine the effects of differences in environment, campsite data are presented for four additional sites not located close to subalpine lakes (table 11). Two are located in timberline meadows close to 8,200 ft (2 500 m) in elevation. Campsite 15 at Pocket Lake is a light-use site, while campsite 20 at Glacier Lake is probably a moderate-use site. The two other campsites are located in forested valley bottoms below 6,500 ft (2 000 m). Campsite 21 along the West Fork of the Wallowa River is a heavy-use site, while campsite 22 on the West Fork of the Lostine River is a moderate-use site.

The two campsites in timberline meadows had lost only 10 percent of their vegetation cover, the change in species composition had been negligible, and there was only 3 to 4 percent more bare ground on campsites than on controls. These measures are dramatically lower than any of the other campsites studied. Visual impact is also less (fig. 17), as is reflected in the low condition class ratings of 1.0 and the impact ratings of 1.20 and 1.17.

Although there is a popular belief that timberline meadows are unusually fragile, studies have consistently shown the relative resistance of *Carex nigricans* (black alpine sedge) meadows, the vegetation type in which these sites are located (Campbell and Scotter 1975; Hartley 1976). These meadows are susceptible to impact during early summer snowmelt, but by the time they dry enough to be usable, they are extremely durable sites.

The lower elevation campsites, in contrast, have been as highly altered as the most heavily impacted subalpine forest sites (fig. 18). Only two other sites have higher overall impact ratings, and the reduction in duff depth on these sites is particularly severe. This supports the results of an earlier study in the Eagle Cap Wilderness which found that more vegetation change had occurred on forested sites, regardless of elevation, than on open grassland or meadow sites (Cole 1981a).

Table 11.--Selected conditions and amount of change on campsites located in alpine *Carex nigricans* meadows (15 and 20) and forests below 2 000 m (21 and 22)

Impact parameter	Campsites 15	20	21	22
Bare area (m^2)	1	2	101	66
Mutilated trees (percent)			100	100
Camp seedlings (number/ha)			0	0
Control seedlings (number/ha)			0	3 980
Absolute change (number/ha)	-		0	3 980
Relative change (percent)			0	100
Camp vegetation (percent)	88	80	3	5
Control vegetation (percent)	98	90	60	40
Absolute change (percent)	10	10	57	35
Relative change (percent)	10	11	95	88
Camp bare ground (percent)	5	4	20	35
Control bare ground (percent)	1	1	1	1
Absolute change (percent)	4	3	19	34
Relative change (percent)	-400	-300	-1,900	3,400
Camp duff depth (cm)	--	0.3	0.6	0.1
Control duff depth (cm)	-	.9	3.4	1.0
Absolute change (cm)	--	.6	2.8	.9
Relative change (percent)	--	67	82	90
Floristic dissimilarity (percent)	25	37	53	84
Condition class	1.0	1.0	4.0	3.5
Impact rating	1.20	1.17	2.43	2.38

Figure 17.--Campsite 20 is located in a timberline meadow at Glacier Lake. Impacts were considerably less pronounced than on forested campsites.

Figure 18.--Campsite 21 is located in lower elevation forests along the West Fork of the Wallowa River. Impacts were as pronounced as on campsites located in subalpine forests.

Are Lakeshore Sites Particularly Fragile?

Lakeshore setbacks are becoming increasingly common in wilderness. Eagle Cap Wilderness regulations prohibit camping within 200 ft (61 m) of any lake. A common justification for this practice is that lakeshores are more fragile than sites set back from the lake. This supposition was tested by comparing conditions on five heavy-use sites located within 200 ft (61 m) of lakes and five heavy-use sites located more than 200 ft (61 m) from lakes.

For the last few years, camping has been prohibited on the lakeshore sites, but enforcement has been difficult. We observed approximately the same numbers of parties still camping on illegal sites as on legal sites. Moreover, lakeshore sites were almost always the longest established sites and the sites that traditionally have received the most use. Therefore, in generalizing about the use history of these two sets of sites, one can safely assume that most lakeshore sites have been more heavily used for a longer period of time, but that in recent years both sets have received relatively similar amounts of use.

In comparison to setback sites, lakeshore sites tend to be somewhat larger, but less of the site is devoid of vegetation (table 12). They have fewer seedlings, but more vegetation cover, with a species composition that has been less highly altered than that on setback sites. Bare ground is less extensive, but the organic horizons are thinner. Soil pH, Ca concentration, and bulk density are all lower on lakeshore sites. Most of these differences are minor, however, in comparison to highly variable site conditions. Consequently, none of these differences were statistically significant at the 0.05 significance level using the Kolmogorov-Smirnov two-sample test (Siegel 1956).

Table 12.--Campsite conditions on lakeshore sites and sites located more than 200 feet from the lakeshore

Impact parameter	Lakeshore sites (N = 5)		Setback sites (N = 5)	
	Median	Mean	Median	Mean
Camp area (m^2)	219	233 ± 37	190	175 ± 76
Bare area (m^2)	92	108 ± 32	139	123 ± 66
Seedlings (number/ha)	274	377 ± 301	637	994 ± 728
Mutilated trees (percent)	96	90 ± 11	99	95 ± 6
Trees with exposed roots (percent)	40	38 ± 25	38	41 ± 32
Felled trees (percent)	34	29 ± 13	33	38 ± 17
Scarred trees (percent)	17	21 ± 28	5	22 ± 24
Floristic dissimilarity (percent)	50	58 ± 18	66	64 ± 11
Vegetation cover (percent)	8	7 ± 3	3	3 ± 2
Bare ground (percent)	24	37 ± 25	41	43 ± 15
Litter (percent)	59	50 ± 24	50	48 ± 20
Duff depth (cm)	0.13	0.16 ± 0.08	0.20	0.20 ± 0.14
pH	5.40	5.48 ± 0.19	5.65	5.68 ± 0.13
Instantaneous infiltration rate (cm/min)	0.26	0.35 ± 0.25	0.28	0.29 ± 0.03
Saturated infiltration rate (cm/min)	0.09	0.12 ± 0.08	0.14	0.13 ± 0.03
Mg (p/m)	63	72 ± 29	60	81 ± 39
Ca (p/m)	475	538 ± 195	587	762 ± 301
Na (p/m)	56	60 ± 13	50	49 ± 4
Organic matter (percent)	19	23 ± 8	17	16 ± 4
Bulk density (g/cm^3)	0.79	0.86 ± 0.20	0.95	0.98 ± 0.07
Impact rating	2.2	2.2 ± 0.1	2.1	2.1 ± 0.3

When relative and absolute amounts of change were compared, differences in the amount of change in seedling density and pH were the only statistically significant differences. Lakeshore sites had lost 97 percent of their seedlings, compared to 75 percent on sites set back from the lakes. Soil pH increased 9 percent on lakeshore campsites, compared to 13 percent on setback sites. For all of the other parameters measured, the amount of change was essentially the same on the two sets of sites.

Given that seedling loss is the only impact which is more extreme on lakeshore sites, the contention that lakeshores are more fragile appears to be unfounded. In trampling experiments conducted in Waterton Lakes National Park, Nagy and Scotter (1974) found less vegetation change in a subalpine lakeshore meadow community than in the coniferous forests away from lakes. This is not to say, however, that there are no justifiable reasons for prohibiting camping close to lakeshores.

Although water quality studies show little evidence of human health hazards associated with heavy use of backcountry lakes (McDowell 1979), there is some evidence that ionic concentrations and benthic plant populations can be altered by heavy use (Taylor and Erman 1979). Where lakes are uncommon and attract abnormally large numbers of visitors, there may be some danger that all of the lakes will be altered by human use. In this case, the justification for setbacks is not that lakeshores are more fragile, but that the lake ecosystem is rare and should receive special protection.

Another justification for setbacks is that more trails tend to develop between campsites and the lakeshore when the site is located close to the lake. This causes more esthetic and ecological impact--not because the lakeshore site is more fragile, but because the flow of traffic between campsite and lakeshore is more destructive.

There are also a number of sociological justifications. Lakes are commonly primary scenic attractions in wilderness areas and should, therefore, be left as pristine as possible. Moreover, parties camping on the lakeshore effectively claim that territory as their own, prohibiting other parties from having free access to the lakeshore (Hendee and others 1977). Finally, the perception of solitude is increased by moving people back from lakeshores because their visibility is decreased and noise does not carry as readily.

Prohibitions on camping close to lakes keep visitors from camping where they most like to camp. The old, traditional campsites were inevitably located close to lakeshores. Managers will need good, justifiable rationales if they are going to convince visitors to camp away from the preferred lakeshores. The argument that mountain lakeshores are more fragile than adjacent areas is generally not tenable. Managers should carefully consider other justifications for setbacks and avoid basing policy on what is often an erroneous argument.

EVALUATION OF IMPACT INDICATORS

Wilderness managers have recognized a need to monitor campsite impacts so they have some objective measure of the changes occurring on a site. Moreover, this is now a requirement under the National Forest Management Act. Most monitoring programs will not be able to measure change in the detail achieved in this study. More often, simple, rapid techniques which can be utilized by personnel with little training will be needed.

One simple system, developed by Frissell (1978), uses condition classes based on visual criteria as follows:

Condition Class 1.	"Ground vegetation flattened, but not permanently injured. Minimal physical change except for possibly a simple rock fireplace."
Condition Class 2.	"Ground vegetation worn away around fireplace or center of activity."
Condition Class 3.	"Ground vegetation lost on most of the site, but humus and litter still present in all but a few areas."
Condition Class 4	"Bare mineral soil widespread. Tree roots exposed on the surface."
Condition Class 5	"Soil erosion obvious. Trees reduced in vigor or dead."

We gave each campsite a condition class rating and then correlated these ratings and other possible impact indicators with campsite condition and change to see how well they predicted impact (table 13).

Frissell's condition class rating was the indicator which correlated most highly with the overall impact ratings. It was also significantly correlated with more measures of impact than any of the other indicators. It is not surprising that condition class is correlated with trees with exposed roots, vegetation cover, or bare ground because these are characteristics used in the derivation of the rating. The rating, however, also predicted the amount of change in vegetation and bare ground that has occurred, as wel as the change in duff depth, floristic dissimilarity, camp area, and bare area. These include most of the impacts which could be noticed by visitors, as well as all of the impacts which are related to amount of use. Soil impacts are notably unrelated to condition class.

Camp radius and bare radius are impact indicators originally used in Olympic National Park by Schreiner and Moorhead (1976). Both of these indicators are significantly correlated with the overall impact ratings although not as highly as condition class. Neither o these indicators are consistently correlated with any o the measures of impact intensity. They do, however provide good estimates of the areal extent of impacts.

Table 13.--Kendall tau correlation coefficients relating campsite impact parameters and impact indicators which might potentially be utilized in a monitoring program. Nonsignificant and redundant relationships have been left blank

Impact parameter	Condition class	Camp radius	Bare radius	Vegetation cover	Bare ground	Trees with exposed roots	Impact class
	Potential indicators of impact						
Camp area	0.38		0.50				[illegible]
Bare area	43	0.52		[illegible]			[illegible]
Mutilated trees			36	[illegible]		0.41	
Trees with exposed roots	40						
Floristic dissimilarity	46	36	26				[illegible]
Seedlings							
Seedling change (absolute)	31	40	24				[illegible]
Seedling change (relative)							
Vegetation cover	48		25				
Vegetation change (absolute)	39					44	[illegible]
Vegetation change (relative)	50				0.26		
Bare ground	36						[illegible]
Bare ground change (absolute)	34						[illegible]
Bare ground change (relative)	33					[illegible]	[illegible]
Duff depth			[illegible]		[illegible]		
Duff depth change (absolute)	31				[illegible]		[illegible]
Duff depth change (relative)	32				47		54
pH							
pH change (absolute)			[illegible]	30			
pH change (relative)			32	[illegible]			
Instantaneous infiltration			30				
Infiltration change (absolute)				[illegible]			[illegible]
Infiltration change (relative)				[illegible]			[illegible]
Bulk density				[illegible]	[illegible]		
Density change (absolute)	33			44	[illegible]	29	
Density change (relative)				[illegible]		[illegible]	
Impact rating	50	38	[illegible]		[illegible]		

Vegetation cover, bare ground, and trees with exposed roots are generally poor indicators of impact, although, surprisingly, vegetation cover is the best indicator of soil changes. Impact rating was included because it should have been highly correlated with the impact measures. It did not, however, predict amount of impact any better than condition class, despite the time and effort required to obtain the impact rating.

At least, for the campsites studied, it appears that Frissell's condition class rating is the best single indicator of campsite condition. Although it does not identify soil changes very well, it does provide a good indication of overall impact, as well as those changes that use management can influence, bare ground and duff depth, in particular. It also is correlated with the areal extent of impacts, although a supplemental measure of camp radius or bare radius could provide valuable additional information.

There were a number of problems with the condition class ratings, however. The biggest problem was the breadth of some of the categories. Despite variability in site conditions, amount of change, and amount of use, 71 percent of the campsites received a condition class rating of 4. In fact, much of the success of this system as an indicator of impact may simply be its ability to separate a few less heavily impacted sites from this majority of sites. To be useful, Condition Class 4 will need to be subdivided so that the concentration of consistently used campsites in this one class is not so high.

Another major problem is that this rating does not describe the condition of individual measurable parameters. For example, it provides no baseline measure of vegetation cover that could be referred to at a later date to see if cover has changed. In other words, the rating provides a good measure of overall campsite condition, but little information about specific conditions. Managers desiring more specific quantitative information will need to use some other measure, such as percent bare ground or vegetation cover.

Finally, many campsites could be given different ratings depending upon the evaluative criteria chosen. For example, some campsites had exposed tree roots (Condition Class 4), but little bare mineral soil (Condition Class 3). We gave these sites a rating of 3.5. Perhaps a system of separate subjective ratings of ground vegetation, bare mineral soil, tree root exposure, and soil erosion, the main criteria in Frissell's system, along with a measure of areal extent, could avoid most of these problems and still remain highly correlated with overall impact. More research is obviously needed.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

The median campsite in this study has changed in the following ways.

1. From 85 to 90 percent of the undergrowth vegetation has been removed from the 2,150-ft^2 (200-m^2) camp area, leaving a sparse vegetation cover quite dissimilar in composition to undisturbed sites;
2. About 30 percent of the organic litter layer has been worn away, exposing patches of mineral soil;
3. This loss of vegetation and litter has been most pronounced toward the center of the site where essentially no vegetation persists and 50 percent of the organic horizons have been removed,
4. Essentially all of the trees on the site have been damaged, at least slightly, by recreational use; one-fourth of the trees have been felled and another one-fourth exhibit substantial trunk scarring;
5. Soil erosion has exposed roots on about one-third of the trees;
6. Over 90 percent of the seedlings have been eliminated, the few remaining seedlings are confined to sites protected from human trampling;
7. The soil has been compacted, although even on the most highly disturbed parts of the campsites, bulk density has increased only 15 percent and infiltration rates have decreased only about 30 percent; and
8. The organic content of the surface soil has increased slightly, as have the pH and the concentration of exchangeable Mg, Ca, and Na ions.

In order to utilize this information, the significance of these changes must be questioned. In terms of an ideal wilderness, all of these changes are significant because they represent deviations from natural conditions. This definition of significance cannot be practically applied to campsites, however, because some impact is necessary just to make the campsite functional. For example, the shrubby understory on most of these campsites must be removed before the site makes a comfortable sleeping area.

Given that a certain amount of impact is inevitable whenever a campsite receives consistent and prolonged use, a significant impact might best be defined as any change which reduces the future utility and desirability of the campsite. In other words, a significant impact would be any change that threatens to make the site either nonfunctional or undesirable.

Most site impacts do not appear to sharply reduce site desirability. Although more definitive research is needed, most evidence suggests that visitors seldom notice or are bothered by impacts on campsites (Lucas 1979). In a study in Yosemite National Park, for example, Lee (1975) found that "the use of wood for fires, destruction of ground cover, damage to trees, and other ecological changes in a pristine environment had less influence on the visitor than the presence of 'unnatural' objects," such as litter, horse manure, or constructed facilities.

Of the changes found on campsites, the impact most likely to decrease the future desirability of the campsites is the loss of seedlings and saplings which may forecast the eventual deforestation of campsites. A number of studies have shown that most campers prefer campsites that are shaded to those in the open (for example, Cordell and James 1972). Another study has shown that, contrary to their stated preferences, visitors to a developed campsite usually chose largely devegetated sites (Hancock 1973). This suggests that maintenance of the overstory is probably more important than maintenance of the understory. It is also more feasible. Maintenance of native understory populations, except on protected sites, is realistically impossible because trampling cannot be eliminated. The overstory could be maintained by establishing tree seedlings on protected sites, behind logs or rocks where they will not be trampled, and then ensuring, through an educational program, that they are not cut down as they mature.

The impact most likely to reduce the functional ability of a campsite is long-term erosion. While erosion was not directly measured in this study, tree-root exposure should provide some indication of the amount of erosion which has occurred on a site. When these sites are reexamined in 1984, we will have a better idea of the magnitude of long-term erosion. Informal observations suggest that severe erosion is rare because campsites are usually flat and because compaction reduces the detachability of soil particles, inhibiting erosion by surface runoff. Managers should, however, consider closing sites on which severe erosion is obvious. Those sites will eventually become unusable and, at that point, will be essentially impossible to rehabilitate.

The common assumption that deteriorated campsites are a result of overuse is true by definition; their deteriorated conditions are a result of "too much use." This study shows, however, that on the campsites studied, even a few nights of use per year are usually "too much," because this use causes most of the change which is likely to occur on a campsite.

Of the 27 impact measurements taken, only seven ncrease significantly in magnitude when campsite use ncreases over the range of use included in this study (that is, about a fiftyfold increase from less than one night per year to perhaps as much as 50 nights per year). Reductions in seedling density, vegetation cover, and duff depth, and increases in bare ground, bare area, trees with exposed roots, and floristic dissimilarity of the undergrowth become more pronounced as use increases. For loss of seedlings and vegetation cover, more than 75 percent of the change occurs, however, on light-use sites (fig. 19). In both cases, essentially any consistent annual use eliminates almost all of the seedlings and undergrowth. Thus, the statistically significant correlation with use does not seem to be very meaningful in either a biological or a managerial sense.

The variables which do show meaningful differences related to amount of use are bare ground, bare area, duff depth, floristic dissimilarity, and trees with exposed roots. As use increases from light to moderate amounts, organic litter continues to be removed, creating more bare ground and reducing duff depth, more tree roots are exposed, the central area devoid of vegetation increases in size; and the composition of the undergrowth continues to change. The size of the site also appears to increase, although this difference was not statistically significant.

As use surpasses moderate amounts--probably 10 to 20 nights per year--further increases in use cause little additional change in any of the variables other than duff depth, which continues to decrease dramatically with increased use.

The two major implications of these results are:

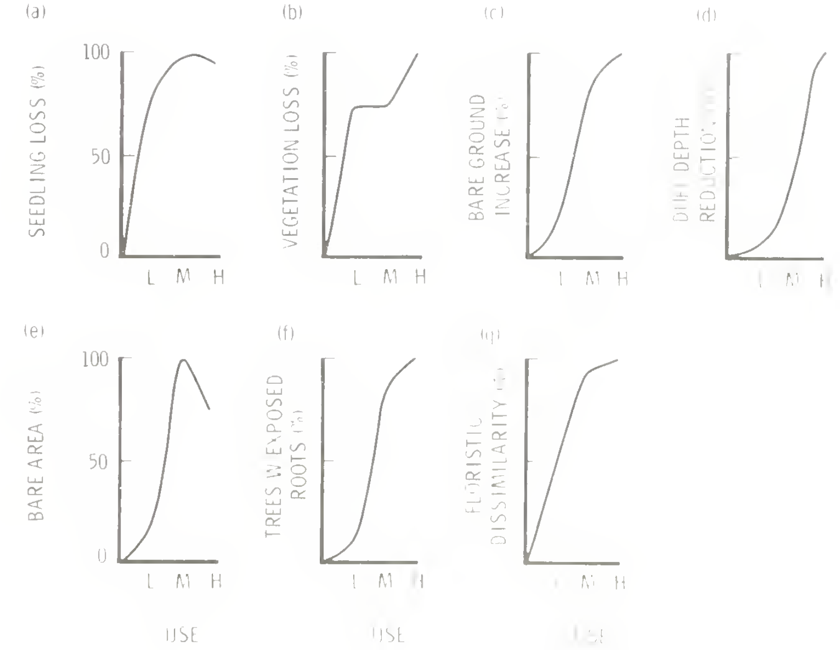
1. **Any** annually repeated use of campsites in this environmental situation will cause major onsite ecological changes.

2. Even fiftyfold use reductions will do relatively little to reduce campsite impacts.

These results only apply strictly to campsites near lakeshores, in *Abies lasiocarpa Vaccinium scoparium* forests of the Eagle Cap Wilderness, between 7,050 and 7,800 ft (2 150 and 2 400 m), on soils derived from granite bedrock. Similar results, however, were also reported by Fichtner (1980) in two Montana areas. Working in *Abies lasiocarpa* forests, with an undergrowth different from that in Eagle Cap on volcanic soils between 5,600 and 7,250 ft (1 700 and 2 200 m), he found that the only significant difference between light- and heavy-use sites was more exposed mineral soil on heavy-use sites.

Less fragile sites, such as low-elevation grasslands, could probably support more use before near-maximum levels of impact were achieved, but even on a low-elevation campground in Pennsylvania in "abandoned field" vegetation on deep, well-drained and productive silt loam flood plain soils, LaPage (1967) found that "the relationship between barren ground and cumulative man-days of use weakened and disappeared entirely" after the campground was 3 years old. More research is needed, but it appears clear that low levels of annual use are sufficient to cause most of the change which is likely to occur on a site. In relatively fragile high-elevation forests where a large proportion of wilderness campsites are located, this threshold appears to be no higher than a few nights of use per year.

In deciding how best to manage impacts, it is important to distinguish between impact intensity and the total aggregate area of impact. The conclusion of this study is that increasing or reducing use has very litle effect



igure 19.--The relationship between a-nount of use and amount of impact for hose variables with a statistically signifi-ant relationship: (a) percent reduction in eedling density; (b) percent reduction in egetative cover; (c) absolute increase in are ground; (d) percent reduction in duff epth; (e) bare area; (f) percent of trees with xposed roots; and (g) floristic dissimilarity. or each use category, the median change expressed as a percentage of the highest edian value for any use category.

on impact intensity, such as the magnitude of vegetation loss. Impact intensity can be more effectively minimized through improved campsite location and changes in visitor behavior.

The good condition of campsites in *Carex nigricans* meadows, in relation to forested sites, suggests the value of improved campsite location. Schreiner and Moorhead (1976), for example, have shown that the bare area of a campsite varies primarily with differences in vegetation. Many studies have shown that sites dominated by graminoids will usually suffer less vegetation loss than sites dominated by shrubs, such as those in this study. Managers might consider closing badly deteriorated sites, particularly those experiencing severe erosion, and opening new sites in more durable locations if necessary.

Visitor behavior can be changed through either minimum-impact camping education or regulations on type of use. A change in visitor behavior could eliminate the scarring and felling of trees and reduce some of the impact on soil chemistry through more careful use of fire and reduced pollution. On the other hand, it can do little to reduce vegetation and litter loss, the increase in bare ground, and soil compaction. These are inevitable consequences of use that are probably acceptable to most visitors, and, in most cases, pose no threat to the long-term usefulness or desirability of the campsite. It might be worth informing people of the problem with tree reproduction, however, in the hope that they might be careful to avoid trampling established seedlings.

Regulations on type of use could also be useful. If effective, a campfire prohibition could at least reduce damage to live trees and changes in soil chemistry. Keeping horses out of camp areas could reduce damage to trees, trampling of seedlings and other undergrowth, soil erosion and tree root exposure, and the size of campsites. Managers must decide if the potential for improvement in site conditions is worth the imposition of regulations.

In contrast to its limited effect on the intensity of impacts on existing campsites, use redistribution could have a pronounced effect on the total aggregate area of impacts. In areas where the amount of use is high enough that annually repeated use of campsites--even once a year in many places--is likely to occur, the area of impact could be reduced by encouraging repetitive use of fewer campsites. Use dispersal, in this situation, will usually increase the number of deteriorated campsites, with little compensatory improvement in conditions on former heavy-use sites. In the Eagle Cap Wilderness, for example, we heard complaints that many areas that were pristine a few years ago now have impacted campsites.

In areas that receive at least moderate amounts of use, such as all the lakes in this study reached by trail, repetitive use of few sites could probably be achieved b merely asking people to camp on previously used sites In most areas, it should not be necessary to officiall designate "legal" campsites, as many areas in the Nationa Park Service and Parks Canada do. Impacts could then b further reduced by closing some campsites in areas havin more campsites than necessary. Some lakes in the Eagl Cap Wilderness, for example, are encircled by more tha 100 campsites.

In areas where use is very low, dispersal could minimiz impacts. This policy requires extreme caution, howeve to insure that repeat use of sites does not occur before th site can recover. If it does, campsites will deteriorate ove time and the number and total aggregate area of campsit impacts will increase greatly.

A program of education in minimum-impact campin techniques is a prerequisite for a dispersal policy Visitors must be well educated **before** dispersal will work Many National Park Service and Parks Canada areas als prohibit fires in areas of dispersed camping to reduce th potential for campsite change. A final necessity is monitoring program capable of evaluating how well th program is working.

Many types of monitoring programs could be suggeste In highly dispersed-use settings, an inventory of sites showing signs of human use may be adequate. In areas which receive more consistent use, more information o site conditions would be desirable. If a manager does no need quantitative baseline data on specific campsite conditions, such as amount of vegetation cover, som modified[7] version of Frissell's condition classes wou provide a good measure of overall site condition. Whe combined with a measure of campsite or bare area, a inventory of campsites utilizing these two measures should enable the manager to identify trends both in th intensity of impact on individual sites and the areal sprea of impacts, either through the enlargement of sites or th proliferation of new campsites.

In many cases, however, managers may need mo detailed information on site conditions. Measurements this type are much more costly because they requi precise replication of previous measurements. O research suggests that percent bare ground measuremen are probably the most valuable because, unlike mo impact parameters, bare ground varies in response amount of use. Managers could attempt to manage use such a manner that bare ground does not increase. On the cost of precise replication is accepted, howeve additional measurements are relatively cheap a should be given serious consideration. In particul some measure of the campsite or bare area should be tak to supplement measures of impact intensity.

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[7] In addition to modifying some of the overly broad categories, managers may also need to redefine categories to more accurately refl their environmental situation. As suggested previously, a system of separa subjective ratings of ground vegetation, bare mineral soil, tree ro exposure, and soil erosion, the main criteria of Frissell's system, along w any additional parameters of concern, might be particularly useful.

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APPENDIX

THE DISTRIBUTION OF VASCULAR PLANT SPECIES ENCOUNTERED ON CAMPSITES OR CONTROL PLOTS.

	Frequency of occurrence[1]		Mean cover[2]		Mean relative cover[2]	
Species	Camps	Controls	Camps	Controls	Camps	Controls
Achillea millefolium	0	3	0	+	0	0.4
Agrostis thurberiana	1	0	+	0	0	+
Agrostis variabilis	4	4	+	.4	0.4	3
Allium validum	0	2	0	+	0	+
Antennaria alpina	4	16	0.2	1.0	1.5	1.6
Antennaria lanata	9	14	.3	2.1	2.5	3.4
Antennaria microphylla	0	1	0	+	0	.1
Arabis lyallii	1	0	+	0	.7	0
Arabis sp.	0	1	0	+	0	.1
Arenaria aculeata	0	5	0	.1	0	.4
Arnica cordifolia	1	3	0	.1	0	.3
Arnica mollis	1	5	.1	.5	.1	.5
Arnica parryi	0	1	0	+	0	+
Aster alpigenus	5	4	.1	.3	1.4	.4
Carex geyeri	1	2	.1	.1	.8	.2
Carex luzulina	0	1	0	+	0	+
Carex microptera	4	5	.2	1.7	2.6	1.7
Carex nigricans	1	2	+	.5	.1	.8
Carex rossii	19	20	.6	1.2	13.4	3.0
Carex scopulorum	0	2	0	0.5	0	0.5
Carex spectabilis[3]	5	6	0.3	.3	2.6	.7
Cassiope mertensiana	2	3	+	.3	+	.2
Castilleja chrysantha	1	6	+	.2	+	.2
Danthonia intermedia	3	6	+	.4	.4	.4
Deschampsia caespitosa	0	2	0	.6	0	.5
Dodecatheon alpinum	1	1	+	+	+	+
Epilobium alpinum	2	2	+	+	+	+
Epilobium angustifolium	1	6	+ .1	+	.1	
Epilobium sp.	0	1	0	+	0	+
Erigeron peregrinus	9	16	.1	1.2	2.9	1.5
Eriogonum flavum piperi	0	1	0	+	0	.3
Eriogonum ovalifolium	3	1	+	+	.3	+
Festuca viridula	4	14	.3	1.6	2.1	2.4
Gaultheria humifusa	1	5	+	.6	.1	.6
Gayophytum humile	2	1	+	+	+	+
Gentiana calycosa	0	2	0	.2	0	+
Hieracium albertinum	1	2	0	+	0	.3
Hieracium gracile	4	14	+	.3	3	.6
Holodiscus discolor	0	1	0	+	0	.1
Hypericum anagalloides	1	0	+	0	+	0
Hypericum formosum	0	6	0	0.4	0	0.4
Juncus drummondii	1	3	+	+	2	+
Juncus mertensianus	0	1	0	+	0	+
Juncus parryi	20	21	1.7	6.2	21.2	12.4
Ledum glandulosum	1	4	+	.7	+	6
Lewisia pygmaea	1	0	+	0	+	0
Ligusticum tenuifolium	4	5	+	1	+	1
Linanthastrum nuttallii	0	1	0	+	0	+
Lonicera utahensis	0	1	0	+	0	+
Luzula campestris	0	1	0	+	0	+
Luzula hitchcockii	7	9	.4	1.8	4.7	2.9
Muhlenbergia filiformis	9	10	2	9	2.5	7

Continued

THE DISTRIBUTION OF VASCULAR PLANT SPECIES ENCOUNTERED ON CAMPSITES OR CONTROL PLOTS.

	Frequency of occurrence[1]		Mean cover[2]		Mean relative cover[2]	
Species	Camps	Controls	Camps	Controls	Camps	Controls
Oryzopsis exigua	1	6	+	.1	.8	.5
Osmorhiza chilensis	0	1	0	+	0	+
Parnassia fimbriata	0	1	0	+	0	+
Pedicularis contorta	0	1	0	+	0	+
Penstemon fruticosus	0	2	0	+	0	.2
Penstemon rydbergii	1	4	0	.3	.4	.6
Phleum alpinum	4	4	+	.3	.2	.2
Phyllodoce empetriformis	12	18	.3	8.8	4.5	10.6
Poa annua	1	0	+	0	.1	0
Poa gracillima	0	1	0	+	0	+
Poa leibergii	0	1	0	+	0	.1
Poa sandbergii	0	1	0	+	0	+
Poa sp.	0	2	0	+	0	+
Polemonium pulcherrimum	1	4	+	0.1	+	0.4
Polygonum phytolaccaefolium	1	4	+	.2	1.2	.4
Potentilla diversifolia	0	1	0	+	0	+
Potentilla flabellifolia	5	6	.1	2.1	.9	1.8
Potentilla glandulosa	0	1	0	+	0	.1
Potentilla gracilis glabrata	0	1	0	+	0	+
Ranunculus eschscholtzii	0	2	0	+	0	+
Ranunculus populago	1	1	+	+	+	+
Sagina saginoides	2	0	.1	0	.9	0
Senecio cymbalarioides	0	2	0	.5	0	.3
Spergularia rubra	1	0	+	0	+	0
Trisetum spicatum	0	6	0	.4	0	.7
Trisetum wolfii	0	1	0	.2	0	.1
Vaccinium caespitosum	1	4	.1	.7	.5	1.5
Vaccinium scoparium	19	21	.6	19.1	12.6	26.4
Veratrum viride	1	2	+	+	.2	+
Veronica cusickii	9	14	.2	1.9	1.9	2.6
Veronica serpyllifolia	1	0	+	0	+	0
Veronica wormskjoldii	1	0	+	0	+	0
Viola adunca	3	5	+	.3	.1	.3

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[1] Number of sites out of a maximum of 22 on which the species was found.

[2] Mean cover is the actual canopy coverage of the species, while relative cover expresses actual cover as a percentage of the tot cover on the site. A plus (+) indicates less than 0.1 percent cover.

[3] This species was determined by Charles Feddema to be *C. tolmei* Boott, which Hitchcock and Cronquist (1973) consider to synonymous with *C. spectabilis*. Some authorities equate *C. tolmei* with *C. paysonis* Clokey (Hermann 1970).

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Cole, David N.
1982. Wilderness campsite impacts: effect of amount of use. USDA For. Serv. Res. Pap. INT-284, 34 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Subalpine lakeshore campsites were studied in the Eagle Cap Wilderness, Oreg. Light-use campsites had experienced almost as much alteration as moderate- and heavy-use sites. Sites set back from lakeshores had changed as much as lakeshore sites. Selected indicators of ecological change were evaluated. Implications of this research to management of wilderness campsites are discussed.

KEYWORDS: ecological impact, campsites, wilderness management

The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

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**Intermountain
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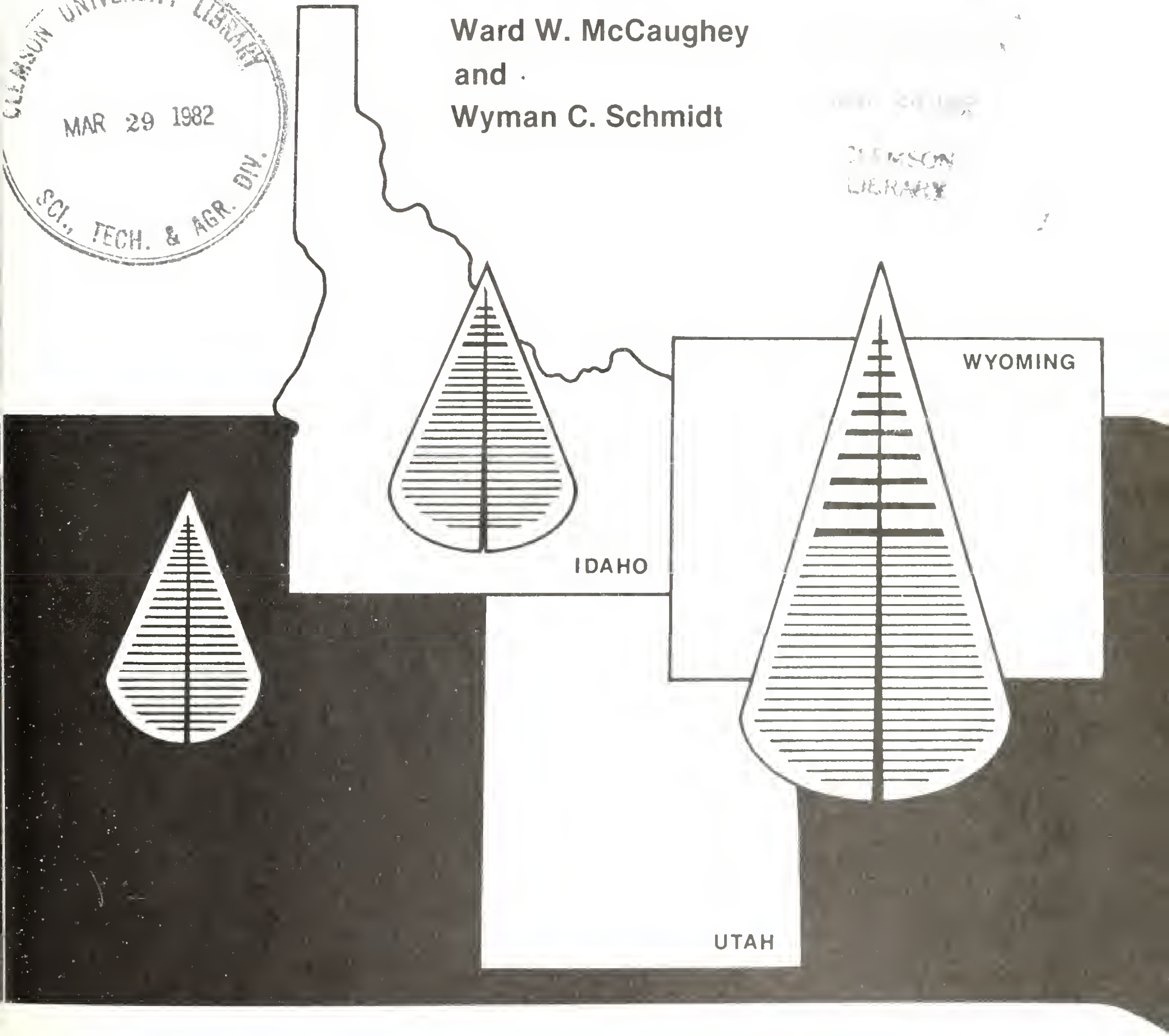
Research Paper
INT-285

March 1982

Understory Tree Release Following Harvest Cutting in Spruce-Fir Forests of the Intermountain West

Ward W. McCaughey
and
Wyman C. Schmidt



THE AUTHORS

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ACKNOWLEDGMENTS

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RESEARCH SUMMARY

This study is aimed at determining height growth response of understory Engelmann spruce *(Picea engelmannii)* and subalpine fir *(Abies lasiocarpa)* trees follo ing clearcutting and partial cutting. Understory trees, released 10 years earlier on four study areas—two in Utah and one each in Idaho and Wyoming—provided t data base. Both spruce and fir responded by substantially increasing their height growth after adjusting to their new environment—growth response was greates the clearcuts, intermedial in the partial cuts, and essentially missing in the uncut areas. Five-year pretre ment height growth and posttreatment basal area wer good predictors of posttreatment response of the und story trees. Fir responded sooner and more than spruc on both clearcuts and partial cuts. Understory trees responded in much the same pattern throughout all fo study areas.

CONTENTS

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Understory Tree Release Following Harvest Cutting in Spruce-Fir Forests of the Intermountain West

Ward W. McCaughey and Wyman C. Schmidt

INTRODUCTION

Successful management of the spruce-fir *(Picea engel- annii-Abies lasiocarpa)* forests of the Intermountain est depends on rapidly and adequately regenerating tover areas. Regeneration difficulties have plagued anagers of these forests. Difficulties are generally most vere in the high elevation forests of the region in south- n Utah with decreasing problems as you go north into e lower elevation forests of south-central Idaho (Roe d Schmidt[1]; Roe and others 1970). A number of silvi- ltural options using even- and uneven-aged anagement techniques are available—plant immedi- ely, direct seed, rely on natural regeneration, retain equate amounts of advance regeneration, or various mbinations of these. Depending on the particular cir- mstances, each has some advantages. One of the ost controversial, however, is the choice of "featuring vance regeneration." Controversy generally centers on e expected response of the advance regeneration to ease. How soon, how much, or will it respond?

There are indications from other areas that understory ruce and fir will respond once released from the over- od. For example, in northeast California on the Swain untain Experimental Forest, red fir *(Abies magnifica)* d white fir *(Abies concolor)* developed rapidly after ease even though they had been suppressed and had own slowly for over 40 years (Gordon 1973). Ferguson and Adams (1979), working with grand fir *(Abies grandis)* understory trees in north Idaho, found that 5-year height growth before release was the best predictor of height growth after release. Also, younger trees responded quicker, short trees more than tall trees, and undamaged trees sooner than damaged trees after release. Shade from scattered residual overstory trees was initially beneficial to release but detrimental to growth after trees adjusted to the new environment. Engelmann spruce and subalpine fir understory trees also responded well following release from overwood in other studies in north Idaho (Roe and DeJarnette 1965). Information about understory spruce and fir growth response in the Intermountain West is sparse, however.

Foresters are interested in cutting methods favoring advance reproduction since advance growth provides immediate growing stock, shade for subsequent seedings, some continuity of green forests, and some soil protection. If these understory trees will not release, however, their use for these purposes is questionable. Knowing when advance regeneration should be left and when it should be destroyed to provide growing space for subsequent reproduction is important for managing these forests.

This paper reports the first 10 years of a cutting methods study started in 1967 on four National Forests in the spruce-fir zone of the Intermountain area. It describes release of advance regeneration between even-aged (clearcuts) and uneven-aged (partial cuts) management systems and provides height growth predictions for forest managers (fig. 1A, B).

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[1] Roe, Arthur L., and Wyman C. Schmidt. 1964. Factors affecting natural eneration of spruce in the Intermountain region. USDA For. Serv. neo rep., 68 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

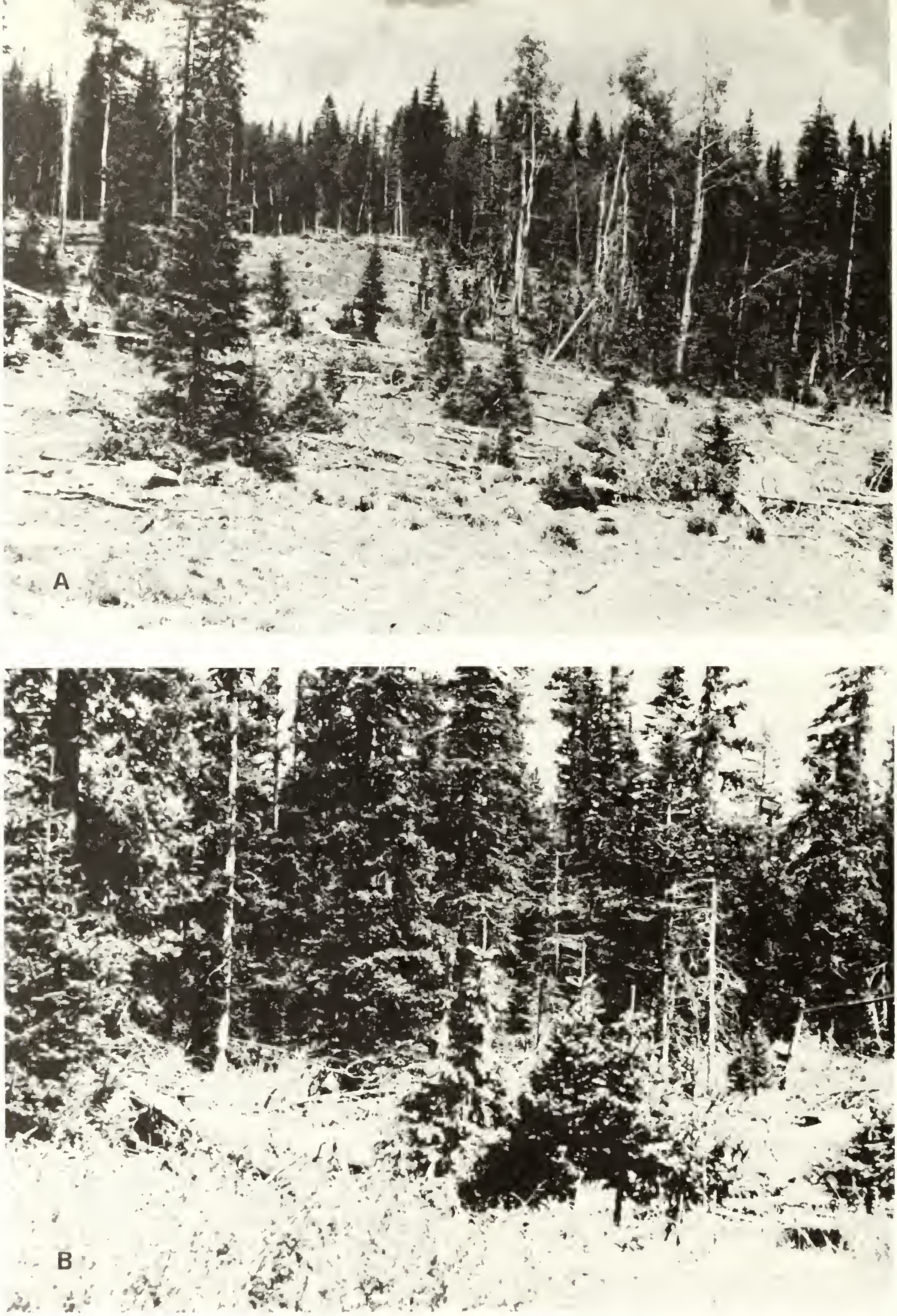

Figure 1.—Advance regeneration of Engelmann spruce and subalpine fir 10 years after harvest cutting treatments: A. Clearcut, Dixie National Forest; B. Partial cut, Uinta National Forest.

METHODS

tudy Areas

Four study area locations extending from southern tah to south-central Idaho were established in 1967. tudy plots were established in 5-acre (2-ha) clearcuts, artial cuts, and control areas on the Payette National orest in Idaho, the Teton (now Bridger-Teton) National orest in Wyoming, the Uinta National Forest in central tah, and the Dixie National Forest in southern Utah ig. 2).

ayette National Forest

The Payette study area is near Cloochman Creek on e McCall Ranger District, at about 6,000 feet (1 829 m) levation with a west to southwest exposure. Slopes ange from 0 to 30 percent and average around 10 ercent.

Soils are of granitic origin, are generally sandy loams, oderate to well drained, and slightly acid. Some of the utting units are bisected by small streams and contain oggy areas.

Composition of the virgin stand was 77 percent Engel- ann spruce, 18 percent subalpine fir, and 5 percent dgepole pine *(Pinus contorta)*. The mature stand was ver 200 years at the time of cutting.

The ages and sizes of the sample understory trees at e time of harvest on the Payette were:

		Average	Range
PRUCE	Age	37	6 to 102
	Height (ft)	3.4 (1.04 m)	0.3 to 12.1 (0.09 to 3.69 m)
R	Age	52	5 to 166
	Height (ft)	3.2 (0.98 m)	0.2 to 12.4 (0.06 to 3.78 m)

Three habitat types (h.t.) are represented on the area teele and others 1981):

ry — *Abies lasiocarpa/Xerophyllum tenax* h.t., mostly *Vaccinium scoparium* phase,
loist — *Abies lasiocarpa/Xerophyllum tenax h.t.,* *Vaccinium globulare* phase, and
let — *Abies lasiocarpa/Calamagrostis canadensis* h.t., *Ligusticum canby* phase.

Average basal areas remaining after the harvest cut- ngs were:

	Uncut forest	Partial cut	Clearcut
erage basal area			
ft^2/acre	129.0	29.0	7.0
m^2/ha	29.6	6.6	1.6

dividual point samples ranged from 0 to 250 ft^2 of basal ea per acre (0 to 57.4 m^2/ha). Remaining basal area thin the clearcuts was due to residual advance regener- ion.

Figure 2.—Location of spruce-fir understory release study areas in the Intermountain West: Payette, Teton, Uinta and Dixie National Forests.

Teton National Forest

The Teton study area is located in Teton County, Wyo., near East Leidy Creek on the Gros Ventre Ranger District at approximately 8,600 ft (2 621 m) elevation on generally north-facing slopes. Slopes range from 0 to 50 percent with some pitches up to 70 percent.

Soils are derived from Mesozoic sedimentary rock primarily limestone, sandstone, and shale. Moisture is adequate at all times of the year, and some areas have excessive soil moisture for ideal growing conditions, as evidenced by the increase of *Equisetum*. Drainage of the area varies from very poor to good.

The Teton has the largest variety of species found on any of the study areas. Stand composition was 85 percent Engelmann spruce, 8 percent subalpine fir, 3 percent lodgepole and limber pine *(Pinus flexilis)*, and 1 percent Douglas-fir *(Pseudotsuga menziesii)* at the time of harvesting.

The ages and sizes of the sample understory trees at the time of harvest were:

		Average	Range
SPRUCE	Age	65	7 to 168
	Height (ft)	3.5 (1.07 m)	0.3 to 10.8 (0.09 to 3.29 m)
FIR	Age	79	7 to 185
	Height (ft)	3.3 (1.01 m)	0.3 to 14.1 (0.09 to 4.30 m)

Stand age of the mature overwood at the time of cutting was between 200 and 300 years old. The general stand condition was good with only minor bark beetle problems in some of the windthrown spruce.

Three habitat types were mapped on the study site (Steele and others [In press]):

Dry — *Abies lasiocarpa/Vaccinium globulare* h.t.,
Moist — *Abies lasiocarpa/Actea rubra* h.t., and
Wet — *Abies lasiocarpa/Streptopus amplexifolius.*

Average basal areas remaining after the harvest cuttings were:

	Uncut forest	**Partial cut**	**Clearcut**
Average basal area			
ft²/acre	132.0	82.0	1.0
m²/ha	30.3	18.8	0.2

Individual point samples ranged from 0 to 280 ft² of basal area per acre (0 to 64.3 m²/ha). The clearcut basal area value was due to residual advance regeneration.

Uinta National Forest

The Uinta National Forest study area is in Wasatch County, Utah, on the Heber Ranger District. The plots are at Wolf Creek Pass at 9,500 ft (2 896 m) elevation on a northerly aspect with slopes from 10 to 30 percent.

Soils are generally well drained on the upper slopes with soil moisture increasing toward the lower base of the study areas. Small intermittent streams bisect the area.

The mature overstory stand consisted of 95 percent Engelmann spruce and 5 percent subalpine fir. Ages and sizes of the sample understory trees at the time of harvest were:

		Average	**Range**
SPRUCE	Age	71	5 to 170
	Height (ft)	3.9	0.2 to 12.6
		(1.19 m)	(0.06 to 3.84 m)
FIR	Age	68	16 to 144
	Height (ft)	2.9	0.3 to 11.5
		(0.88 m)	(0.09 to 3.51 m)

General stand condition was good with minimal windthrow and light bark beetle damage.

One habitat was found on the area—*Abies lasiocarpa/Berberis repens* h.t., *Berberis* phase (Pfister 1972).

Average basal areas remaining after the harvest cuttings were:

	Uncut forest	**Partial cut**	**Clearcut**
Average basal area			
ft²/acre	146.0	109.0	42.0
m²/ha	33.5	25.0	9.6

Individual point samples ranged from 0 to 230 ft² of basal area per acre (0 to 52.8 m²/ha). The large basal are value in the clearcuts was due to advance regeneration left on the site. Partial cut treatments were somewhat atypical in that they were small half-acre (0.2-ha) clearcuts randomly located throughout the 5-acre (2-ha) treatment block.

Dixie National Forest

The Dixie study units are located in Garfield County, Utah, on the Aquarius Plateau of the Escalante Ranger District at 10,300 ft (3 139 m) elevation on nearly level terrain.

Soils are glacial deposits overlaying basalt flows. Soil are gravelly, clay, and sandy loams, 12 to 21 inches (0.30 to 0.53 m) deep, with pH values of from 5 to 6.

Stand composition of the mature forest was 90 percer Engelmann spruce, 10 percent subalpine fir, and a few small scattered aspen *(Populus tremuloides)* clones. Overstory Engelmann spruce were even-aged while subalpine fir was uneven-aged, but not all-aged (Hanley and others 1975).

Ages and sizes of the sample understory trees at the time of harvest were:

		Average	**Range**
SPRUCE	Age	59	5 to 150
	Height (ft)	3.7	0.2 to 14.0
		(1.13 m)	(0.06 to 4.27 r
FIR	Age	57	8 to 126
	Height (ft)	4.0	0.2 to 11.8
		(1.22 m)	(0.06 to 3.60 r

General condition of the mature stand was good, but many snags indicated past beetle attacks. Recent bark beetle activity was light.

One habitat type, *Abies lasiocarpa/Ribes montigenun* h.t., *Ribes* phase (Pfister 1972) was found on the study area.

Average basal areas remaining after the harvest cuttings were:

	Uncut forest	**Partial cut**	**Clearcut**
Average basal area			
ft²/acre	141.0	40.0	6.0
m²/ha	32.4	9.2	1.4

Individual point samples ranged from 0 to 210 ft² of basal area per acre (0 to 48.2 m²/ha). Advance regeneration accounted for the clearcut basal area value. Partia cut treatments were somewhat atypical in that they we small half-acre (0.2-ha) clearcuts randomly scattered throughout the 5-acre (2-ha) treatment block.

tudy Design

Four study areas, one each on the Payette, Teton, inta, and Dixie National Forests were established with vo replications of three treatments (clearcut, partial cut, nd control) randomly located within each area. Engeliann spruce and subalpine fir advance regeneration om two height classes (1.0 to 4.5 ft [0.3 to 1.3 m] and 4.6) 15.0 ft [1.4 to 4.5 m]) was sampled at 10 randomly cated plots within each treatment. Sample trees met iree study criteria: (1) must be closest of that species nd height class to the plot center, (2) cannot be used for ore than one plot, and (3) must be at least one tree eight (mature stand) distance from treatment edge. ncut control trees were sampled to determine climatic fects. We measured annual height increment of the dvance regeneration to determine how it responded to lease after overwood removal. Sample trees were colcted and later measured in the laboratory. Stem ialysis was used to accurately measure yearly height owth for the previous 15-year period—the 5-year preeatment period and the 10-year posttreatment period. asal discs were used to age sample trees.

We also measured total tree height, live crown length, id diameter at breast height (d.b.h.). Overstory competion was measured by two methods: (1) crown density sing a spherical densiometer, and (2) volume/acre olume/ha) and basal area/acre (basal area/ha) using a isal-area gage (10-factor).

ialyses

Segmented regression using a special case (two-linear iase) of the general multiple phase regression technique (Johnson 1968) was used to date release response. iis technique is an overall least squares solution of two ted submodels each having their own least squares lution (Hudson 1966). Periodic height growth and time ere the dependent and independent variables, respecely.

Height growth models were developed for both Engeliann spruce and subalpine fir from each of the four ational Forests (Teton, Uinta, Dixie, and Payette) cause Bartlet's test of homogeneity showed highly sigificant differences between species and forests. This as based on the dependent variable, posttreatment -year height growth. The standard regression model ed was:

$$\hat{Y} = B_0 + B_1X_1 + B_2X_2 + \ldots B_nX_n$$

Each model was developed through step-wise regreson analysis techniques using the following variables:

ependent Variables

DHG = Posttreatment 10-year height growth (feet)

NPOHG = Natural log posttreatment 10-year height growth (feet)

Independent Variables

PRHG = Pretreatment 5-year height growth (feet)

POBA = Posttreatment basal area (ft^2/acre)

IH = Initial height (feet)

ICL = Initial crown length (feet)

ICR = Initial crown ratio $\left(\frac{\text{crown length (feet)}}{\text{total height (feet)}} \right)$

IA = Initial age

LNIH = Natural log initial height (feet)

LNICR = Natural log initial crown ratio $\left(\frac{\text{crown length (feet)}}{\text{total height (feet)}} \right)$

Initial age, height, and crown length were reconstructed using stem analysis techniques. Using step-wise regression, the F-statistic (0.01 significance level) and the improvement in R^2 were used to determine how much variance was explained by each of the variables entering into the model. Based on regression means and variances, a log function transformation was used to improve some models.

Although nearly all of the independent variables strengthened the regression models, 5-year pretreatment height growth and posttreatment basal area were generally the best predictors of 10-year posttreatment height growth. Fortunately, both variables are easily measured in the field and provide reasonable estimates of future height growth response. In light of this, we developed condensed models and tables using only these variables (appendix tables 2 through 5). It should be recognized, however, that the condensed models are less sensitive than the step-wise regression models shown for each of the forests in the following sections.

RESULTS

Results of the evaluations of all four study areas—the Payette, Teton, Uinta, and Dixie National Forests—were surprisingly consistent, considering distances between the study areas. Approximately 425 north-south air miles (684 km) separated the Payette and Dixie National Forests, and 325 east-west air miles (523 km) separated the Payette and the Teton National Forests. In spite of this geographical separation, understory tree components of the four study areas were very similar, with Engelmann spruce and subalpine fir predominating. Although lodgepole pine occurred on the Teton and Payette, limber pine on the Teton, and aspen on the Dixie, the small numbers of these species were insignificant from an advance regeneration management standpoint. Therefore, these results focus entirely on advance regeneration of Engelmann spruce and subalpine fir. Included are the evaluations of the following periods: 5 years prior to harvest cutting treatments, the first 5 years after treatments, and the 6- to 10-year period after treatments.

Models were developed to show 10-year height growth release of understory spruce and subalpine fir following varying harvest cutting intensities on the four study areas. Independent variables used in the models were: 5-year pretreatment height growth, posttreatment basal area, and initial age, height, crown length, and crown ratio.

Payette National Forest

Both spruce and subalpine fir on the Payette National Forest responded to release by increasing height growth over that of their pretreatment rate for both measurement periods—the 0- to 5- and 6- to 10-year periods. Height growth increase was greatest in clearcuts, intermedial in partial cuts, and essentially missing in uncut stands (fig. 3). Growth response was modest in the 0- to 5-year posttreatment period; but during the 6- to 10-year posttreatment period, both species in clearcuts grew about three and one-half times and in partial cuts, just over three times their pretreatment rates—both significantly greater than the controls, but not significantly different from each other.

A severe blowdown in 1969 on one partial cut created a near clearcut situation which may account for the relatively small difference in growth response between the partial cut and clearcut treatments. A minor amount of stand disturbance in the uncut controls from windthrow possibly accounted for minor increases in height growth in the 6- to 10-year posttreatment period.

The Payette was one of two study sites where Engelmann spruce height growth responded about equal to c better than subalpine fir in both the 0- to 5- and 6- to 10 year posttreatment periods (fig. 3). Both species gradually increased in height growth as time since treatment on both partial cuts and clearcuts increased.

Segmented regression results (fig. 4, 5) show upward height growth trends at the end of the 10-year posttrea ment period. We have nothing in these data to predict when this upward trend will level off.

Subalpine fir responded to release sooner than Enge mann spruce (fig. 4, 5). Segmented regression analyses show that it took fir 1 to 2 years and spruce 3 to 5 year to accelerate height growth. The only exception occurr in the partial cut where the upper height class (4.6 to 1 ft [1.4 to 4.5 m] tall) of spruce responded in a pattern similar to that of fir.

Subalpine fir of both height classes (1.0 to 4.5 ft [0.0 to 1.37 m] and 4.6 to 15.0 ft [1.38 to 4.57 m]) responded about the same time, but grew more and faster than th shorter fir on both clearcuts and partial cuts. Engelma spruce response patterns were similar to those of fir, b the time of response was inconsistent between tree si and stand treatments. Spruce height growth in the tall height class was greater but took place at rates simila to those of the shorter height class.

Some trees, particularly subalpine fir, exhibited a decline in height growth for a year or two after release fr overwood competition (fig. 4, 5). Upon adjustment to th

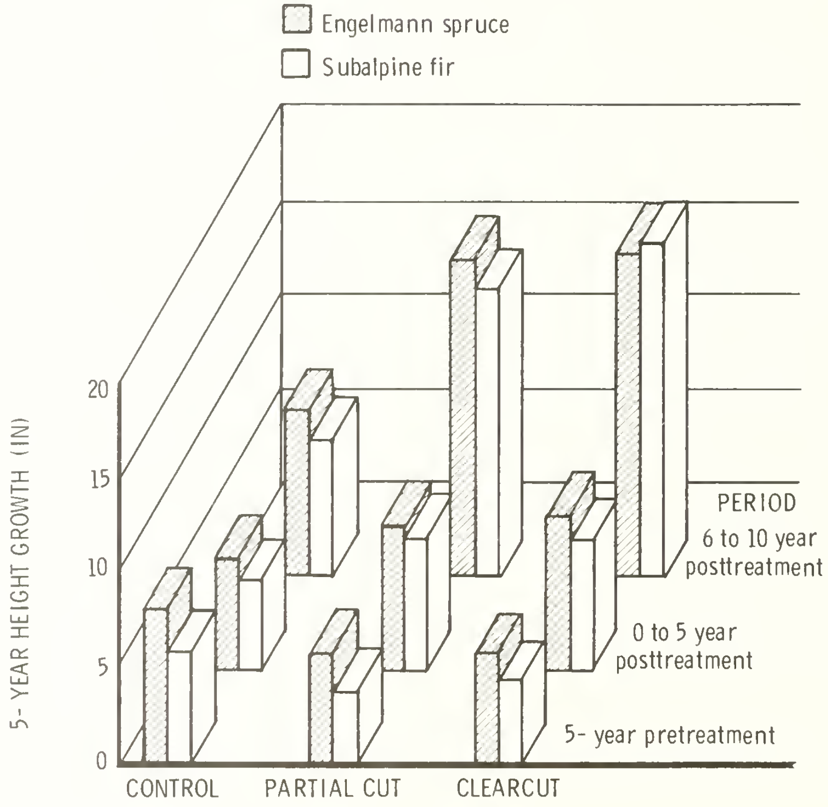

Figure 3.—Periodic height growth of understory Engelmann spruce and subalpine fir (height classes combined) 5-year pretreatment, 0- to 5-year posttreatment, and 6- to 10-year posttreatment on uncut controls, partial cuts, and clearcuts on the Payette National Forest.

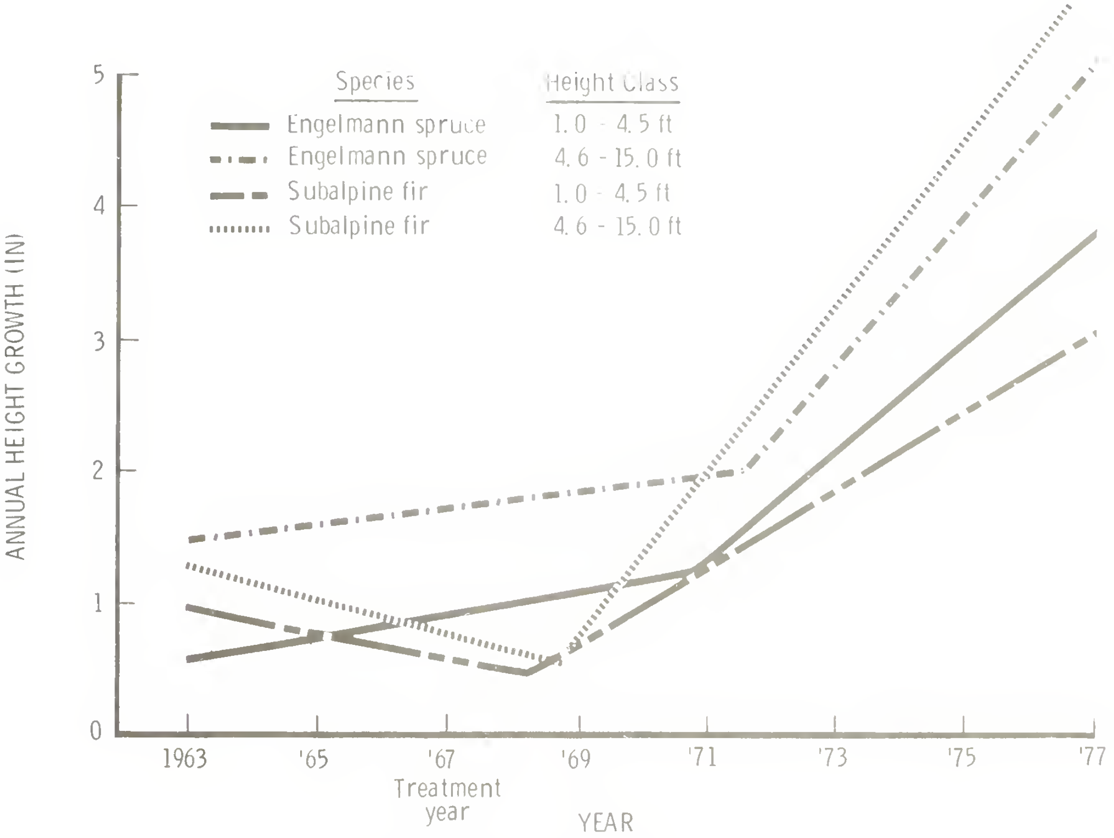

Figure 4 —Annual height growth of Engelmann spruce and subalpine fir on clearcuts on the Payette National Forest by year and height class. Lines are plotted from segmented regression values.

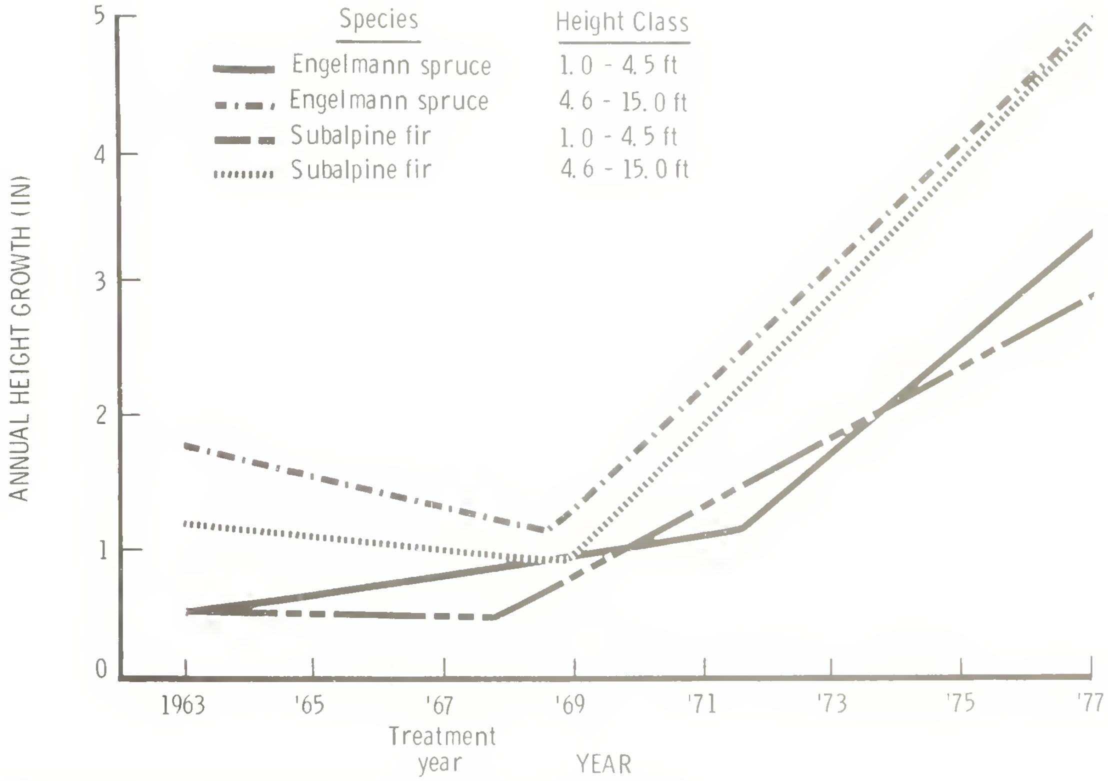

Figure 5.—Annual height growth of Engelmann spruce and subalpine fir on partial cuts on the Payette National Forest by year and height class. Lines are plotted from segmented regression values.

change in environment, however, the trees regained and subsequently exceeded their pretreatment growth rates.

Using variables described in the analysis section, height growth release models predicting 10-year posttreatment height growth for Engelmann spruce and subalpine fir on the Payette are:

Engelmann spruce:

$$\begin{aligned} POHG &= 1.7975 + 0.2078PRHG - 0.3207\,IH \\ &\quad - 0.0167POBA + 0.2622ICL \\ &\quad R^2 = 0.40 \qquad SSE = 0.9136 \qquad n = 79 \end{aligned}$$

Subalpine fir:

$$\begin{aligned} LNPOHG &= 0.6188 - 0.0111POBA \\ &\quad + 0.0534PRHG - 0.0041ICR \\ &\quad R^2 = 0.16 \qquad SSE = 0.6066 \qquad n = 77 \end{aligned}$$

Teton National Forest

Both Engelmann spruce and subalpine fir on the Teto National Forest responded significantly to release. Posttreatment height growth response was greatest in clearcuts, intermediate in partial cuts, and essentially none i the uncut controls (fig. 6). During the 6- to 10-year posttreatment period, trees in the clearcut grew an average c over four times their pretreatment growth and about twice that of their 0- to 5-year posttreatment period. Tree in the partial cut grew significantly less, about half that of trees in the clearcuts during the 6- to 10-year period, but still doubled their own pretreatment rate. A minor amount of windthrow in the controls prompted a slight increase of height growth in the 6- to 10-year period ove the pretreatment period.

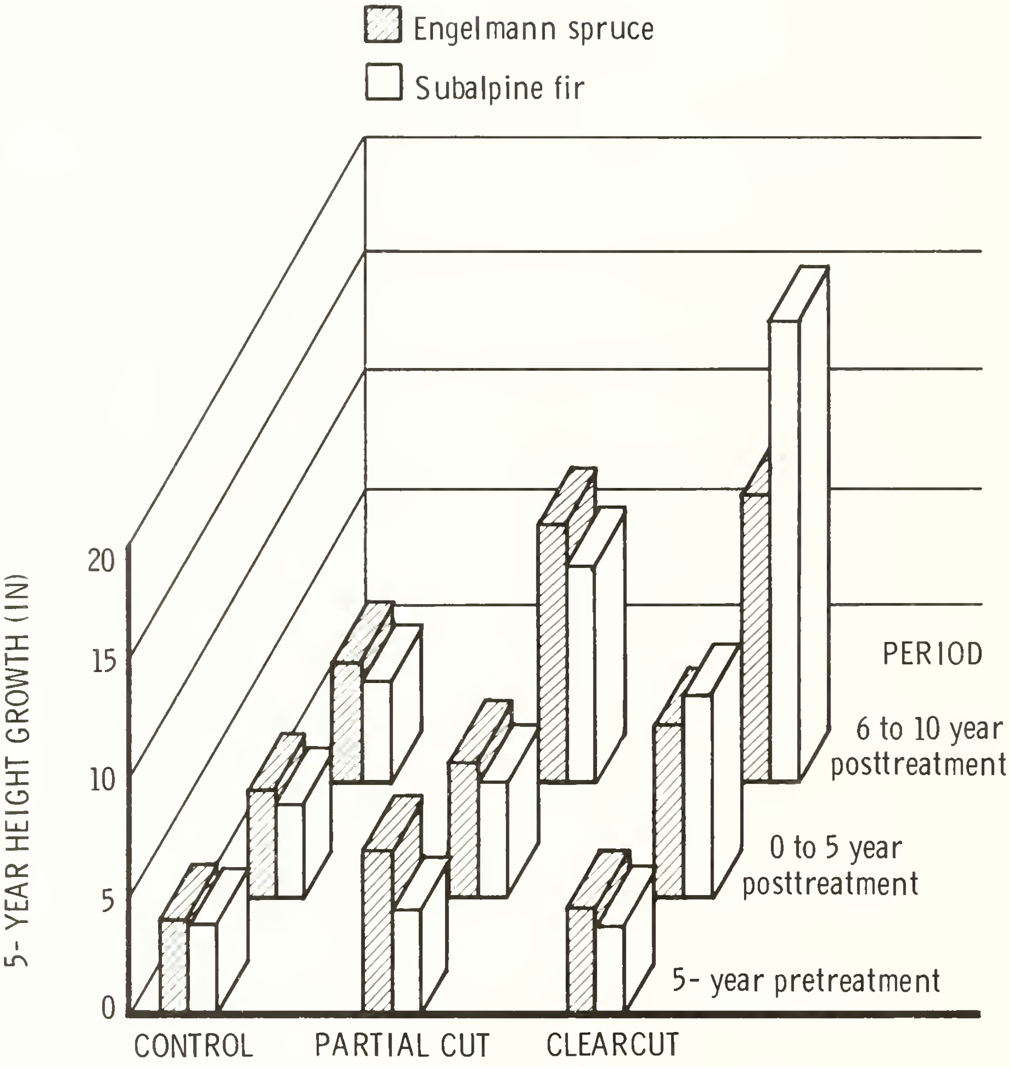

Figure 6.—Periodic height growth of understory Engelmann spruce and subalpine fir (height classes combined) 5-year pretreatment, 0- to 5-year posttreatment, and 6- to 10-year posttreatment on uncut controls, partial cuts, and clearcuts on the Teton National Forest.

Subalpine fir outgrew Engelmann spruce in height on clearcuts, but within each height class, they responded about the same on partial cuts (fig. 7, 8). Fir responded the first year after clearcutting, spruce 3 to 4 years later. This relationship was not apparent on partial cuts where taller trees (4.6 to 15.0 ft [1.40 to 4.57 m]) of both species responded 2 to 4 years later than shorter trees (1.0 to 4.5 ft [0.3 to 1.37 m]).

Taller trees of both species generally responded more than smaller trees. The substantial differences in growth response between clearcuts and partial cuts held true for both large and small trees.

As in the Payette, the upward trend in height growth was still apparent the 10th year of the study, and we do not know when this will level off.

Using variables described in the analysis section, height growth release models predicting 10-year posttreatment height growth for Engelmann spruce and subalpine fir on the Teton are:

Engelmann spruce:

$$\begin{aligned} \mathrm{POHG} &= 0.3379 + 0.1430\mathrm{PRHG} \\ &\quad - 0.0057\mathrm{POBA} + 0.0135\mathrm{ICR} \\ &\quad R^2 = 0.58 \qquad \mathrm{SSE} = 0.7495 \qquad n = 71 \end{aligned}$$

Subalpine fir:

$$\begin{aligned} \mathrm{LNPOHG} &= 0.4697 - 0.0087\mathrm{POBA} \\ &\quad + 0.1644\mathrm{LNIH} + 0.0253\mathrm{PRHG} \\ &\quad R^2 = 0.34 \qquad \mathrm{SSE} = 0.6288 \qquad n = 66 \end{aligned}$$

Uinta National Forest

Engelmann spruce and subalpine fir on the Uinta National Forest responded much like those on the Teton National Forest, with only modest increases in height growth in the 0- to 5-year posttreatment period, but significant increases in height growth during the 6- to 10-year posttreatment period over that of their pretreatment growth (fig. 9). Average growth of spruce and fir increased 5 to 6 times that of their pretreatment growth on both clearcuts and partial cuts. It should be noted, however, that pretreatment growth here was very low—only about an inch (2.5 cm) a year. In the 0- to 5-year posttreatment period, there were only minor increases in height growth. Trees on the clearcut grew the most; those in the partial cut were next in growth. Tree growth in the uncut controls remained essentially static.

Subalpine fir height growth was greater than Engelmann spruce on both clearcuts and partial cuts, particularly in the 6- to 10-year post-treatment period (fig. 9). This difference appears related to the time lag needed by the taller trees (4.6 to 15.0 ft [1.4 to 4.6 m]) to adjust to their new environment (fig. 10, 11). The shorter trees (1.0 to 4.6 ft [0.3 to 1.37 m]) show this relation as a function of slope differences. The pattern of response time with treatment and species showed no consistency. Response time ranged from 1 to 5 years after release. The larger trees responded generally later than smaller trees, but their overall height growth was more on both cutting treatments.

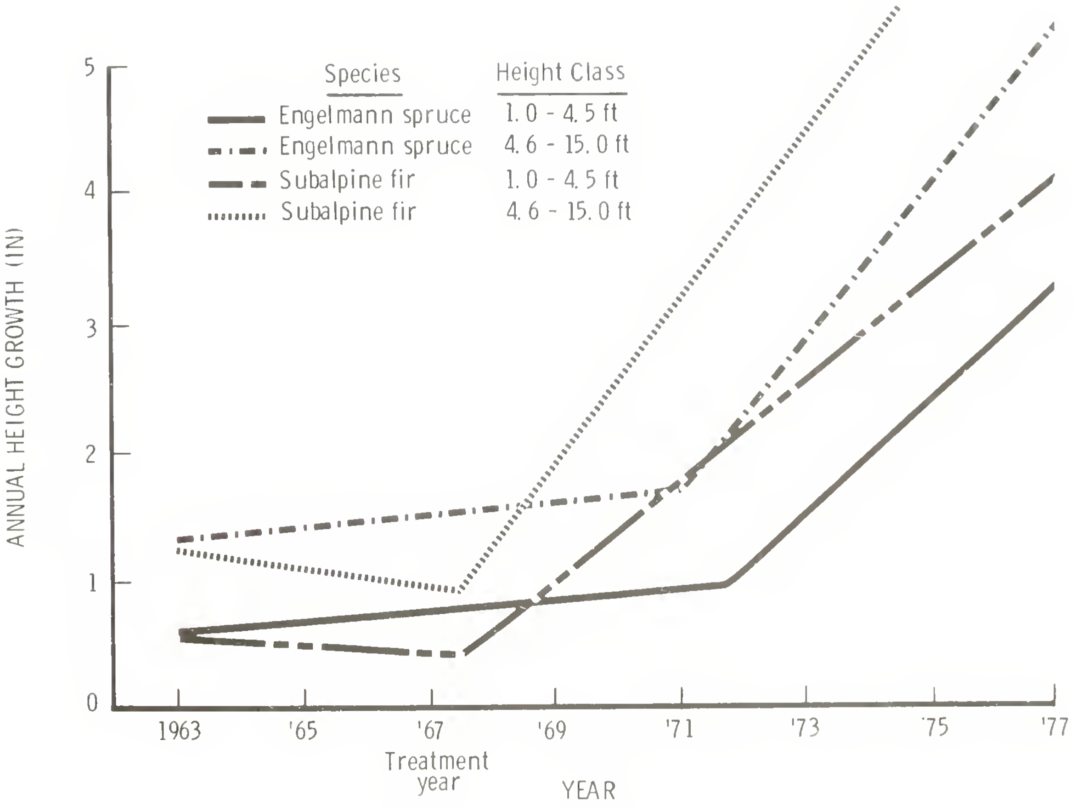

Figure 7.—Annual height growth of Engelmann spruce and subalpine fir on clearcuts on the Teton National Forest by year and height class. Lines are plotted from segmented regression values.

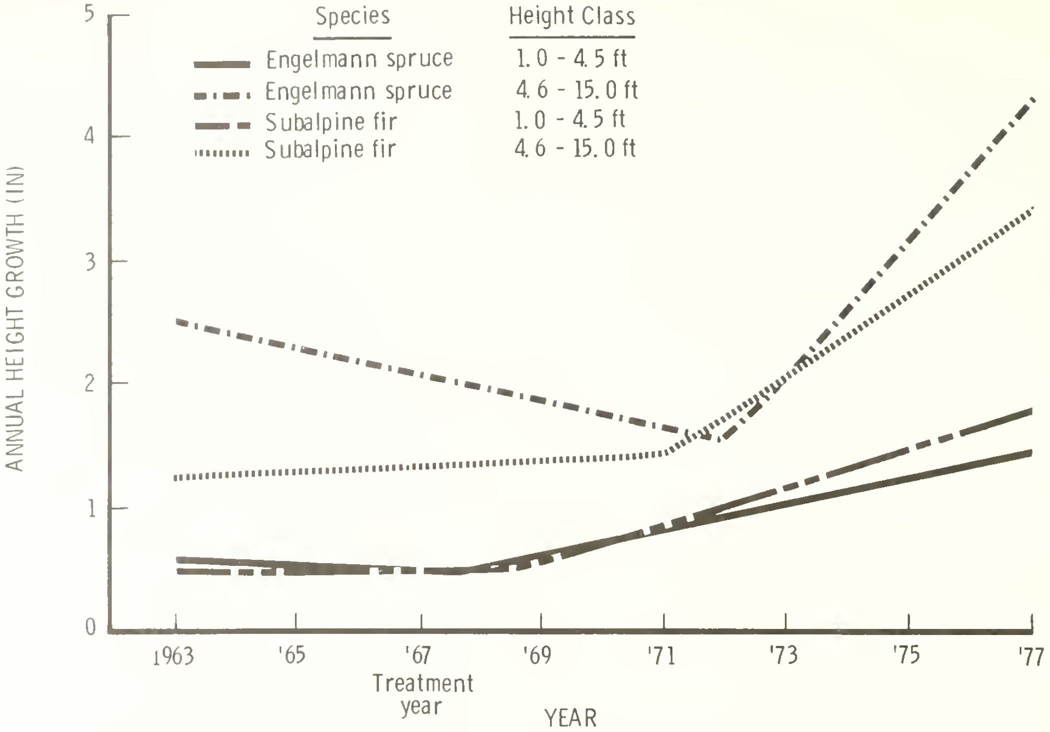

Figure 8.—Annual height growth of Engelmann spruce and subalpine fir on partial cuts on the Teton National Forest by year and height class. Lines are plotted from segmented regression values.

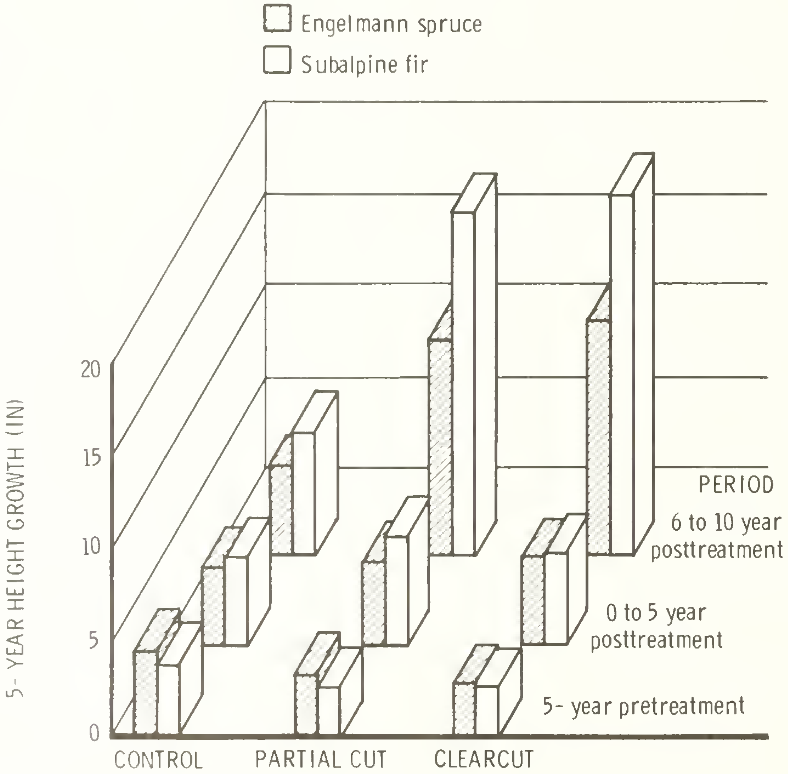

Figure 9.—Periodic height growth of understory Engelmann spruce and subalpine fir (height classes combined) 5-year pretreatment, 0- to 5-year posttreatment, and 6- to 10-year posttreatment on uncut controls, partial cuts, and clearcuts on the Uinta National Forest.

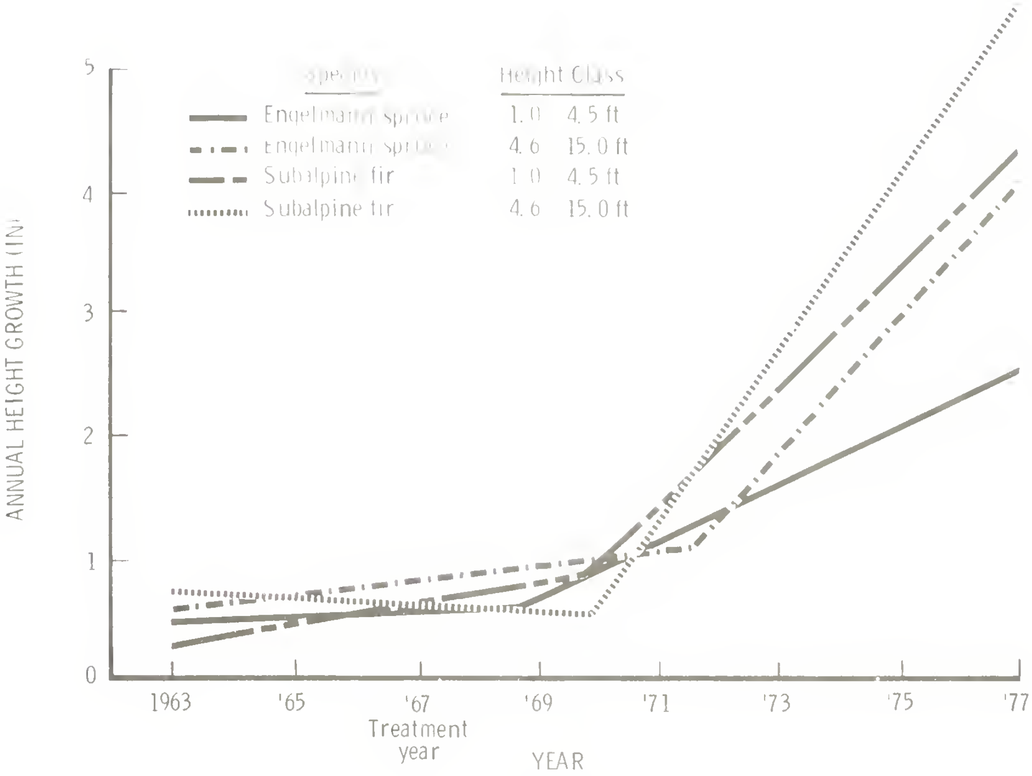

Figure 10.—Annual height growth of Engelmann spruce and subalpine fir on clearcuts on the Uinta National Forest by year and height class. Lines are plotted from segmented regression values.

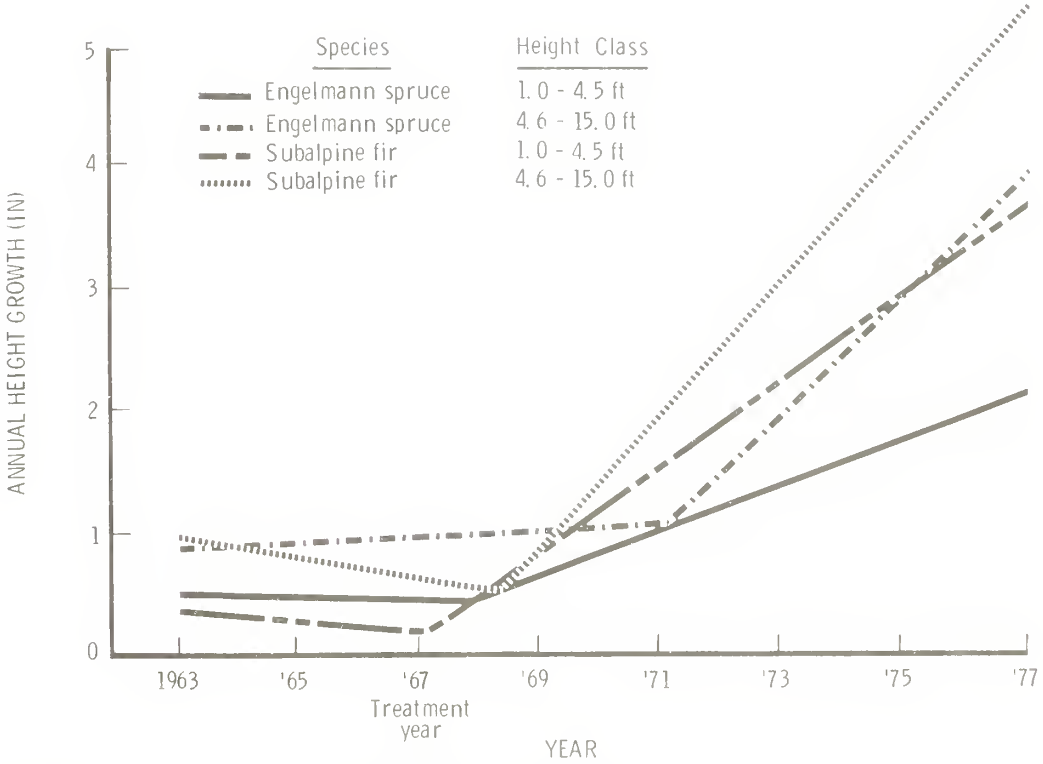

Figure 11.—Annual height growth of Engelmann spruce and subalpine fir on partial cuts on the Uinta National Forest by year and height class. Lines are plotted from segmented regression values.

The generally upward trend in height growth at the end of the 10-year period showed no signs of decelerating, and these data provide no indication of how long that upward trend will continue.

The nature of the cuttings on the Uinta study area likely explains why the differences between the clearcut and partial cut treatments were so small. The clearcuttings were conventional, but the partial cuttings are probably best described as group selection rather than single tree selection. The sample points were within the small group cuttings. These small group cuts created environmental conditions more like small clearcuts than of single tree selection.

Using variables described in the analysis section, height growth release models predicting 10-year posttreatment height growth for Engelmann spruce and subalpine fir on the Uinta are:

Engelmann spruce:

$$\begin{aligned} \text{POHG} &= 1.0574 + 0.1391\text{PRHG} \\ &\quad - 0.0073\text{POBA} + 0.0921\text{ICL} \\ &\quad R^2 = 0.27 \qquad \text{SSE} = 0.7339 \qquad n = 79 \end{aligned}$$

Subalpine fir:

$$\begin{aligned} \text{LNPOHG} &= 0.4621 - 0.0072\text{IA} \\ &\quad + 0.1360\text{LNIH} + 0.1477\text{LNICR} \\ &\quad R^2 = 0.11 \qquad \text{SSE} = 0.4867 \qquad n = 77 \end{aligned}$$

Dixie National Forest

Engelmann spruce and subalpine fir responded signi cantly in height growth during the 6- to 10-year posttrea ment period following both partial cutting and clearcutting on the Dixie National Forest (fig. 12). Trees that were averaging 2 to 3 inches (5 to 8 cm) annual height growth under pretreatment conditions averaged over 6 inches (15 cm) annually during the 6- to 10-year posttrea ment period.

Trees within clearcuts grew significantly faster than trees in partial cuts, more than doubling their pretreatment height growth, while those in the partial cut increased their height growth about 50 percent. Averag height growth during the 0- to 5-year posttreatment period was about the same or slightly less than the pretreatment growth on both cutting treatments. Dixie site conditions placed rigorous stresses on the trees while they adjusted to their new environment following treatment. Trees in uncut controls remained essentially stat in height growth for the 15-year measurement period.

Subalpine fir height growth was slightly greater than Engelmann spruce, but the differences were not significant (fig. 12). Delays in response of the trees were more function of tree size than species (fig. 13, 14). Small tre (1.0 to 4.5 ft [0.3 to 1.37 m]) of both species responded t first year on clearcuts. Small spruce on the partial cuts exhibited no significant release time. Larger trees (4.6 t 15.0 ft [1.4 to 4.57 m]) of both species delayed about 4 years on clearcuts and 2 years on partial cuts before th responded. During that 2- to 4-year delay period, they

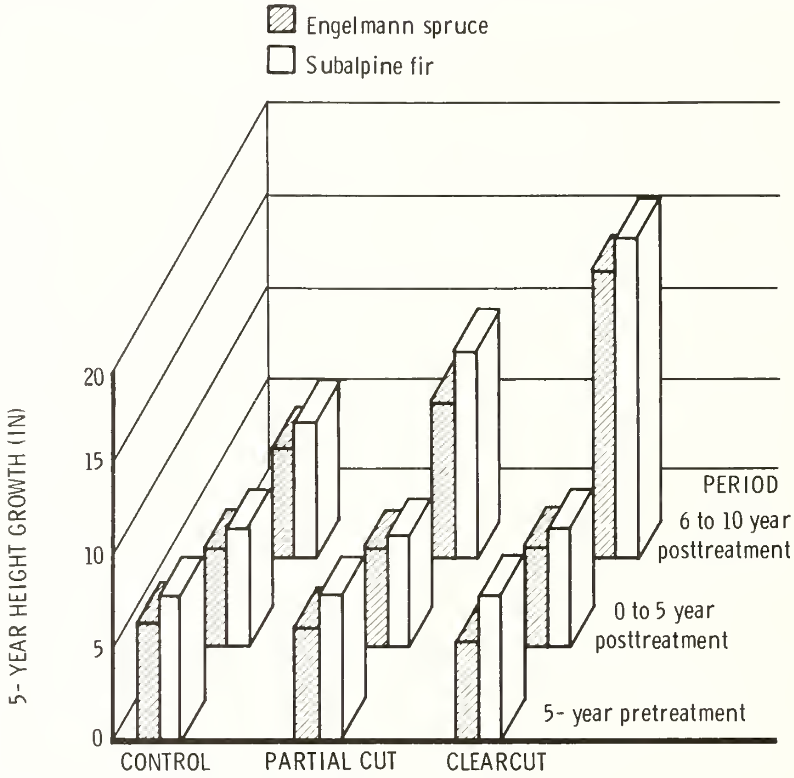

Figure 12.—Periodic height growth of understory Engelmann spruce and subalpine fir (height classes combined) 5-year pretreatment, 0- to 5-year posttreatment, and 6- to 10-year posttreatment on uncut controls, partial cuts, and clearcuts on the Dixie National Forest.

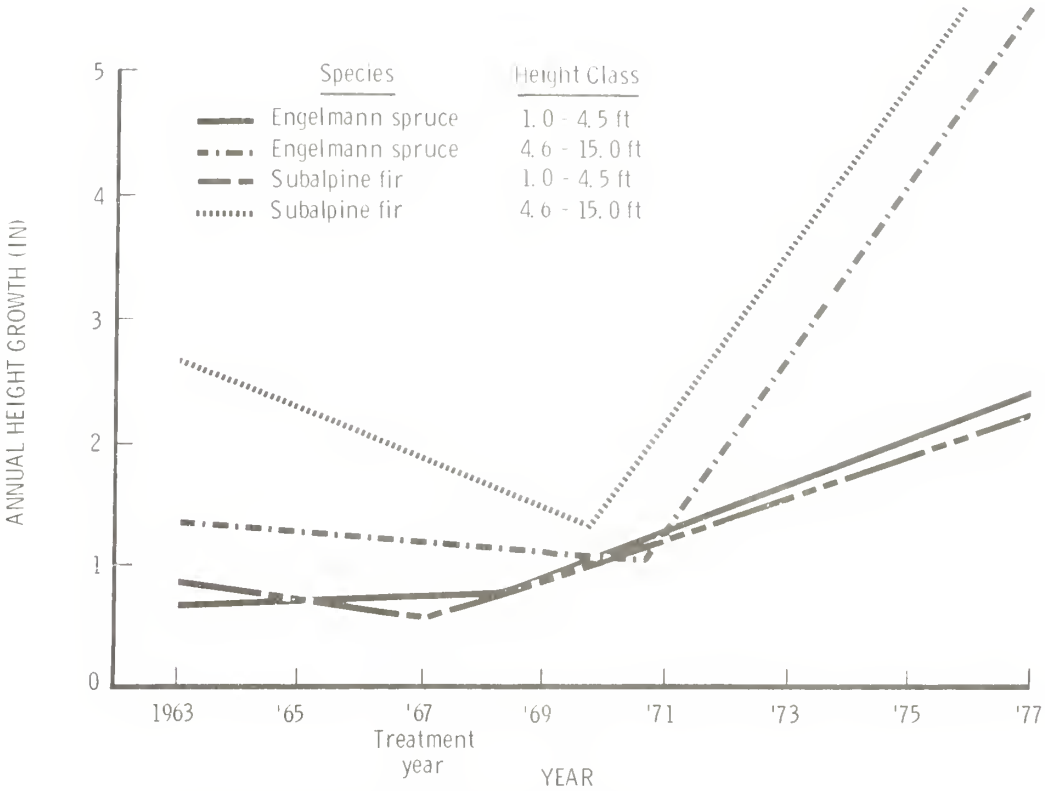

Figure 13.—Annual height growth of Engelmann spruce and subalpine fir on clearcuts on the Dixie National Forest by year and height class. Lines are plotted from segmented regression values.

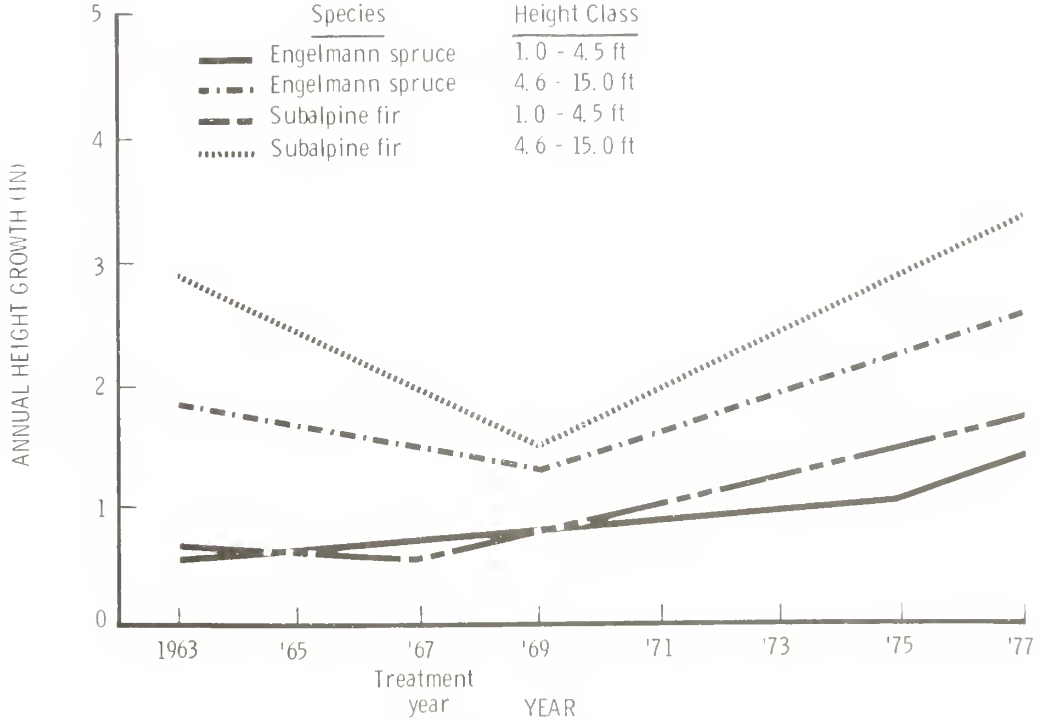

Figure 14.—Annual height growth of Engelmann spruce and subalpine fir on partial cuts on the Dixie National Forest by year and height class. Lines are plotted from segmented regression values

grew slower in height than they had prior to cutting. After the taller trees of both species adjusted to their new environment, they grew significantly faster than their shorter counterparts on both clearcuts and partial cuts.

The strong upward trend in height growth at the end of the 10-year posttreatment period is encouraging. The data, however, provide no basis for extrapolation since a leveling-off trend can be expected. When? is the question.

Using variables described in the analysis section, height growth release models predicting 10-year posttreatment height growth for Engelmann spruce and subalpine fir on the Dixie are:

Engelmann spruce:

$$\begin{aligned} \text{LNPOHG} &= 0.3652 - 0.0056\text{POBA} + 0.0608\text{PRHG} \\ &\quad - 0.0066\text{IA} + 0.2315\ \text{LNIH} \\ &\quad R^2 = 0.58 \qquad \text{SSE} = 0.4587 \qquad n = 78 \end{aligned}$$

Subalpine fir:

$$\begin{aligned} \text{LNPOHG} &= -1.8550 + 0.0483\text{PRHG} \\ &\quad + 0.0052\text{IA} + 0.3557\text{LNICR} \\ &\quad R^2 = 0.41 \qquad \text{SSE} = 0.5366 \qquad n = 73 \end{aligned}$$

GENERAL SUMMARY AND DISCUSSION

Height growth response of both Engelmann spruce ar subalpine fir understory trees exhibited a similar pattern throughout all four study areas. Their overall summary (fig. 15) shows the same general trends. From this summary the following generalizations can be made:

1. Both species responded to release by substantially increasing their height growth—greatest in clearcuts, intermedial in partial cuts, and essentially none in uncut controls—a direct relationship to the amount of residua overwood (fig. 15).

2. Trees on clearcuts grew an average of nearly four times faster during the 6- to 10-year posttreatment perio than before treatment. This compares with Gordon's (1973) findings in northern California. Trees in partial cu averaged about two and one-half times their pretreatme growth.

3. Although both spruce and fir responded by increasing their height growth during the first 5 years after trea ment, increases during this period were relatively minor compared to those in the 6- to 10-year period. This also compares with Gordon's (1973) findings for white and re fir.

4. Prior to release, spruce and fir height growth, with only minor exceptions, was about the same on all areas. Subalpine fir responded sooner, however, than Engelmann spruce on both partial cuts and clearcuts.

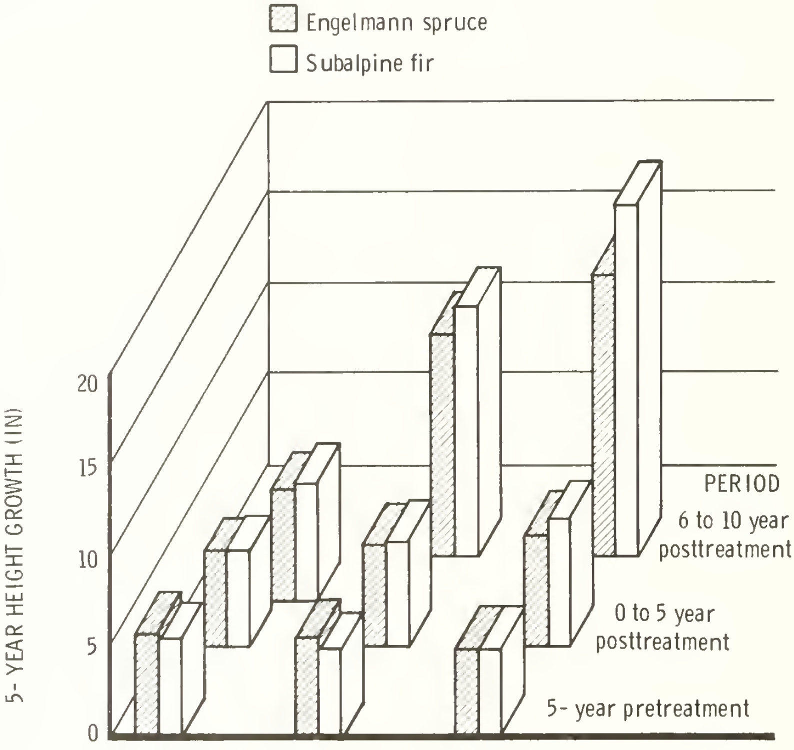

Figure 15.—Average periodic height growth of understory Engelmann spruce and subalpine fir 5-year pretreatment, 0- to 5-year posttreatment, and 6- to 10-year posttreatment on uncut controls, partial cuts, and clearcuts for the combined Payette, Teton, Uinta, and Dixie National Forests.

5. Height growth release began from 1 to 7 years after reatment, with fir response delayed an average of 1 to 2 ears, and spruce 3 to 4 years (table 1).

6. Taller trees (4.6 to 15.0 ft [1.4 to 4.57 m]) responded ater than shorter trees (1.0 to 4.5 ft [0.3 to 1.37 m])—fir bout 1 year later and spruce a little less than a year ater than their shorter counterparts.

7. Spruce and fir height growth of both height classes nd on both cutting treatments was still accelerating on ll four areas 10 years after treatment. An obvious unnown is how long the acceleration in growth will connue and when and at what rate it will level off. This will e a function of site and stand conditions and tree potenal. Advance regeneration of subalpine fir and ngelmann spruce in British Columbia grew substantially aster than some of its natural regeneration counterparts 1 years after site treatment (Herring and McMinn 1980). his comparison, however, was somewhat clouded ecause natural regeneration occurred where excessive carification had deteriorated the site. Based on observaons by Roe and DeJarnette (1965), increased height rowth may continue for at least 25 to 30 years. There is ome European evidence that spruce and fir "can endure rown competition over several decades without it inibiting their later growing capabilities" (Assmann 1970). ssmann goes on to present some response data that ndicate that once released, spruce and fir height growth ssentially parallels the growth of trees that have been ee to grow.

8. A factor, not well identified in this study, is the long-erm effect of logging damage. Although some of our ample trees were damaged during logging, we found no vidence of rot in our evaluations. Ten years may be inufficient time, however, for rots to become apparent nder these cold conditions.

9. Understory tree height growth within the uncut controls remained virtually constant on all four study areas during the observed 15-year period. Some control trees showed a slight decline in growth over time, and some a slight increase where there had been minor disturbances, but both of these exceptions were minor.

10. Average ages of the understory trees were much higher than one would expect for trees under 15 ft (4.57 m) tall—spruce averaged 68 years and fir 74 years on the four study areas, with a total age range of 5 to 195. Sixty-eight percent of the spruce and fir sampled were in the age range between 31 to 104 years and 38 to 109 years, respectively. This compares well with the age and successional data from earlier work in southern Utah (Hanley and others 1975). Height and age were poorly correlated.

11. With the best combinations of area, treatment, and species, annual height growth the 10th year after treatment averaged about 6 inches (15.2 cm). The overall average the 10th year was about 4.5 inches (11.4 cm) on clearcuts and 3.2 inches (8.13 cm) on partial cuts. As pointed out earlier, however, height growth was still increasing at the end of the observation period. We do not have data for comparing this advanced regeneration growth with that of subsequent natural or artificial regeneration from the immediate study areas. Hanley and Pfister,[2] however, measured natural and planted regeneration on the Dixie National Forest in the proximity of our study area. Here, 8-year-old plantations of spruce have reached 2 ft (0.61 cm) in height and current annual increments are approaching 6 inches (15.2 cm). Natural regeneration in the same period had reached a height of 1 ft (30.5 cm) with annual increments of about 3 inches (7.6 cm). Nearby, on the Fishlake National Forest, 5-year-old planted spruce averaged 20 inches (51 cm) in height.[3]

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[2] Hanley, Donald P., and Robert D. Pfister. Germination and seedling survival of Engelmann spruce on the Dixie National Forest. [In process.]

[3] Data from files of USDA Forest Service, Intermountain Region, Division of Timber Management, Ogden, Utah.

MANAGEMENT IMPLICATIONS

Nearly all mature spruce-fir forests have an understory of advance regeneration that some managers regard as a hindrance to, and others regard as their salvation for, posttreatment management. As Roe and others (1970) concluded, advance regeneration should be evaluated before harvesting to determine whether it qualifies as acceptable growing stock and has management potential. One of the unknowns has been the response potential of these understory trees. This study begins to help define this response for the first 10 years after harvesting. It reports that these understory trees do show substantial response after they have adjusted to their new environment; that they respond in relation to the amount of residual overwood; that their previous 5-year's growth tells much about their response potential; that they are probably a lot older than thought; and that even though height growth increases dramatically percentagewise, their absolute growth, even after 10 years of release, is modest.

Some advantages of using advance regeneration for at least part of the new stand after harvest cutting are:

1. It serves as immediate growing stock.
2. It provides shade needed for supplemental natural and artificial regeneration.
3. It may provide sufficient continuity of "green" forest to help meet wildlife cover and esthetic objectives.
4. Soil protection is afforded by retaining at least some forest cover.
5. Time needed to grow merchantable-sized trees may be reduced.
6. It reduces the amount of site preparation needed for subsequent natural and artificial regeneration.
7. Species diversity may be enhanced.

Some disadvantages of featuring advance regeneration in management are:

1. Logging damage to the advance regeneration predisposes it to long-term disease problems.
2. Subalpine fir is usually the predominant advance regeneration, but has more disease and insect problems and less management potential than spruce.
3. Advance regeneration is already physiologically old and thus prone to insect and disease problems associated with old age.
4. Featuring advance regeneration often encourages disgenic practices.
5. It may shortsightedly be used on sites where more intensive management practices are justified.
6. Harvesting costs are increased because of the need to protect the advance regeneration.
7. Site preparation needed for subsequent regeneration is made more difficult.

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APPENDIX

Table 1.—Average number of years after harvesting before height growth response started by harvest treatment, species, and height class

Treatment	Species	Height class 1.0 to 4.5 ft (0.3 to 1.31 m)	 4.6 to 15.0 ft (1.4 to 4.5 m)	Average
		Years to respond		
Clearcut	Spruce	2.8	4.3	3.6
	Fir	1.2	1.9	1.6
Partial cut	Spruce	3.4	3.1	3.2
	Fir	0.7	2.3	2.5
	Average	2.0	2.9	2.5

Table 2.—Ten-year height growth projections of released understory spruce and fir following harvest cutting on the Payette National Forest[1] [2]

Posttreatment basal area	Five-year pretreatment height growth (ft) 0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
Ft^2	*Feet*							
				Engelmann Spruce				
0	2.0	2.4	2.9	3.3	3.7	4.1	*4.5*	*5.0*
40	1.3	1.7	2.2	2.6	3.0	3.4	*3.8*	*4.3*
80	.6	1.0	1.5	1.9	2.3	2.7	*3.2*	*3.6*
120	—	*.4*	*.8*	*1.2*	*1.6*	*2.0*	*2.5*	*2.9*
160	—	—	*.1*	*.5*	*.9*	*1.3*	*1.8*	*2.2*
$Y = 1.5979 + 1.6838X_1 - 0.0174X_2$				($R^2 = 0.28$)				(SSE = 0.99)
				Subalpine Fir				
0	2.0	2.3	2.5	2.8	3.0	*3.3*	*3.5*	*3.8*
40	1.5	1.8	2.0	2.3	2.5	*2.8*	*3.0*	*3.3*
80	1.0	1.2	1.5	1.7	2.0	*2.2*	*2.5*	*2.8*
120	*.5*	*.7*	*1.0*	*1.2*	*1.5*	*1.7*	*2.0*	*2.2*
160	—	*.2*	*.5*	*.7*	*1.0*	*1.2*	*1.5*	*1.7*
$Y = 1.7867 + 1.0013X_1 - 0.0130X_2$				($R^2 = 0.10$)				(SSE = 1.04)

---

[1] Y = 10-year posttreatment height growth, feet.
X_1 = pretreatment 5-year height growth, feet.
X_2 = posttreatment basal area, square feet.

[2] Values in italics are outside the range of data.

Table 3.—Ten-year height growth projections of released understory spruce and fir following harvest cutting on the Teton National Forest[1] [2]

Posttreatment basal area	Five-year pretreatment height growth (ft)							
	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
Ft²				*Feet*				
				Engelmann Spruce				
0	1.4	1.9	2.4	2.8	3.3	3.8	4.2	4.7
40	1.2	1.6	2.1	2.6	3.0	3.5	4.0	4.4
80	.9	1.4	1.9	2.3	2.8	3.2	3.7	4.2
120	.7	1.1	1.6	2.1	2.5	3.0	3.4	3.9
160	*.4*	*.9*	*1.3*	*1.8*	*2.3*	*2.7*	*3.2*	*3.7*
$Y = 0.9762 + 1.8590X_1 - 0.0065X_2$				($R^2 = 0.54$)				(SSE = 0.78)
				Subalpine Fir				
0	2.2	2.4	2.7	2.9	3.1	3.4	*3.6*	*3.9*
40	1.7	1.9	2.2	2.4	2.6	2.9	*3.1*	*3.4*
80	1.2	1.4	1.7	1.9	2.1	2.4	*2.6*	*2.9*
120	.7	.9	1.2	1.4	1.7	1.9	*2.1*	*2.4*
160	.2	.4	.7	.9	1.2	1.4	*1.6*	*1.9*
$Y = 1.9556 + 0.9473X_1 - 0.0124X_2$				($R^2 = 0.30$)				(SSE = 1.00)

---

[1] Y = 10-year posttreatment height growth, feet.
X_1 = pretreatment 5-year height growth, feet.
X_2 = posttreatment basal area, square feet.

[2] Values in italics are outside the range of data.

Table 4.—Ten-year height growth projections of released understory spruce and fir following harvest cutting on the Uinta National Forest[1] [2]

Posttreatment basal area	Five-year pretreatment height growth (ft)							
	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
0800 *Ft²*				*Feet*				
				Engelmann Spruce				
0	1.6	2.1	2.6	3.2	3.7	*4.2*	*4.7*	*5.2*
40	1.4	1.9	2.4	2.9	3.4	*3.9*	*4.4*	*4.9*
80	1.1	1.6	2.1	2.6	3.1	*3.6*	*4.1*	*4.6*
120	.8	1.3	1.8	2.3	2.8	*3.3*	*3.8*	*4.3*
160	*.5*	*1.0*	*1.5*	*2.0*	*2.5*	*3.0*	*3.6*	*4.1*
$Y = 1.1268 + 2.0282X_1 - 0.0070X_2$				($R^2 = 0.24$)				(SSE = 0.74)
				Subalpine Fir[3]				

---

[1] Y = 10-year posttreatment height growth, feet.
X_1 = pretreatment 5-year height growth, feet.
X_2 = posttreatment basal area, square feet.

[2] Values in italics are outside the range of data.

[3] Neither pretreatment height growth or posttreatment basal area were good predictors of subalpine fir response on the Uinta. See the RESULTS section for the equation that best describes this response.

Table 5.—Ten-year height growth projections of released understory spruce and fir following harvest cutting on the Dixie National Forest[1] [2]

Posttreatment basal area	Five-year pretreatment height growth (ft)							
	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
Ft^2	*Feet*							
	Engelmann Spruce							
0	1.7	2.0	2.2	2.5	2.8	3.1	*3.4*	*3.7*
40	1.4	1.7	2.0	2.3	2.5	2.8	*3.1*	*3.4*
80	1.1	1.4	1.7	2.0	2.3	2.5	*2.8*	*3.1*
120	.8	1.1	1.4	1.7	2.0	2.3	*2.6*	*2.8*
160	.6	.8	1.1	1.4	1.7	2.0	*2.3*	*2.6*
$Y = 1.3830 + 1.1480X_1 - 0.0070X_2$				($R^2 = 0.41$)				(SSE = 0.73)
	Subalpine Fir							
0	1.4	1.7	2.0	2.3	2.6	2.9	3.2	3.5
40	1.3	1.6	1.9	2.2	2.5	2.8	3.1	3.5
80	1.2	1.6	1.9	2.2	2.5	2.8	3.1	3.4
120	1.2	1.5	1.8	2.1	2.4	2.7	3.0	3.3
160	1.1	1.4	1.7	2.0	2.3	2.6	2.9	3.2
$Y = 1.0972 + 1.2160X_1 - 0.0019X_2$				($R^2 = 0.35$)				(SSE = 1.03)

[1] Y = 10-year posttreatment height growth, feet.
X_1 = pretreatment 5-year height growth, feet.
X_2 = posttreatment basal area, square feet.

[2] Values in italics are outside the range of data.

McCaughey, Ward W., and Wyman C. Schmidt.
1982. Understory tree release following harvest cutting in spruce-fir forests of the Intermountain West. USDA For. Serv. Res. Pap. INT-285, 19 p. Intermt. Forest and Range Experiment Station, Ogden, Utah 84401.

This paper describes 10-year response of understory Engelmann spruce and subalpine fir following partial cutting and clearcutting of the overwood. This study in forests of Idaho, Wyoming, and Utah demonstrated that both spruce and fir understory trees responded to release by increasing in height growth slightly in the first 5-year, and substantially in the second 5-year post-harvest period. Trees responded more in the clearcuts than in the partial cuts.

KEYWORDS: *Picea engelmannii, Abies lasiocarpa,* advance regeneration, release response, understory tree release, overwood removal

The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

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**Intermountain
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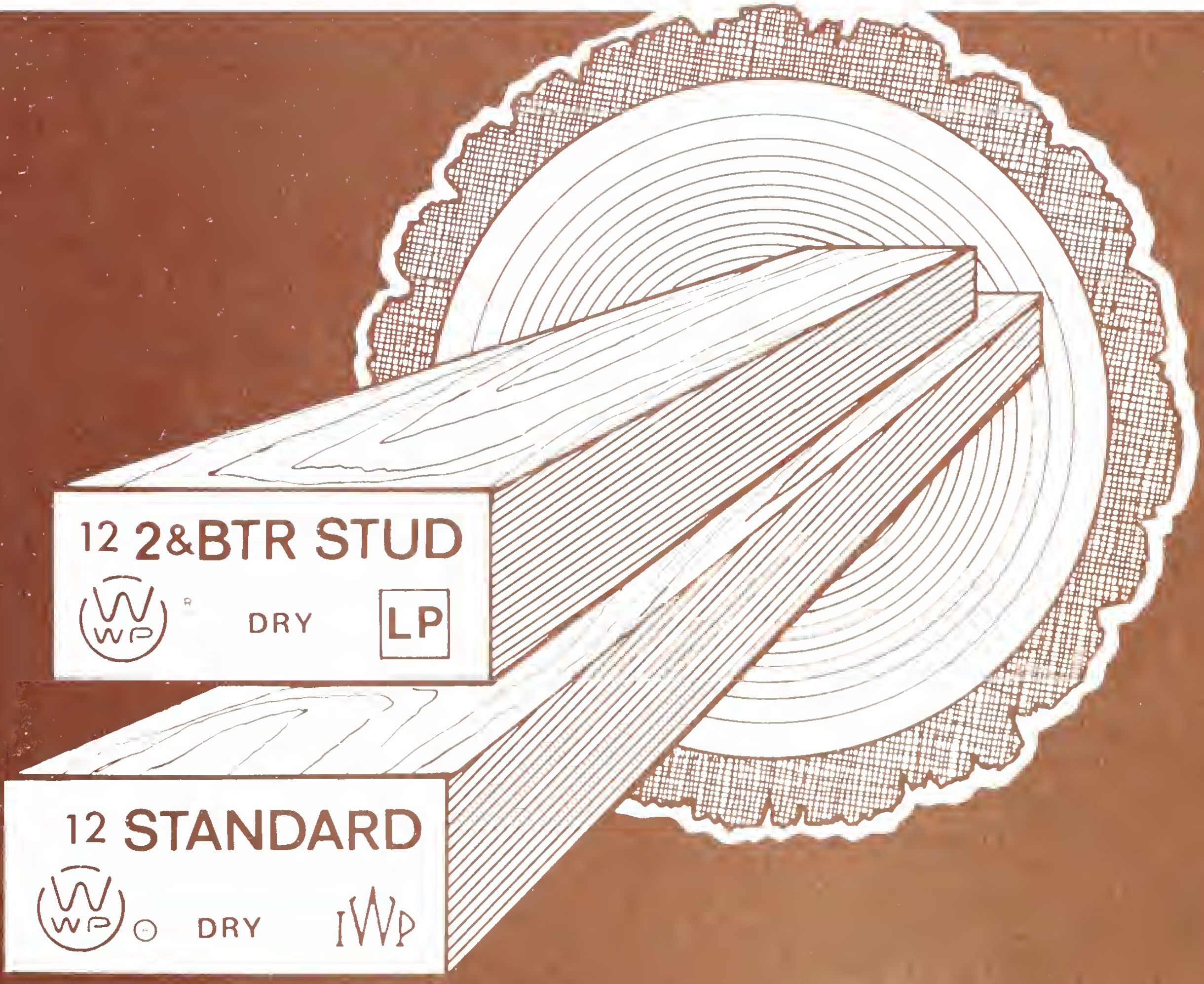
Research Paper
INT-286

January 1982

Evaluation of Dimension Lumber Made from Dead-Tree Logs

David P. Lowery and Roy F. Pellerin



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RESEARCH SUMMARY

Dimension lumber made from dead lodgepole and western white pine was evaluated nondestructively by the E-computer, and stress-wave testing methods. The same material was then tested on edge to failure. Analysis of the test data showed that the modulus of elasticity could be predicted fairly well by the nondestructive methods, and the results from the two methods were closely related. Test results showed no marked differences in moduli of elasticity between lumber cut from dead trees and lumber cut from live trees.

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David P. Lowery and Roy F. Pellerin

INTRODUCTION

The Northern Rocky Mountain area contains a large number of dead trees, primarily lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) and western white pine (*Pinus monticola* Dougl.) that were killed by insect and disease epidemics. Some of these dead trees are being harvested as a part of green-timber sales. Thus logs from dead trees and green trees are mixed for processing and the resulting lumber is mixed for sales and use. The design loads of dimension lumber used in construction are based on the strength properties of green-tree lumber. There is, then, an urgent need to determine the comparable strength properties of dead-tree dimension lumber. As more of the dead trees are utilized, strength property knowledge becomes of greater importance.

Sinclair and coworkers (1979) found that the modulus of rupture and modulus of elasticity may be significantly reduced by incipient decay and associated sapstain as early as 2 months following foliage discoloration in beetle-killed southern pine. The report emphasizes the need for additional information on the strength characteristics of dead-tree lumber. The Rocky Mountains are colder and drier than the South and Atlantic seaboard; therefore, beetle-killed lodgepole and western white pine trees often remain standing and free of decay for years after their death.

As a part of its wood research program which relies on destructive test machinery, Washington State University has developed nondestructive testing equipment and procedures. The equipment measures the modulus of elasticity, from which corresponding values of the modulus of rupture can be assigned (Marra and others 1966; Pellerin 1965). Studies indicate that nondestructive testing can be used to evaluate log and lumber quality (Galligan and others 1967; Pellerin and Kern 1974). The availability of this nondestructive and destructive testing equipment provided an opportunity to investigate the strength properties of dead-tree dimension lumber.

The objectives of this study were: to obtain nondestructive data for dimension lumber from dead lodgepole and western white pine trees; to test to failure a sample of the dead-tree lumber; and to establish the relationship between nondestructive and destructive test values.

TEST PROCEDURE

Dimension lumber of two species of dead trees, lodgepole pine and western white pine, was used in this study. The lodgepole pine lumber was obtained from a sawmill in western Montana and the white pine lumber from a sawmill in northern Idaho.

Logs for both species were cut from trees that had been dead for various periods of time. The lodgepole logs were segregated in the mill yard and processed through the mill as a batch in accordance with the mill's usual operating procedure; however, the production of dimension lumber was favored. Both nominal 2 by 4's and 2 by 6's (5 by 10 cm and 5 by 15 cm) were made from the logs All the dimension lumber produced from the batch of dead logs was set aside at the green chain. The lumber was not graded, but as the sample included all the pieces from the log batch, the grade distribution was considered representative of material made from dead tree logs. The distribution by size and length of the 148-piece sample was as follows:

Nominal size	Length in feet				
	16 (4.9 m)	14 (4.3 m)	12 (3.7 m)	10 (3.1 m)	8 (2.4 m)
2 × 6 (5 × 15 cm)	8	10	12	8	
2 × 4 (5 × 10 cm)	20	27	40	20	3
Total	28	37	52	28	3

The dead white pine logs were obtained from trees included in a grade recovery study for the species. A variety of boards as well as 2 by 4 (5 by 10 cm) dimension lumber was cut from the logs. All of the grade recovery study material was kiln dried, surfaced, and graded. The dimension lumber from the dead trees was sampled at the dry chain after the pieces had been sorted into piles by grade. An effort was made to select representative pieces that had various types of defects and also to distribute the pieces by length and grade. The distribution of the 238-piece sample by grade is shown in the following tabulation:

Grade	Length in feet				
	16 (4.9 m)	14 (4.3 m)	12 (3.7 m)	10 (3.1 m)	8 (2.4 m)
Construction and better	38	10	8	2	3
Standard	28	29	19	3	1
Utility	32	13	11	5	0
Economy	14	5	9	8	0
Total	112	57	47	18	4

The two lumber samples were transported by truck to the university. Here, tests indicated the lodgepole sample was too wet for evaluation so the material was stickered and piled in a greenhouse-type dryer for approximately 3 months. The white pine sample was also stickered and piled indoors for a few weeks to permit the pieces to attain equilibrium moisture content before testing. The moisture content of all lumber at the time of test was 6 to 7 percent. The lodgepole lumber was surfaced to nominal size before testing.

After conditioning, each board was nondestructively evaluated with the E-computer, the stress-wave equipment, and the static bending method. The E-computer calculates the modulus of elasticity of a board from its resonant frequency while supported near its ends. The longitudinal stress-wave method determines the modulu of elasticity of the board from the velocity of propagatio of a stress wave passing longitudinally through the boa and the density of the board (Pellerin 1965; Kaiserlik an Pellerin 1977).

After nondestructive testing, each board was tested o edge to failure in flexure according to ASTM D198 standards (ASTM 1974). Specimens were cut from each piece for determination of moisture content and specifi gravity. Percentage of moisture content was determine by the ovendrying method and the specific gravity was based on green volume and weight.

RESULTS AND DISCUSSION

A summary of the nondestructive and destructive test for lodgepole pine by size and length is shown in table For the 2-by-6-inch (5-by-15-cm) lumber the average modulus of elasticity by the computer method (Ec) was 1.38×10^6 (9.5 GPa), with a range in values from 0.91×10^6 to 2.04×10^6 (6.27 to 14.07 GPa); the average modulus of elasticity by the stress wave method (Esw) was 1.67×10^6 (11.5 GPa), with a range from 0.98×10^6 to 2.66×10^6 (6.76 to 18.34 GPa) and the modulus of elasticity by the static bending method (Es) was 1.31×10^6 (9.0 GPa), with a range in values from 0.76×10^6 to 2.6×10^6 (5.24 to 17.93 GPa). The average modulus of rupture was 4,984 pounds per square inch (psi) (34 363 kilopascals [kPa]). The Wood Handbook (1974) reports a average modulus of rupture value of 5,500 psi (38 921 kPa) and an average modulus of elasticity value of 1.08×10^6 psi (7.4 GPa) for lodgepole pine.

Table 1.—Results of nondestructive and destructive tests of lodgepole pine dimension lumber made from dead trees

Size	Length	No. of pieces	Average				
			Moisture content	Modulus of rupture	Modulus of elasticity		
					Computer	Stress wave	Static
Inches (cm)	*Feet (m)*		*Percent*	*Psi*	*Million psi*		
2 × 6 (5 × 15)	10 (3.1)	8	7.44	6,085	1.50	1.82	1.37
	12 (3.7)	12	7.98	5,386	1.38	1.72	1.47
	14 (4.3)	10	7.71	3,944	1.26	1.51	1.14
	16 (4.9)	8	7.51	4,583	1.41	1.66	1.24
Average			7.70	4,984 (34 363 kPa)	1.38 (9.5 GPa)	1.67 (11.5 GPa)	1.31 (9.0 GPa)
2 × 4 (5 × 10)	8 (2.4)	3	6.87	6,793	1.43	1.72	1.48
	10 (3.1)	20	6.52	4,695	1.23	1.49	1.17
	12 (3.7)	40	6.67	4,992	1.28	1.55	1.21
	14 (4.3)	27	6.96	5,789	1.30	1.61	1.29
	16 (4.9)	20	6.97	5,831	1.36	1.57	1.32
Average			6.77	5,331 (36 756 kPa))	1.29 (8.9 GPa)	1.56 (10.7 GPa)	1.25 (8.6 GPa)

For the lodgepole 2 by 4 (5 by 10 cm) lumber, the average Ec was 1.29 × 10^6 (8.9 GPa), with a range from 0.75 × 10^6 to 1.90 × 10^6 (5.17 to 13.1 GPa) the average Esw was 1.56 × 10^6 (10.7 GPa), with a range from 0.87 X 10^6 to 2.23 × 10^6 (6.00 to 15.38 GPa); and the average Es was 1.25 × 10^6 (8.6 GPa), with a range from 0.49 × 10^6 to 1.90 × 10^6 (3.38 to 13.10 GPa). The average modulus of rupture was 5,331 psi (36 756 kPa).

The results of the nondestructive and destructive tests for western white pine are summarized by piece length in table 2. The average Ec was 1.54 × 10^6 (10.6 GPa), with a range from 0.54 × 10^6 to 2.49 × 10^6 (3.72 to 17.17 GPa); the average Esw was 1.81 × 10^6 (12.5 GPa) and the range from 0.64 × 10^6 to 2.79 × 10^6 (4.41 to 19.24 GPa) and the average Es was 1.29 × 10^6 (8.9 GPa), with a range from 0.58 × 10^6 to 2.14 × 10^6 (4.00 to 14.75 GPa). The average modulus of rupture was 4,557 psi (31 419 kPa). For western white pine, the Wood Handbook (1974) reports an average modulus of rupture value of 4,700 psi (32 405 kPa) and an average modulus of elasticity value of 1.19 × 10^6 psi (8.2 GPa).

The white pine dimension lumber had been graded and the results, summarized by this characteristic, are shown in table 3. The table shows a decrease in average nondestructive and destructive test values associated with the visual grades, construction grade having the best values, economy grade the poorest.

Table 2.—Results of nondestructive and destructive tests on western white pine dimension lumber cut from dead-tree logs

				Average			
					Modulus of elasticity		
Size	Length	No. of pieces	Moisture content	Modulus of rupture	Computer	Stress wave	Static
Inches (cm)	*Feet (m)*		*Percent*	*Psi*		*Million psi*	
2 × 4 (5 × 10)	8 (2.4)	4	6.0	3,972	1.57	1.84	1.44
	10 (3.1)	19	6.0	4,031	1.39	1.76	1.31
	12 (3.7)	46	6.0	4,003	1.55	1.86	1.37
	14 (4.3)	57	6.0	5,102	1.57	1.86	1.34
	16 (4.9)	112	6.0	4,616	1.54	1.77	1.23
Average			6.0	4,557 (31 419 kPa)	1.54 (10.6 GPa)	1.81 (12.5 GPa)	1.29 (8.9 GPa)

Table 3.—Results of nondestructive and destructive tests on western white pine dimension lumber, by grade, cut from dead-tree logs

			Average			
					Modulus of elasticity	
Grade	No. of pieces	Moisture content	Modulus of rupture	Computer	Stress wave	Static
		Percent	*Psi*		*Million psi*	
Construction	57	6.0	5,719	1.63	1.86	1.40
Standard	84	6.0	4,964	1.65	1.91	1.39
Utility	62	6.0	3,653	1.41	1.68	1.14
Economy	35	6.0	3,286	1.35	1.70	1.14
Average		6.0	4,557 (31 419 kPa)	1.54 (10.6 GPa)	1.81 12.5 GPa)	1.29 (8.9 GPa)

The test results for both species were subjected to regression analysis (tables 4 and 5) for the lodgepole and western white pine, respectively. In these tables the r² values are a measure of the variation explained by the regression equations and indicate the predictive capability of the equations. For the lodgepole pine lumber, the Ec and Esw test results had an r² of 0.90 for 2-by-6-inch (5-by-15-cm) pieces and an r² of 0.88 for the 2-by-4-inch (5-by-10-cm) lumber. Ec versus Es and Esw versus Es bo had an r² of 0.76. The lowest r² values were obtained when the nondestructive test data were used to predict the modulus of rupture.

Table 4.—Results of regression analyses of nondestructive and destructive test data of lodgepole pine dimension lumber made from dead-tree logs

Size	Variables		Number of specimens	Regression equation			
	Abscissa	Ordinate		Intercept	Slope	r^2	r
2 × 6 in (5 × 15 cm)	E-computer Ec	E-stress wave Esw	38	-0.038	1.237	0.90	0.95
	E-computer Ec	E-static Es	38	-.360	.976	.76	.87
	E-computer Ec	Modulus of rupture Mor	38	-632.9	4067.0	.46	.68
	E-stress wave Esw	E-static Es	38	.059	.750	.76	.87
	E-stress wave Esw	Modulus of rupture Mor	38	-578.4	3328.9	.53	.73
2 × 4 in (5 × 10 cm)	E-computer Ec	E-stress wave Esw	110	.132	1.106	.88	.94
	E-computer Ec	E-static Es	110	-.130	1.608	.76	.87
	E-computer Ec	Modulus of rupture Mor	110	-2597.1	6174.5	.51	.71
	E-stress wave Esw	E-static Es	110	-.093	.860	.69	.83
	E-stress wave Esw	Modulus of rupture Mor	110	-2158.2	4829.6	.43	.66

Table 5.—Results of regression analyses of nondestructive and destructive test data from western white pine dimension lumber made from dead trees

Size	Variables		Number of specimens	Regression equation			
	Abscissa	Ordinate		Intercept	Slope	r^2	r
2 × 4 in (5 × 10 cm)	E-computer Ec	E-stress wave Esw	238	0.417	9.906	0.81	0.90
	E-computer Ec	E-static Es	238	.148	.756	.64	.80
	E-computer Ec	Modulus of rupture Mor	238	-1063.2	.756	.32	.57
	E-stress wave Esw	E-static Es	238	.015	.717	.58	.76
	E-stress wave Esw	Modulus of rupture Mor	238	-614.1	2860.322	.20	.45

For western white pine the results were the same. the nondestructive test methods had an r^2 of 0.81 and the owest r^2 values were obtained when the nondestructive est results were used to predict the modulus of rupture.

The results of regression analysis of test data obtained rom green-tree lumber of other species are shown in able 6. The developmental work on the nondestructive esting methods had indicated the species effect to be minimal. The data of table 6 show that nondestructive evaluation of green tree lumber has a great deal of promise, with fairly high r^2 values. The r^2 values for the dead and green-tree lumber are shown in table 7 and graphs of some of the regression lines are shown in figures 1 and 2. The r^2 values show that nondestructive testing methods can be used to evaluate dead-tree lumber

able 6.—Results of regression analyses of nondestructive and destructive test data from dimension lumber made from green trees

Size	Variables		Number of specimens	Regression equation			
	Abscissa	Ordinate		Intercept	Slope	r^2	r
[1]2 × 8 in (5 × 20 cm)	E-computer Ec	E-static Es	44	0.036	0.964	0.96	0.98
	Modulus of Rupture Mor	E-computer Ec	24	-4.440	5560.0	79	89
[2]2 × 6 in (5 × 15 cm)	E-stress wave Esw	E-static Es	40	105	1.046	90	95
	E-computer Ec	E-stress wave Esw	40	.074	969	93	97
[3]2 × 4 in (5 × 10 cm)	E-computer Ec	E-stress wave Esw	107	250	.940	83	91
	E-computer Ec	E-static Es	107	110	773	62	79
	E-static Es	Modulus of rupture Mor	107	2416.0	2815.0	17	41

[1] Douglas-fir data obtained from a report by Marra and others. (1966)

[2] Douglas-fir data obtained from a report by Pellerin (1965)

[3] Hemlock-fir data obtained from a report by Hoyle (1977).

able 7.—Comparison of the regression coefficients for dead- and green-tree dimension lumber of different species evaluated by nondestructive and destructive test methods

Size	Variables	Dead lodgepole		Dead white pine		Green[1]	
		r^2	r	r^2	r	r^2	r
2 × 6 in (5 × 15 cm)	Ec - Esw	0.90	0.95			0.93	0.97
	Ec - Es	76	.87				
	Ec - Mor	.46	.68				
	Esw - Es	.76	87			90	95
	Esw - Mor	.53	.73				
2 × 4 in (5 × 10 cm)	Ec - Esw	.88	94	81	90	83	91
	Ec - Es	.76	.87	64	80	62	79
	Ec - Mor	.51	.71	32	57		
	Esw - Es	.69	.83	58	76		
	Esw - Mor	.43	.66	20	45		

[1] The 2 × 6 in values were obtained for Douglas-fir by Pellerin (1965) the 2 × 4 in values were obtained for hemlock-fir by Hoyle (1977)

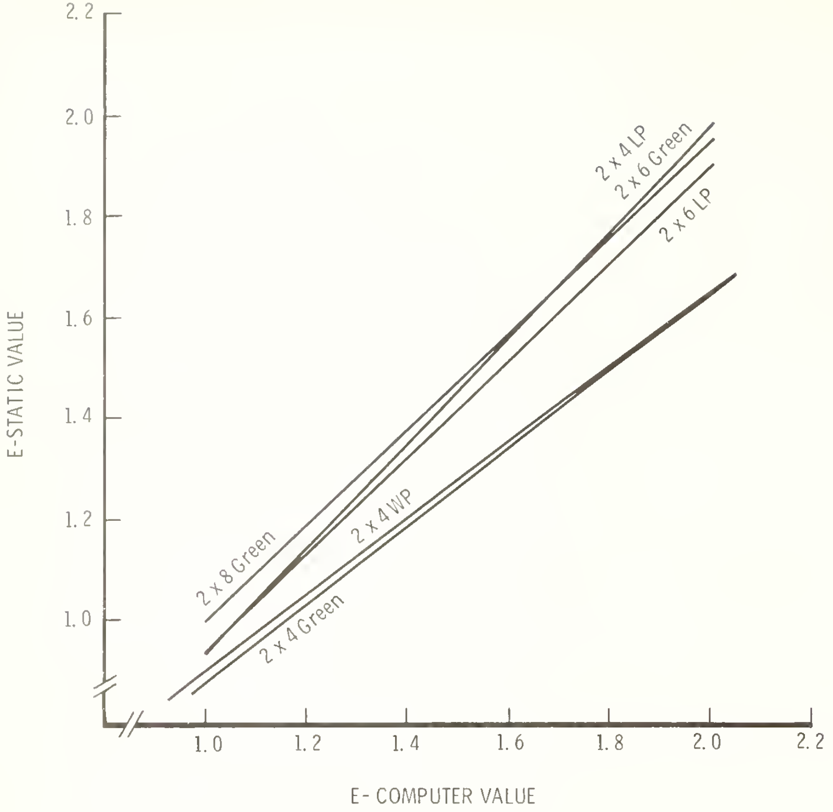

Figure 1.—Regression lines showing the relati ship between E-static and E-computer values for dimension lumber obtained from green and dead lodgepole and western white pine trees.

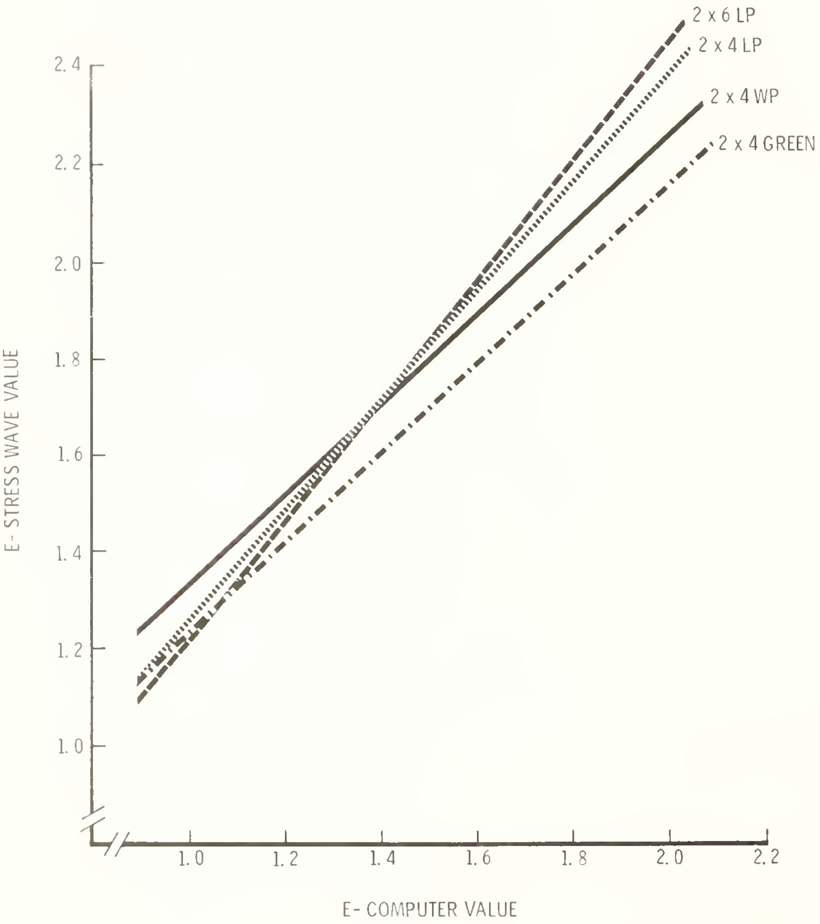

Figure 2.—Regression lines showing the relat ship between E-stress wave values and E-computer values for dimensional lumber obtained from green and dead lodgepole a western white pine trees.

ONCLUSIONS

The results of this study indicate that dead tree lumber n be tested nondestructively by the E-computer and the ngitudinal stress-wave methods. Regression analyses the test data showed the two nondestructive test ethods adequately predicted modulus of elasticity for th lodgepole and western white pine. Also, the results m the two methods were closely related. The lowest r^2 ues were obtained when the nondestructive test data re used to predict the modulus of rupture.

Nondestructive test data for the western white pine nber were in general agreement with visual grades.

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Dimension lumber cut from dead lodgepole pine and western white pine trees was evaluated nondestructively and destructively. Analysis of test results showed no marked difference in the moduli of elasticity between lumber cut from dead-tree logs and live-tree logs.

KEYWORDS: nondestructive testing, dead trees, dimension lumber, strength properties

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Changes in Sodium Adsorption Ratios Following Revegetation of Coal Mine Spoils in Southeastern Montana

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BLAND Z. RICHARDSON, research forester on the Mined-Land Reclamation research work unit at Logan, Utah, joined the staff of Intermountain Forest and Range Experiment Station in 1962. His research activities have included studies to determine the effect of multiple logging roads on moisture regimen, the hydrologic and pedologic effect of grazing on rangelands, the infiltration and erosional behavior of contour trenches on high elevation watersheds, and the effect of voids on the accuracy of neutron moisture measurements. Since 1966 his research has been exclusively on surface mine problems, evaluating research results, and furnishing recommendations to Federal and State agencies as well as private industry.

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RESEARCH SUMMARY

This paper presents the results of a 7-year study of the magnitude of reduction in the sodium adsorption ratios (SAR) following revegetation of coal mine spoils in southeastern Montana. Results show a decrease in SAR value from greater than 12 to less than 3 resulting in an improvement in both the chemical and physical quality of sodic spoils. Results indicate that 5 to 7 years were sufficient to eliminate sodium as a serious obstacle in future vegetal development. Increases in biomass production resulting from revegetation produced further decreases in a relative proportion of sodium ions to other cations in sodic spoils at the Decker coal mine.

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Changes in Sodium Adsorption Ratios Following Revegetation of Coal Mine Spoils in Southeastern Montana

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INTRODUCTION

An important problem in the Interior West is the poten-ally adverse effect on environmental quality of spoils left fter surface mining for coal. Needed are definitions and rescriptions for revegetation treatments and post-nanagement measures on various kinds of surface mined and. Equally important is the need for criteria and guides o predict how well such land may be revegetated. The urface Mining Control and Reclamation Act (P.L. 95-87) nd its regulations have placed new emphasis on revege-ation of spoil materials at western coal surface mines. Currently, many research activities are under way to etermine the best "mix" of cultural practices and plant pecies needed to satisfactorily revegetate disturbed land.

Surface mining for coal usually requires removal of nany feet of overburden to expose the coal bed. Follow-ng removal of the coal, the overburden materials are usually redeposited as spoils. Because many surface ninable coal areas in the West have alkaline, saline, or odic soils typically found where climates are semiarid or rid, the spoil materials left after surface mining have hese same or more concentrated chemical properties. The characteristics of any alkaline-saline-sodic soil or spoil material that appear to be most important in letermining its ability to support plant growth are: (1) total concentration of soluble salts; (2) relative proportion of sodium to other cations; (3) concentration of boron or other elements that may be toxic; and (4) under some conditions, the bicarbonate concentration as related to he concentration of calcium plus magnesium. Among the nost important of these characteristics is the relative proportion of sodium to other cations.

Sodic spoils have been identified as a problem in reclamation at a number of coal surface mine sites in the Interior West. One of these problem areas is the Decker coal mine in southeastern Montana approximately 20 miles (32 km) north of Sheridan, Wyo. Because of the uncertainty that revegetating sodic spoil materials at the Decker mine would be successful, an investigation was begun in 1972 by the Intermountain Forest and Range Experiment Station of the USDA Forest Service. Scientists sought to determine the effects of various soil amendments upon production of vegetation and the relative proportion of sodium to other cations in these sodic spoils. This study was predicated on the following hypotheses:

1. The relative proportion of sodium to other cations would decrease with time.
2. Addition of mulch, fertilizer, or both would increase production of vegetation on these sodic spoils.
3. Increase in production of vegetation would further decrease the relative proportion of sodium to other cations at the Decker mine.

METHODS

Methods used in this investigation were based on the assumption that the primary goal of revegetation of the Decker coal mine would be to establish a productive and protective cover of durable plants, consisting predominantly of species adapted to and characteristic of that area before mining. It was further assumed that differences in the degree of success of revegetation would be related to differences in the revegetation methods used. The degree to which plant cover is established can be measured and evaluated in several ways, one of the most important of which is the capability of the vegetation to produce aboveground biomass. Therefore, the degree of success of revegetation on our research plots was measured in terms of total weight of aboveground biomass.

The research site was on spoil materials that had been graded level in order to avoid differences in erosion, runoff, evaporation, and transpiration—processes that characterize sloping sites on different aspects. The spoils originated as overburden removed from the test pit about 200 ft (60 m) from the study site.

On the study site, 48 plots, each 8 ft (2.4 m) square, were established in each of three blocks. The plots in one block were located on raw spoils and received no irrigation. The plots in a second block were also located on raw spoils and were irrigated periodically throughout the first growing season. The plots in the third block were covered with 8 inches (20 cm) of topsoil that had previously been removed from the study site (Farmer and others 1974). This paper is concerned only with the information obtained from those plots in the unirrigated block on raw spoils.

Revegetation Treatments

Twelve revegetation treatments, each replicated four times in a randomized block, were applied to the 48 plots. These treatments consisted of all possible combinations of three different grass-seed mixtures, two levels of fertilizing, and two levels of mulching.

Grass-Seed Mixtures

The three grass-seed mixtures were native species, introduced species, and a combination of native and introduced species. All native grass species used are native to the general area of Decker. The seed was collected by hand during the summer and cleaned before use. Seed for the introduced species, all of which grow successfully in the vicinity of the Decker mine, were obtained commercially. All the species used appeared to be useful for revegetation at the Decker mine site because they grew well on other disturbed sites in the area, such as road cuts, fills and old mining sites.

The native grass mixture consisted of green needlegrass (*Stipa viridula*), western wheatgrass (*Agropyron smithii*), blue grama (*Bouteloua gracilis*), little bluestem (*Andropogon scoparius*), sideoats grama (*Bouteloua curtipendula*), Indian ricegrass (*Oryzopsis hymenoides*), slender wheatgrass (*Agropyron trachycaulum*), and big bluestem (*Andropogon gerardi*).

The introduced grass mixture included fairway crested wheatgrass (*Agropyron cristatum*), Nordan crested wheatgrass (*Agropyron desertorum*), Russian wildrye (*Elymus junceus*), pubescent wheatgrass (*Agropyron trichophorum*), intermediate wheatgrass (*Agropyron intermedium*), Manchar smooth brome (*Bromus inermis*), winter rye (*Secale cereale*), and tall wheatgrass (*Agrophyron elongatum*).

The native-introduced grass mixture contained green needlegrass, western wheatgrass, blue grama, slender wheatgrass, Nordan crested wheatgrass, Russian wildrye, intermediate wheatgrass, and Manchar smooth brome.

Fertilizer

The fertilizer used as a spoil amendment was a commercial granular 15-40-5 type mixed with a silica sand carrying agent.

Mulch

The mulch used was a commercial sphagnum peat moss; it was covered by a single layer of jute netting.

Plot Preparation and Treatment Application

The surface of each study plot was prepared as a seedbed by ripping the spoils to a depth of 10 inches (25 cm), then harrowing the surface several times with a spring-tooth harrow until the spoils were friable and no large clods were present. Great care was taken to ensure that the following treatments were applied uniformly and confined to the appropriate plot area.

1. A small seed spreader was used to apply fertilizer o appropriate plots at the rate of 300 lb/acre (336 kg/ha), an the fertilizer was hand raked into the spoils.
2. All three seed mixtures were applied to appropriate plots at the rate of 25.5 lb/acre (28.6 kg/ha), and the seed was covered by hand raking the surface lightly.
3. Mulch was spread over the appropriate plots at the rate of 2.5 tons/acre (5 604.3 kg/ha) and was packed down with a Brillion cultipacker.

DATA COLLECTION

Measurements of vegetation and spoil properties were made on all 48 study plots in 1972 and in each year from 1975 through 1979. All measurements were made on the interior 6- by 6-ft (1.8- by 1.8-m) area of each plot; this separated the measurement location on each plot from that of any other plot by a buffer zone of 2 ft (0.6 m).

The dry-weight production of grass on each plot was measured every year near the time of peak vegetation development. These measurements were made with a Neal Capacitance Meter (Neal and Neal 1973) calibrated by clipping, drying, and weighing one of every six herbag plots read with the meter. The effect of weeds was eliminated by clipping them separately from the grasses an excluding their weight from all analyses.

Samples were collected from the surface foot (0.3 m) o spoils and analyzed in the laboratory to determine pH, total salt as measured by electrical conductivity (EC_e), sodium, calcium, and magnesium. The sodium, calcium, and magnesium values were used to calculate sodium adsorption ratio (SAR) values. The alkali hazard involved soils or spoils is determined by the absolute and relative concentrations of the sodium, calcium, and magnesium cations. If the proportion of sodium is high, the alkali hazard is high; and conversely, if calcium and magnesiu predominate, the hazard is low. The sodium adsorption ratio of a soil or spoil solution is simply related to the adsorption of sodium by the soil; consequently, this rati has distinct advantages for use as an index for the sodiu or alkali hazard. This ratio is defined by the equation:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

where Na, Ca, and Mg represent the concentrations of the respective cations in milliequivalents per liter (U.S. Salinity Laboratory 1954). Generally, spoils with SAR values of less than 5 present no alkali hazard; spoils with SAR values from 6 to 9 cause some hazard; and those greater than 9 usually create a severe hazard.

Monthly preicipitation data at Decker were summarized for the 9 years 1971 through 1979 (National Oceanic and Atmospheric Administration 1971-79.)

DATA ANALYSES AND RESULTS

Analyses followed multiple regression strategies for estimating sodium adsorption ratios as a function of both annual and growing season precipitation, fertilizer and mulch treatments, production of aboveground biomass, and time elapsed since revegetation. The simple linear effects of these independent variables on sodium adsorption ratios were examined statistically as a means of isolating the stronger variables for use in synthesizing a final regression model.

These analyses reveal that the number of years since revegetation and the production of aboveground biomass were the independent variables that added most significantly to the regression for sodium adsorption ratio. Growing season precipitation, fertilizer, and mulch were also significantly related to sodium adsorption ratios however, when these three variables were compared with biomass production, they supplied no additional significant variance to sodium adsorption ratios beyond that explained by [illegible] biomass production [illegible] Biomass production was [illegible] to be highly correlated with growing season precipitation, fertilizer, and mulch, and [illegible] a [illegible] of those variables. Accordingly these variables were dropped from further consideration and a regression model was developed to describe changes in sodium adsorption ratios associated with differences in time since revegetation and variability in biomass production. These relations are expressed by the following equation:

$$SAR = 15.76443 - 3.91277t + 0.29586t^2 - 0.000000072106(t \times p)$$

where SAR = sodium adsorption ratio, t = number of years since revegetation, and p = pounds per acre of biomass production. This equation accounts for 35 percent of the variance in sodium adsorption ratios of these mine spoils during the first 7 years after they were revegetated.

Multiple solutions of this equation for selected biomass production values in each of the 7 years of study produced the series of regression curves shown in figure 1.

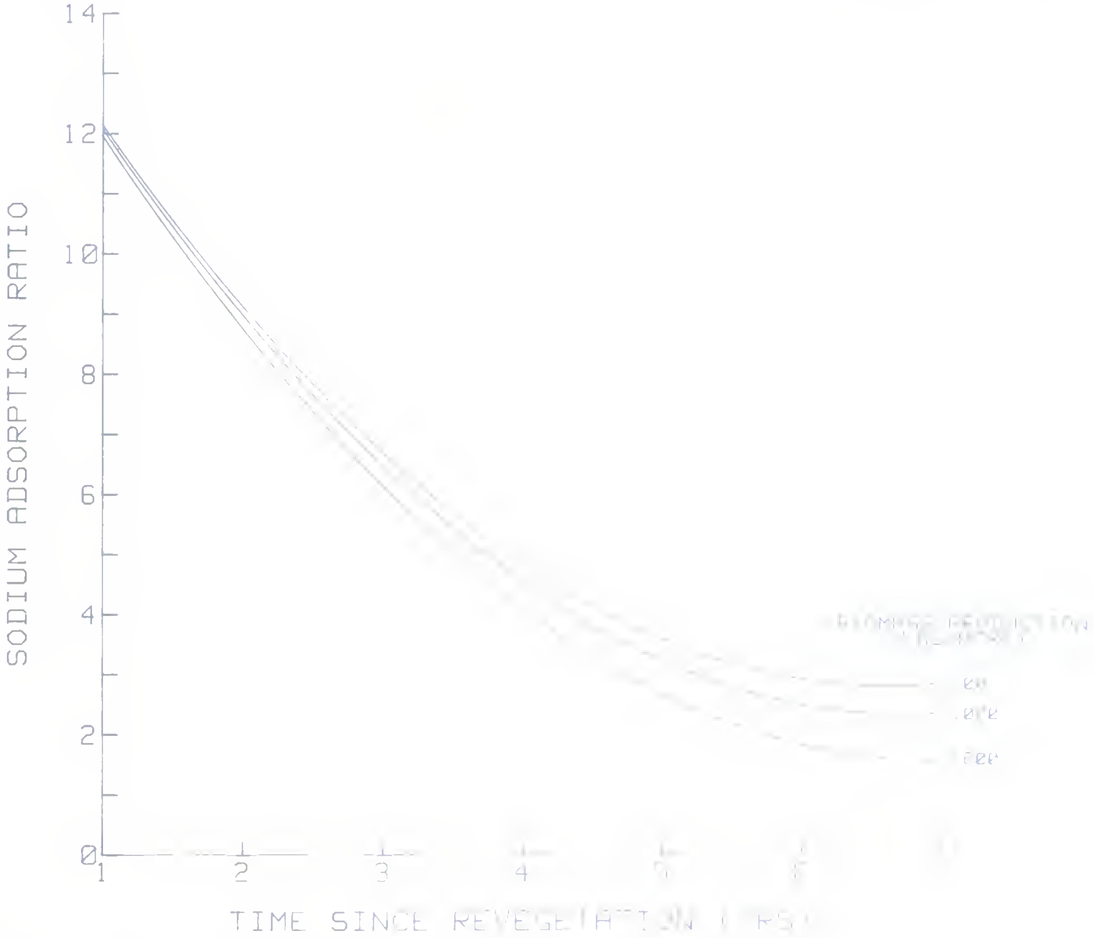

Figure 1.—Effects of time since revegetation and aboveground biomass production on sodium adsorption ratios of sodic mine spoils at Decker, Mont.

Sodium adsorption ratios consistently decreased throughout the 7 years following revegetation. Most of these decreases occurred in the first 5 years. For example, where the amount of biomass produced was a negligible 100 lb/acre (112 kg/ha), sodium adsorption ratios decreased from about 12 to 3.6 after 5 years, and to 2.8 after 7 years. While further decreases in sodium adsorption ratios might occur as revegetated stands become older than 7 years, the shape of regression curves suggest that such decreases are likely to be inconsequential. Sodium adsorption ratios also decreased as the amount of biomass produced by revegetated plant cover increased from less than 100 to more than 1,600 lb/acre (less than 112 to more than 1 792 kg/ha). The effectiveness of increased amounts of biomass for reducing sodium adsorption ratios became greater as the revegetated stands became older. For example, when the revegetated plant cover was 2 years old, an increase of biomass from 100 to 1,600 lb/acre (112 to 1 792 kg/ha) reduced the sodium adsorption ratio only 0.4—from 9.1 to 8.7. In comparison, when these stands became 7 years old, a similar increase in production of biomass resulted in a somewhat greater sodium adsorption ratio reduction of 1.1—from 2.8 to 1.7.

DISCUSSION

The pattern of reduction in sodium adsorption ratio values encountered confirms the study's first hypothesis: the relative proportion of sodium to other cations would decrease with time. These decreases are believed to be attributable to the leaching of sodium ions from the surface foot (0.3 m) of spoil materials by percolating water from rain and melting snow. The magnitude of reductions in sodium adsorption ratios—from about 12 to 3 or less—indicated improvement within 5 to 7 years in both the chemical and physical qualities of sodic spoils at the Decker mine sufficient to eliminate sodium as a serious obstacle to future vegetal development.

The revegetation treatments that produced the most biomass were those that included fertilizer, mulch, and a mixture of native and introduced grasses as components of the treatment. This confirms the second hypothesis, that the addition of fertilizer, mulch, or both would increase vegetal production on these spoils.

The reductions in sodium adsorption ratios associated with increases in production of biomass are believed due largely to increased leaching of sodium ions from the surface foot (0.3 m) of spoil materials. This came as a result of enhanced water percolation created by the enlarged root systems that accompany increased production of biomass. These relations confirm the third hypothesis, that increases in vegetal production would result in further decreases in the relative proportion of sodium ions to other cations in the sodic spoils at the Decker coal mine.

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The magnitude of reductions in sodium adsorption ratios of coal mine spoils following revegetation at the Decker coal mine in southeastern Montana indicates improvement in both the chemical and physical quality of sodic spoils within a 5- to 7-year period. This reduction is sufficient to eliminate sodium as a serious obstacle in future vegetal development. Increases in biomass production resulting from revegetation produced further decreases in a relative proportion of sodium ions to other cations in sodic spoils at the Decker coal mine.

KEYWORDS: sodium soils, alkali soils, saline soils, revegetation research, surface mine revegetation, coal mine reclamation, Northern Great Plains

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Vegetation of Two Drainages in Eagle Cap Wilderness, Wallowa Mountains, Oregon

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RESEARCH SUMMARY

A classification of vegetation is presented for part of the Eagle Cap Wilderness. Compositional data and descriptions are supplied for 14 coniferous forest types and nine other community types. An additional four communities are described. Under each type the author discusses implications for wilderness management: campsite and trail suitability, unusual problems, fire management, and so on. This work should be expanded to include the entire Wallowa Mountains and incorporated into a habitat type classification while still retaining information on seral vegetation types.

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INTRODUCTION

When the National Wilderness Preservation System was established in 1964, Congress stated explicitly that each wilderness area was to be "protected and managed so as to preserve its natural condition." In order to provide this protection, the Forest Service requires that a wilderness management plan be developed for each area. Three of the six specifications for management plans mentioned in the Forest Service Manual (FSM 2322.1) are to: (1) "describe the current condition of all resources and biotic associations"; (2) "describe the interrelationships of all resources, existing uses, and activities and highlight unique ecological situations"; and (3) "identify problems associated with maintaining an enduring wilderness resource and the reasons for the problem."

Classification and description of vegetation is an important step in this direction. Classification provides an organizational framework for research and the communication of information about different plant communities and environments. It would be particularly valuable to collect information about specific problems resulting from various types of use and organize this information by vegetation type.

Descriptions of vegetation structure and floristic composition and their relation to selected environmental characteristics, such as elevation and aspect, will provide baseline data about "current conditions" and allow managers to evaluate and respond to future vegetational changes. This information also reveals unique ecological situations that might require special management strategies for preservation.

Successional relationships are an important component of these descriptions. Succession in response to "natural" disturbances will have to be distinguished from changes resulting from human activities. In particular, successional changes resulting from fire suppression need to be understood, as suppression is causing uncharacteristically rapid changes in vegetation structure and composition over large tracts of wilderness (see, for example, Heinselman 1973; Vankat and Major 1978).

This paper classifies and describes the vegetation of a part of the Eagle Cap Wilderness in the Wallowa Mountains of northeastern Oregon (fig. 1). Aside from several theses (Sturges 1957; Head 1959; Johnson 1959; Woodland 1965), little information is available on the community ecology of the Wallowa Mountains. Information on vegetation is usually extrapolated from a study by Hall (1973) who worked in the neighboring Blue Mountains, which are topographically and geologically different from much of the Wallowa Mountains.

The primary purpose of this paper, however, is to present wilderness management implications for each vegetation type. Each type responds uniquely to recreational use and management practices and offers distinctive recreational opportunities. Although these implications are specific to the study area, they can be cautiously applied to floristically similar and, to a lesser extent, morphologically similar types which occur elsewhere. For example, in a recent study of trampling impact in the Tyrolean Alps, alpine meadows dominated by *Carex curvula* were found to be resistant to damage, a response quite similar to that of the morphologically similar *Carex nigricans* meadows in the Wallowas (personal communication, Dr. G. Grabherr).

The implications presented here should serve as a foundation on which an increasingly accurate and detailed information base can be developed for the Eagle Cap Wilderness and for other areas. Information of this type will ultimately lead to management that is sensitive to inherent differences in the character of land types, the opportunities they provide, and the management problems they present.

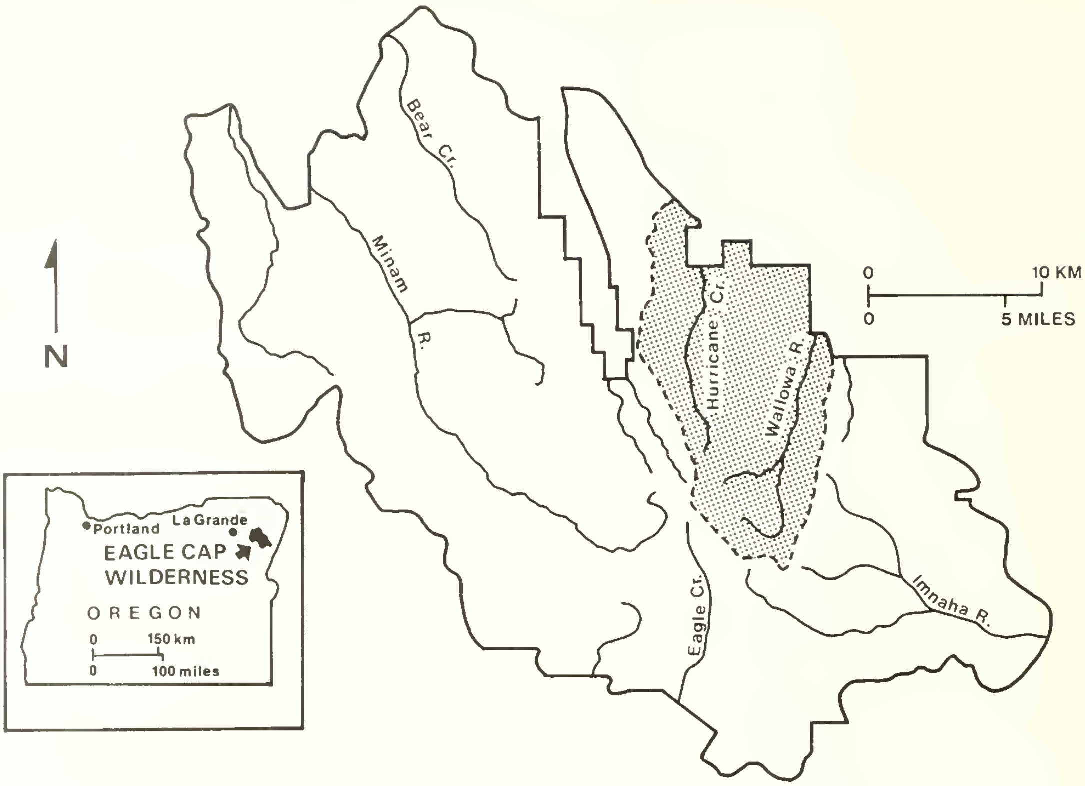

Figure 1.—Location of the study area within the Eagle Cap Wilderness in northeastern Oregon.

THE STUDY AREA

The Wallowa Mountains are the highest and most rugged range in the Blue Mountain Province of northeastern Oregon. The Wallowas are bordered on the south and west by the basins of the Powder and Grande Ronde Rivers. On the east they are separated from the mountains of Idaho by the Hells Canyon of the Snake River and, to the north, they drop off abruptly to the Wallowa River Valley and dissected plateau country.

The Wallowa Mountains, uplifted along faults to the northeast and south, have a central core of granitic rocks. These are surrounded by folded, partially metamorphosed limestones, shales, and greenstones. Basalts cover extensive areas except around the granitic core of the range where they are only occasionally found on some of the higher peaks (Smith and Allen 1941). The tallest peaks exceed 9,500 feet (2 850 m) and tower more than 5,000 feet (1 500 m) above the surrounding plains. Extensive glaciation occurred during the Pleistocene, with glaciers reaching out to the edge of the range on the northeast side. Consequently, the range is characterized by numerous lakes and meadows in cirque basins (fig. 2) and steep, jagged ridges separating deep valleys, which radiate from the granitic core of the range (fig. 3).

The area experiences short, mild summers and long, cold winters. At Joseph, Oreg., immediately to the north of the mountains, mean minimum and maximum temperatures have averaged 12° F (– 11° C) and 32° F (0° C) in January and 46° F (8° C) and 79° F (26° C) in July. Temperatures at higher elevations in the mountains are undoubtedly cooler. Mean annual precipitation in the moun tains probably varies between 20 and 80 inches (50 and 200 cm). Except for a short summer dry season, precipit tion is distributed equitably throughout the year (U.S. Department of Commerce 1965).

An approximately 15 000-ha area was selected for intensive study (fig. 4). The area consisted of the contiguous drainage basins of Hurricane Creek and the West Fork of the Wallowa River within the Eagle Cap Wilderness.[1] This area was chosen because it contained a particularly wide range of rock types that outcrop over the complete elevational range of the mountains and because it is the most heavily used part of the wilderness (fig. 5). The study area is unrepresentative of the range a a whole in that its location to the north of the core resulted in particularly intensive glacial oversteepening of slopes and an underrepresentation of southerly aspects In addition, basalt rocks, common elsewhere in the Wallowa Mountains, are rare in the study area. Observation also suggest that high-elevation species extend downward to unusually low elevations, perhaps in response t cold air drainage.

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[1] Several sample stands were located outside of, but within a mile of the wilderness.

igure 2.—Moccasin Lake is typical of the numerous lakes scattered throughout the subalpine zone of the Wallowa Mountains.

igure 3.—The Matterhorn (right) and Sacajawea (left) tower more than 3,000 ft above Hurricane Creek. The contact between calcareous and noncalcareous bedrock coincides with the upper limit of continuous forest.

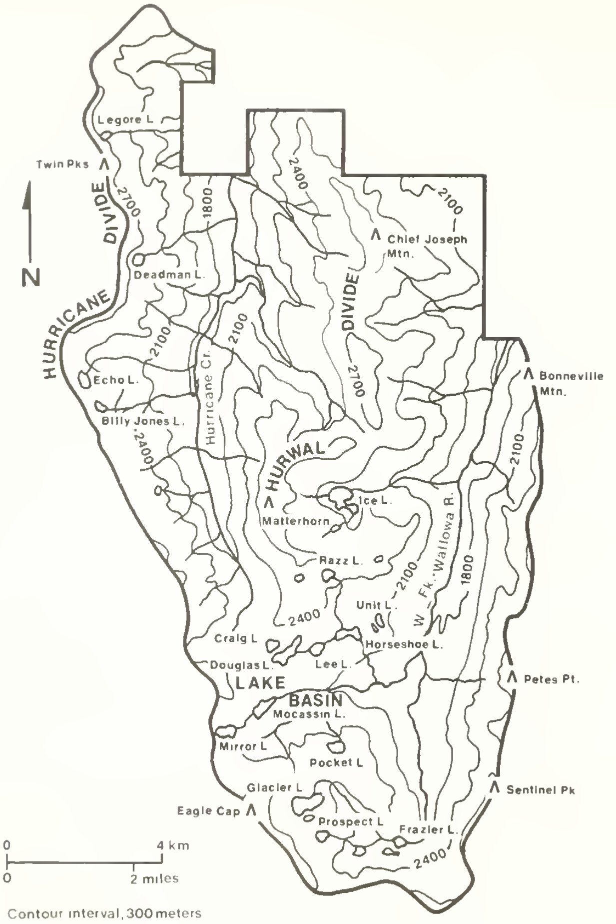

Figure 4.—Topographic map of the study area.

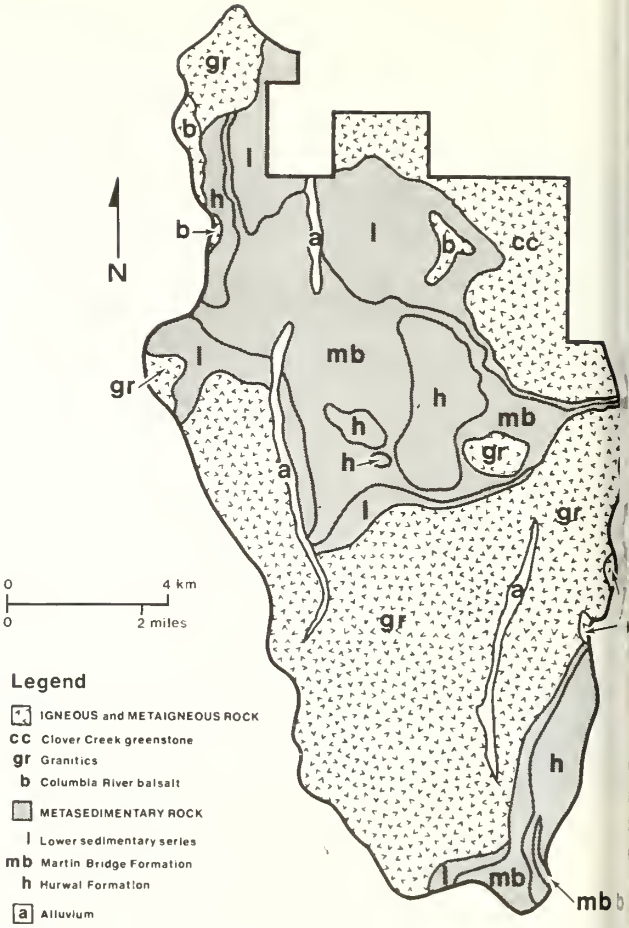

Figure 5.—Geologic map of the study area.

METHODS

A reconnaissance survey of the vegetation in the study area was conducted during the summer of 1974. This resulted in a first approximation of possible plant community types and identification of stands suitable for more intensive sampling. During the summers of 1975 and 1976, 90 coniferous forest stands were sampled. Stands were selected that were representative of broadly distributed community types. Within each type, stands were dispersed throughout the range of rock types, elevations, aspects, and localities. This led to less similar stand compositions, but it more fully described the variation within each type.

An additional 38 stands were sampled in community types other than coniferous forest. This coverage was not as comprehensive as the survey of coniferous forests, but it did identify the major types.

Within each stand, a macroplot was located in a relatively homogeneous area away from ecotones and areas of direct human disturbance. Each 32.8 - × - 65.6-ft (10- × - 20-m) macroplot contained ten, 3.28-×-3.28-ft (1- × -1-m) microplots, located at 9.8-ft (3-m) intervals along strips 9.8 and 19.7 ft (3 and 6 m) upslope from the lower boundary of the macroplot. Long dimensions were oriented parallel to contours.[2]

On forested macroplots, species and diameter at breast height were recorded for each tree. Trees less than 4.5 ft (137 cm) in height were counted as seedling and included with the trees less than 0.8-inch (2-cm) d.b.h. Data on tree size class were combined by commu ity type and presented as mean values per macroplot (table 2, appendix 2).

Within the microplots, canopy coverage of each unde story species was recorded in one of six coverage classes (0-5, 6-10, 11-25, 26-50, 51-75, and 76-100 percen The midpoints of coverage classes were used to derive mean percent coverage for each understory species. Fr quency of occurrence in the 10 microplots was also recorded. Frequency and mean coverage for each specie are presented in table 3 in appendix 2. Voucher specimens of these species have been deposited in the herb ium at the University of Oregon, Eugene. Nomenclature follows Hitchcock and Cronquist (1973).

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[2] Classification methods in forests of the western United States have become increasingly standardized. In the future it would be more appro ate to utilize the sample design of Pfister and Arno (1980).

The name assigned to each community type is usually a binomial consisting of the mature tree species and undergrowth species that are currently most abundant. Where several tree species commonly codominate, the ype is named after the codominant that is reproducing most frequently. Details on composition are provided in he descriptions. Exceptions to this are the *Pinus albicaulis-Abies lasiocarpa* type and several nonforested ypes named after the type of environment they occupy (for example, avalanche slope).

This concept of a community type should not be conused with the habitat type concept, which also uses a nomenclature based on combinations of overstory and undergrowth species. A habitat type is the collection of geographic areas capable of being occupied by the same "association," a **climax** plant community type named for potential climax tree species and indicator species in the undergrowth (Daubenmire and Daubenmire 1968). The community types described here are named for **currently dominant** species and do not imply any particular successional stage. Several distinct community types may occupy the same habitat type, either as different seral stages in a predictable sere or as different responses to perturbations. A community type may also overlap several habitat types, if the type is climax in one area and seral in another (fig. 6). Inferences about successional relationships both within and between community ypes are included in the descriptions of the coniferous orest types.

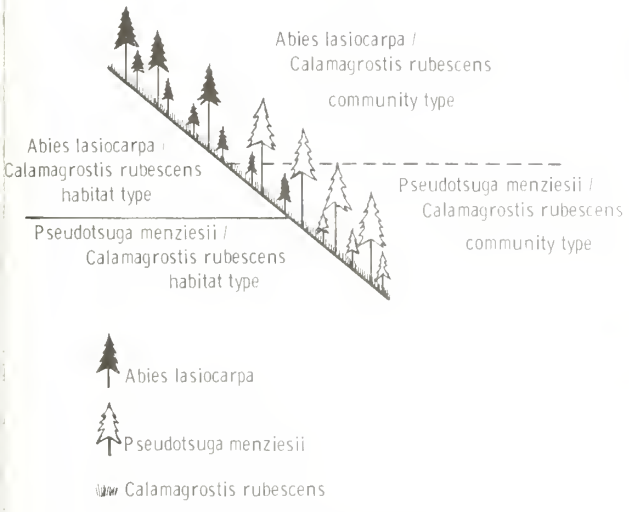

Figure 6.—Example of how community types and habitat types overlap along an environmental gradient. In the middle portion of the gradient, the *Pseudotsuga menziesii/Calamagrostis rubescens* community type occurs as a seral stage on the *Abies lasiocarpa/Calamagrostis rubescens* habitat type. (Modified from Layser and Schubert 1979.)

Some of the management implications provided are supported by research data, while others are based on personal judgment. Most of the comments on trail and campsite location are based on detailed studies reported elsewhere (Cole 1977, 1981). Comments on the magnitude of successional change resulting from fire suppression are inferences drawn from analysis of stand structure rather than research on actual burns. No other research results are available, so additional suggestions should be treated as personal judgment.

A key to the community types is presented in appendix 1.

THE COMMUNITY TYPES

Pseudotsuga menziesii/Agropyron spicatum (PSME/AGSP)

Description.—This community type (c.t.) is occasionally encountered on droughty south-facing slopes, usually below 5,300 ft (1 600 m). It is more common on the partially metamorphosed rocks than on the granitics.

Trees are widely spaced, creating relatively open stands (fig. 7). *Pseudotsuga menziesii* is the most abundant tree species, although large, old *Pinus ponderosa* are more abundant here than in any other c.t. *Pinus* is no longer establishing seedlings, however, so that the seedling and sapling population consists almost entirely of *Pseudotsuga*.

Figure 7.—*Pseudotsuga menziesii/Agropyron spicatum* stand located on a south slope above Hurricane Creek.

The understory is dominated by *Agropyron spicatum*. Associates are highly variable, as indicated by the dissimilar composition of the two stands sampled. *Achillea millefolium, Balsamorhiza sagittata,* and *Lomatium grayi* are particularly abundant. Annuals and exotics, such as *Bromus tectorum,* are more prominent in this c.t. than in any other.

Most of these stands are mature and the overstory composition appears to be relatively stable. Observations suggest that tree density is often increasing, probably in response to suppression of formerly frequent surface fires. This often coincides with a decline in *Pinus* regeneration and a decrease in the cover of bunchgrass

Management implications.—Low moisture and early snowmelt make this c.t. a particularly good trail location. Moreover, the open canopy provides scenic vistas and the diversity of wild flowers is high. Suitability for campsites is low because the c.t. is limited to steep slopes. Recreational values will tend to decline with increasing tree density, a trend observed in some areas, apparently in response to recent fire suppression. Rehabilitation of disturbances will be difficult due to soil drought and steep, unstable slopes.

Other studies.—Similar vegetation has been described in central Idaho (Steele and others, 1981), Montana (Pfister and others 1977), and interior British Columbia (McLean 1970; McLean and Holland 1958). It has not been described in the published literature elsewhere in Oregon and Washington, although *Pinus ponderosa/Agropyron spicatum* types without any *Pseudotsuga* have been reported in the Blue Mountains of Oregon, in eastern Washington and northern Idaho, and in the Bighorn Mountains of Wyoming (Hall 1973; Daubenmire and Daubenmire 1968; Hoffman and Alexander 1976).

Pseudotsuga menziesii/Physocarpus malvaceous (PSME/PHMA)

Description.—This type occurs below 6,000 ft (1 800 m), particularly on slopes with large concentrations of boulders. It is uncommon on calcareous substrates. *PSME/PHMA* occurs on all aspects, but is somewhat more common on slopes with a northerly aspect. In the study area, it is most frequent on lower slopes above the West Fork of the Wallowa River.

The overstory is relatively open and dominated by *Pseudotsuga menziesii. Larix occidentalis* is the only associate of any significance. *Pseudotsuga* is the most abundant seedling. *Abies grandis*[3] is also establishing seedlings in some locations, but *Larix* seedlings are essentially nonexistent.

This type is easily distinguished by its dense shrub cover (59 percent mean cover — see table 4, appendix 2) and complex vertical structure (fig. 8). In addition to the 4- to 6-ft (1.5- to 2.0-m) tall layer of *Physocarpus malvaceous*, there is typically a low shrub layer of *Symphoricarpos albus* and *Spiraea betulifolia*, and a layer of herbaceous species such as *Calamagrostis rubescens* and *Thalictrum occidentale. Acer glabrum* frequently rises above the *Physocarpus* layer. Total canopy coverage is unusually high (76 percent), while species richness is only moderate (table 4, appendix 2).

Management implications.—This type is usually too steep, rocky, and brushy for campsites. It appears to be a good location for trails. Soils are well drained and the rough topography and brush confine the hiker to the trail tread. Fall colors are quite attractive and the relatively open canopy allows frequent distant views.

Figure 8.—Widely spaced trees and undergrowth dominated by tall shrubs typify the *Pseudotsuga menziesii/ Physocarpus malvaceous* community type.

Other studies.—Similar vegetation has been described as representative of community types in the Blue Mountains of eastern Oregon (Hall 1973), and habitat types in eastern Washington and northern Idaho (Daubenmire and Daubenmire 1968), central Idaho (Steele and others 1981; Montana (Pfister and others 1977), northeastern Wyoming (Steele and others 1979, preliminary draft, USDA Forest Service, Intermountain Station), and northern Utah (Mauk and Henderson 1980, preliminary draft, USDA Forest Service, Intermountain Station).

Pseudotsuga menziesii/Calamagrostis rubescens (PSME/CARU)

Description.—This type is common on midelevation—5,300 to 6,700 ft (1 600 to 2 000 m)—slopes, with well-developed soils and little exposed rock. It occurs on various aspects and in the study area is most common on lower slopes. If the topography of the area were less rugged, it would probably be more widespread.

Pseudotsuga menziesii is the most abundant species in the overstory, although *Larix occidentalis* and *Pinus ponderosa* are locally important. Individual trees are usually large and often exhibit an open-grown growth habit, even where currently surrounded by dense forests (fig. 9). Fire scars are common. Of the eight stands sampled, regeneration is primarily *Pseudotsuga* in two, primarily *Abies lasiocarpa* in three, and a mixture of the two in three stands. *Abies* reproduction is greater at higher elevations, on more protected sites, and on granitic rocks. *Larix* and *Pinus* seedlings are seldom encountered.

The understory can easily be distinguished by the luxuriant growth of *Calamagrostis rubescens* (mean cover of 32 percent). Tall shrubs are conspicuously absent, but low shrubs particularly *Berberis repens* and

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[3] Many of these individuals appear to be *Abies grandis* × *A. concolor* hybrids similar to those in central Idaho studied by Daniels (1969). I will refer to them as *A. grandis*.

'igure 9.—Typical *Pseudotsuga* *nenziesii/Calamagrostis rubescens* tand displays the parklike stand tructure and luxuriant growth of rass.

ymphoricarpos albus, and forbs, such as *Thalictrum* *ccidentale* and *Arnica cordifolia,* occasionally interrupt he grass cover. Species richness is quite low and lespite the high graminoid cover, very few graminoid pecies occur in this type.

Some of these stands (14 and 92) have relatively stable, elf-perpetuating population structures. In others, *Pseu-* *lotsuga* is a seral dominant while *Abies* appears to be he major climax species. No mature *Abies lasiocarpa/* *Calamagrostis rubescens* stands could be found in the rea, however. Stand densities appear to be increasing. ncreased density, in conjunction with an increase in the elative abundance of *Abies,* is often associated with lecreased *Calamagrostis* cover and increased cover of hade-tolerant forbs, particularly *Thalictrum occidentale.*

Management implications.—These parklike stands are articularly attractive sites to locate trails or campsites.)rainage is generally good and little more than basic onstruction should be necessary. The visibility and entle topography suggest that hikers leaving the trail, articularly to shortcut switchbacks, could be a problem. lthough the ground cover is relatively resistant to amage from trampling, damaged sites are particularly bvious and esthetically displeasing when adjacent to ne nearly continuous cover of undisturbed sites. This uggests that these sites are durable, but that efforts hould be made to reduce the obtrusiveness of impacts.)ispersed camping, that is rotation of use among a large umber of sites, may be preferable to concentration of se on a few sites, provided use of individual sites is very nfrequent and low impact camping techniques are prac- ced. Suitably flat sites for camping may be hard to find, owever. Recovery of these sites is facilitated by the izomatous habit of *Calamagrostis* and the lack of hade on many of these sites. Increasing canopy closure nd successional trends toward *Abies lasiocarpa,* prob- bly resulting in large part from fire suppression, may ecrease the natural attractions, durability, and regenera- ve abilities of this type.

Other studies.—Generally similar vegetation has been described from interior British Columbia (McLean and Holland 1958, Tisdale and McLean 1957, McLean 1970) and Alberta (Ogilvie 1962), south through eastern Washington, Idaho (Daubenmire and Daubenmire 1968, Steele and others 1981), and Montana (Pfister and others 1977) to the Blue Mountains of eastern Oregon (Hall 1973), the southern Wallowa Mountains (Head 1959), and the mountains of northwestern Wyoming (Steele and others 1979 preliminary draft, USDA Forest Service, Intermountain Station) and northern Utah (Mauk and Henderson 1980 preliminary draft, USDA Forest Service, Intermountain Station).

Pseudotsuga menziesii/Thalictrum occidentale (PSME/THOC)

Description.—This c.t. can be found on moderately moist, lower slopes, between 5,200 and 6,700 ft (1 550 and 2 000 m). It often grades to *Pseudotsuga menziesii/Calamagrostis rubescens* on drier sites and to *Abies lasiocarpa/Thalictrum occidentale* in valley bottoms or on more mesic exposures.

The overstory consists of *Pseudotsuga menziesii* and *Larix occidentalis,* with the seedling and sapling size classes consisting almost exclusively of *Abies lasiocarpa* and *Picea engelmannii.* All of these stands are seral and related to the successionally more advanced *Abies lasiocarpa/Thalictrum occidentale* c.t. (see below), with which this type could probably be grouped on the basis of site potential.

The understory is distinguished by its lush cover of shade-tolerant, moist-site forbs (mean cover of 47 percent). Medium-sized forbs—8 to 32 inches (2 to 8 dm)—particularly *Thalictrum occidentale* and *Arnica cordifolia,* provide most of the cover, but there is also a ground-level layer of plants (such as *Pyrola secunda* and *Viola adunca)* as well as a patchy shrub layer. Species richness is high.

Management implications.—The forb ground cover of this type is rapidly destroyed by trampling; recreation sites are frequently invaded by exotic species, such as *Taraxacum officinale* and *Trifolium repens.* Consequently, the number of trails and campsites in this type should be minimized by discouraging the dispersal of campsites and trails.[4] Rehabilitation of disturbances should be moderately rapid, if assisted, because of relatively long growing seasons and adequate soil moisture. A more serious problem is maintenance of this seral type. With continued fire suppression, *Pseudotsuga* and *Larix* will be replaced by *Abies lasiocarpa,* and yet successful burning in these dense forests, particularly after years of fuel accumulation, will be difficult. Prescribed underburning may be the only solution.

Other studies.—No similar types have been described because other studies have focused attention on near climax stands.

[4] Dispersal of use is most practical on durable sites. On fragile sites unless use levels are very low, use should be either curtailed or concentrated on as few sites as possible.

Pseudotsuga menziesii/Berberis repens (PSME/BERE)

Description.—This is a common c.t. below 6,000 ft (1 800 m) on calcareous rock types, although it occasionally occurs on noncalcareous metamorphic rocks as well. It is usually found in valley bottoms and on lower slopes, particularly in areas disturbed at periodic but infrequent intervals by debris slides and mudflows. It is essentially restricted to the lower part of Hurricane Creek.

Pseudotsuga menziesii is usually the most abundant tree species, but *Picea engelmannii* is abundant in concavities and on protected sites, while *Juniperus scopulorum* frequently occurs on dry, open sites, particularly on colluvial fans. All of these species, in addition to *Abies lasiocarpa*, are reproducing abundantly.

The ground cover is characterized by various combinations of low shrubs, particularly *Berberis repens, Symphoricarpos albus, S. oreophilus,* and *Spiraea betulifolia. Calamagrostis rubescens* and *Thalictrum occidentale* are common, but usually subordinate to the shrubs, particularly on more xeric sites. Total cover is only moderately dense (50 percent mean cover), but species richness is very high.

This type is highly variable and not well defined. It is also difficult to draw conclusions about the successional status of these stands. Some seem to be stable and self-perpetuating, while *Abies lasiocarpa* appears to be climax in others. More work on this type would clarify successional relationships and might lead to the recognition of several distinct types.

Management implications.—The ground cover of this type is quickly destroyed by camping, but the esthetic impact of the ground cover loss is not striking. This suggests that concentrated use of a few sites might be acceptable, if the use cannot be diverted to the more desirable avalanche slopes (see below). There appears to be little potential for trail deterioration problems (fig. 10). Moreover, there are no widespread successional trends among tree species, so maintenance of this type does not appear to be a problem.

Figure 10.—Trails in the *Pseudotsuga menziesii/Berberis repens* community type seldom deteriorate. This stand, in the valley bottom adjacent to Hurricane Creek, has unusually luxuriant undergrowth.

Other studies.—No other community descriptions appear to be highly similar, although *PSME/BERE* habitat types have been described in southern and eastern Idaho, western Wyoming (Steele and others 1979, preliminary draft, USDA Forest Service, Intermountain Station), the Bighorn Mountains of north-central Wyoming (Hoffman and Alexander 1976), and northern Utah (Mauk and Henderson 1980, preliminary draft, USDA Forest Service, Intermountain Station).

Pinus flexilis (PIFL)

Description.—This type is confined to calcareous bare rock and unstable slopes of weathered limestone. It extends from 5,000 ft (1 500 m) to timberline, which is rarely above 7,000 ft (2 100 m) on calcareous rocks in the study area. Only two stands were sampled and these were highly dissimilar. Consequently, there was no attempt to define an understory union.

The most common associates of *Pinus flexilis* are *Pseudotsuga menziesii* and *Juniperus scopulorum,* and all of these species are capable of maintaining stable populations. The understory is sparse and characterized by xeric low shrubs and forbs (fig. 11). The only species common to both stands are *Achillea millefolium, Erigeron chrysopsida* var. *brevifolius,* and *Phacelia hastata* var. *leucophylla.*

Management implications.—This type is not suitable for campsites and trail construction is difficult due to the extent of bare rock and the rapid downslope movement of colluvium. Although not significantly threatened, this unique type deserves special protection because of its botanical interest. These are some of the westernmost stands of *Pinus flexilis* within the Pacific Northwest as defined by Hitchcock and Cronquist (1973).

Other studies.—*Pinus flexilis* has not been described elsewhere in Oregon and Washington. Apparently, there are stands in the Strawberry Mountains (Charlie Johnson personal communication), however. Stands have been described in east-central Idaho (Steele and others 1981), Montana, along and east of the Continental Divide (Pfister and others 1977), and south into Wyoming (Steele and others 1979, preliminary draft, USDA Forest Service, Intermountain Station), and Utah (Mauk and Henderson 1980, preliminary draft, USDA Forest Service, Intermountain Station). None of the stand descriptions appear to be very similar to these in the Wallowa Mountains.

Figure 11.—Widely spaced, stunted trees and sparse undergrowth charac- erize *Pinus flexilis* stands.

Abies grandis/Thalictrum occidentale (ABGR/THOC)

Description.—This type is uncommon in the study area, as it is confined to valley bottoms below 5,300 ft (1 600 m). These sites are probably warmer than those occupied by *PSME/THOC* or *ABLA/THOC*. It is probably more widespread in other parts of the range. For example, Head (1959) describes similar vegetation along the East Fork of Eagle Creek in the southern part of the range.

Abies grandis is the most abundant species in all size classes (fig. 12). *Pseudotsuga menziesii* and *Larix occidentalis* are the most common associates in the overstory, but they are no longer establishing seedlings consistently. The most common associates in the smaller size classes are *Abies lasiocarpa* and *Picea engelmannii*.

The understory is similar to *PSME/THOC*, although the diversity of species is lower and total cover is less (40 percent). This may reflect the denser tree canopy coverage in this type. Occasionally, *Linnaea borealis* dominates the ground cover, but these sites were not sufficiently numerous to warrant separate classification.

Management implications.—Implications are generally similar to those of the *PSME/THOC* type. Although these sites are warmer than *PSME/THOC* sites, rehabilitation of disturbances may be more difficult due to the greater canopy coverage of these stands. Because these stands are more successionally advanced, however, maintenance of *Abies grandis*, at least, should not be difficult.

Figure 12.—*Abies grandis* is the most abundant seedling, sapling, and mature tree in this *Abies grandis/ Thalictrum occidentale* stand. The undergrowth of shade-tolerant forbs is unusually dense for this type.

Other studies.—This type has not been described elsewhere. Many of the common species in this understory union are members of the *Pachistima myrsinites* union and other moist site unions that occur in *Abies grandis* forests from eastern Oregon (Hall 1973) and Washington (Daubenmire and Daubenmire 1968) through Idaho (Steele and others 1981) to western Montana (Pfister and others 1977). In the Wallowa Mountains, however, many of the indicator species from these other locations are either infrequent (for example, *Clintonia uniflora* and *Pachistima myrsinites*) or only locally abundant (for example, *Linnaea borealis*).

Abies lasiocarpa/Thalictrum occidentale (*ABLA/THOC*)

Description.—This widespread type occupies moist valley bottoms and north slopes between 5,200 and 7,000 ft (1 550 and 2 100 m). Topography is usually smooth and soils are relatively well developed. This appears to be an extension of the *ABGR/THOC* c.t. on higher elevation sites that are cool and moist enough to support more abundant *Abies lasiocarpa.* It differs from *PSME/THOC* in that *PSME/THOC* is a seral stage on sites near the warm, dry limit of those sites capable of being occupied by the *ABLA/THOC* c.t.

The overstory is unusually dense and either *Picea engelmannii* or *Abies lasiocarpa* may be the most abundant mature tree. Typically, more of the large trees are *Picea,* while most of the trees less than 12 to 16 inches (3 to 4 dm) d.b.h. are *Abies.* The abundance of *Picea,* in relation to *Abies,* tends to decrease with increasing elevation and decreasing soil moisture. *Picea* is also much more abundant on calcareous rocks. *Pseudotsuga menziesii* and *Larix occidentalis* occur in the overstory, but seldom establish seedlings.

The understory is broadly similar to the other *Thalictrum* types, but species richness and total cover are even lower than in the *ABGR/THOC* type. Shrubs and graminoids are less important than in other types. Characteristic associates of *Thalictrum* include *Arnica cordifolia, Chimaphila umbellata, Fragaria vesca, Osmorhiza chilensis, Pyrola secunda, Viola adunca,* and *Viola orbiculata* (fig. 13). On some sites, *Thalictrum* may be less abundant than *Arnica* and *Pyrola* or even absent. These are usually extremely dense stands with thick organic soil horizons and a total understory cover of 20 percent or less.

Figure 13.—*Abies lasiocarpa/Thalictrum occidentale* stand located along Hurricane Creek at 6,000 ft.

Management implications.—This type is not very urable for campsites, because the lush vegetative cover s quickly eliminated and the soil becomes compacted ig. 14). Such changes are not particularly displeasing sthetically, however, and many campsites are located in his type. If permitted in this type, camping should be oncentrated on as few sites as possible to prevent wide- pread damage. These sites are well watered, hence re- abilitation should be relatively rapid for forested sites. carification and either seeding or transplanting may be ecessary to overcome extreme soil compaction. A easonally high water table leads to bog formation on ome of the trails in this type. Additional work could robably identify a phase of this type that is particularly usceptible to trail deterioration. *Streptopus amplexi- olius* and *Senecio triangularis* are common indicators of igh water tables. These areas should be avoided when- ver possible. Otherwise it will be necessary to construct corduroy or turnpikes and to maintain natural drainage. Continued fire suppression will probably lead to increased prominence of *Abies lasiocarpa*, increased stand density, and reduced diversity.

Other studies.—An *ABLA/THOC* type has been specifically identified from Yellowstone National Park south to the Wind River Range, Wyo. (Steele and others 1979, preliminary draft, USDA Forest Service Intermountain Station). The stands in the Wallowas, however, are probably more similar to other types named for less abundant indicator species. The stands with a depauperate ground cover and little *Thalictrum* appear to be similar to *Abies lasiocarpa/Arnica cordifolia* types described in east-central Idaho (Steele and others 1981), Montana (Pfister and others 1977), and northwestern (Steele and others 1979, preliminary draft, USDA Forest Service, Intermountain Station) and north-central Wyoming (Hoffman and Alexander 1976).

Figure 14.—Undergrowth is easily destroyed on campsites located in the *Abies lasiocarpa/Thalictrum occidentale* community type. On many sites, damage to trees is also severe.

Abies lasiocarpa/Vaccinium membranaceum (*ABLA/VAME*)

Description.—This rather infrequent type is most common on granitic soils at moderate elevations—5,300 to 7,000 ft (1 600 to 2 100 m). It occupies various exposures but occurs most frequently on flats, benches, and northerly aspects.

Abies lasiocarpa and *Picea engelmannii* are codominant, with *Picea* the more abundant large tree and *Abies* the more abundant smaller tree. *Pseudotsuga menziesii, Larix occidentalis,* and *Pinus contorta* are occasional associates that seldom establish seedlings. These stands are considerably less dense than other *Abies lasiocarpa* types (fig. 15).

The understory is characterized by high shrub coverage, with a mean *Vaccinium membranaceum* cover of 31 percent. Total cover and species richness are also quite high. The most common associated species are *Thalictrum occidentale, Viola orbiculata,* and *Arnica cordifolia.* As stand density increases, *Vaccinium* cover decreases and these forbs become increasingly prominent.

Management implications.—*Vaccinium membranaceum* berries are an attraction in this type, but berry crops are usually poor, particularly under a dense canopy. The brittleness of *Vaccinium* makes this type extremely susceptible to trampling damage. Again, such damage is seldom esthetically displeasing, and campers appear to be willing to clear off enough of the shrub cover to set up tent pads. There appears to be little potential for trail deterioration problems and rehabilitation of these sites should be easier than in higher elevation *Abies lasiocarpa* types, but more difficult than on *THOC* and meadow sites. Increasing stand density will probably inhibit the future establishment of tree species other than *Abies,* and cause reduction in both *Vaccinium* cover and berry production.

Other studies.—Similar vegetation has been described by Hall (1973) in the Blue Mountains of eastern Oregon and Mauk and Henderson (1980, preliminary draft, USDA Forest Service, Intermountain Station) in northern Utah. Related types, in which *Vaccinium membranaceum* is replaced by *V. globulare,* have been described in central Idaho (Steele and others 1981), south-central Montana (Pfister and others 1977), and northwestern Wyoming (Steele and others 1979, preliminary draft, USDA Forest Service, Intermountain Station).

Figure 15.—*Abies lasiocarpa/Vaccinium membranaceum* stand on a slope above the West Fork of the Wallowa River. *Picea engelmannii* is less abundant than usual.

Abies lasiocarpa/Vaccinium scoparium (*ABLA/VASC*)

Description.—This is the most common forested type in the study area, occupying most noncalcareous forested sites between 6,700 ft and 7,600 ft (2 000 and 2 300 m). Glacial scouring was extreme in these areas and, consequently, soils are poorly developed and exposed bedrock is widespread.

The tree stratum is dominated by both *Abies lasiocarpa* and *Picea engelmannii*, but again the importance of *Abies* appears to be increasing with time. The only other associates are *Pinus albicaulis*, at higher elevations, and *Pinus contorta*, at lower elevations.

Although the understory is strongly dominated by *Vaccinium scoparium* (fig. 16), the great environmental diversity encompassed by this type is reflected in a wide variety of understory species that associate with *Vaccinium*. Fifty vascular species were identified in the 19 stands sampled, despite low species richness. In addition to *Vaccinium*, only *Phyllodoce empetriformis*, *Lonicera utahensis,* and *Ledum glandulosum* have mean percent coverages of more than 1 percent, and only *Phyllodoce* is present in more than 50 percent of the stands sampled.

In a preliminary subdivision of this type, four "subtypes" were identified: (1) a *Ledum glandulosum* subtype on particularly moist sites, such as streambanks and lakeshores (stands 81, 72, 69, and 1); (2) a *Phyllodoce empetriformis* subtype in well-drained areas that experience late snowmelt (stands 93, 82, 79, 80, 74, and 71); (3) a *Juncus parryi-Carex rossii* subtype on dry, open, rocky sites (stands 94, 130, 78, and 75); and (4) a *Vaccinium scoparium* subtype on modal sites (stands 77, 10, 2, 76, and 34).

Management implications.—Vegetation is quickly destroyed with recreational use, as *Vaccinium scoparium* is notably susceptible to trampling (Dale and Weaver 1974; Cole 1981). Of the subtypes, the *Ledum glandulosum* and *Phyllodoce empetriformis* subtypes are most susceptible to damage, particularly from early season use during snowmelt. Campsite use should be discouraged on these subtypes; and, where allowed, it should be concentrated rather than dispersed. Visitors should be encouraged to camp on the *Juncus-Carex* subtype, which has little ground cover to be destroyed and soils that are seldom wet. Dispersed use is more appropriate here, except in areas that are heavily used (around the lakes in the Lake Basin, for example). Rehabilitation will be an extremely difficult and slow process throughout this type, however. Maintenance of stand composition, in areas which do not receive much recreational use, should not require much management effort.

Other studies.—Similar vegetation has been recognized from British Columbia (McLean 1970), south through Idaho (Daubenmire and Daubenmire 1968; Steele and others 1981), eastern Oregon (Hall 1973), and Montana (Pfister and others 1977), to Wyoming (Wirsing and Alexander 1975; Hoffman and Alexander 1976; Steele and others 1979, preliminary draft, USDA Forest Service, Intermountain Station), Utah (Mauk and Henderson 1980, preliminary draft, USDA Forest Service, Intermountain Station), and Colorado (Daubenmire and Daubenmire 1968).

Figure 16.—*Abies lasiocarpa/Vaccinium scoparium* stand, with abundant *Phyllodoce empetriformis*.

Pinus albicaulis-Abies lasiocarpa (PIAL-ABLA)

Description.—This type occurs at the highest elevations reached by erect trees, occupying most of the sites between 7,600 and 8,500 ft (2 300 and 2 550 m) that are suitable for tree establishment. It is both widespread and environmentally variable. Further study might allow the differentiation of several types.

These stands are codominated by *Pinus albicaulis* and *Abies lasiocarpa* (fig. 17). The oldest and largest trees are usually *Pinus*, which has a much longer lifespan than *Abies*. With increasing elevation, the height attained by *Abies* decreases, and *Pinus* may occur alone in the highest stands. *Abies* also grows poorly on the partially metamorphosed rocks, where *Pinus* often dominates all size classes. *Picea engelmannii* may be present at lower elevations.

The understory is highly variable. On most, but not all sites, the most consistently abundant species is *Vaccinium scoparium*. *Vaccinium* is particularly common on granitic rocks, where it commonly associates with graminoids such as *Carex rossii*, *Juncus parryi*, and *Oryzopsis exigua*. Other species which can be locally common include *Juniperus communis*, *Carex geyeri*, *Festuca viridula*, *Arnica cordifolia*, and *Linanthastrum nuttallii*. Mean cover is quite low (28 percent), as is species richness.

Management implications.—Most of the ground cover species are susceptible to trampling damage, and rehabilitation at these high elevations is a long, slow process. Moreover, the low productivity of these forests means that supplies of downed wood for fires are quickly eliminated close to campsites. Many of the most popular lakes in the Eagle Cap Wilderness are located in this type, however, suggesting that bare campsites, devoid of downed wood, may have to be accepted, with management striving to limit these impacted areas in size and number. Encouraging the use of stoves or prohibiting fires would help, as would encouraging use of adjacent *Carex nigricans* meadows (see below). Trails, in contrast, are well suited to this type, although in some places the openness of the forest allows hikers to leave the trail. Maintenance of stand composition, in areas which do not receive much recreational use, should not require much management effort.

Other studies.—Similar vegetation has been described elsewhere in the Wallowa Mountains (Head 1959) and from eastern Washington (Daubenmire and Daubenmire 1968), Idaho (Steele and others 1981), and Montana (Pfister and others 1977) south to northwestern Wyoming (Steele and others 1979, preliminary draft, USDA Forest Service, Intermountain Station). The *Pinus albicaulis-Abies lasiocarpa* stands in the Blue Mountains (Hall 1973) have an understory dominated by *Carex geyeri*, which is only occasionally important in the stands in the study area.

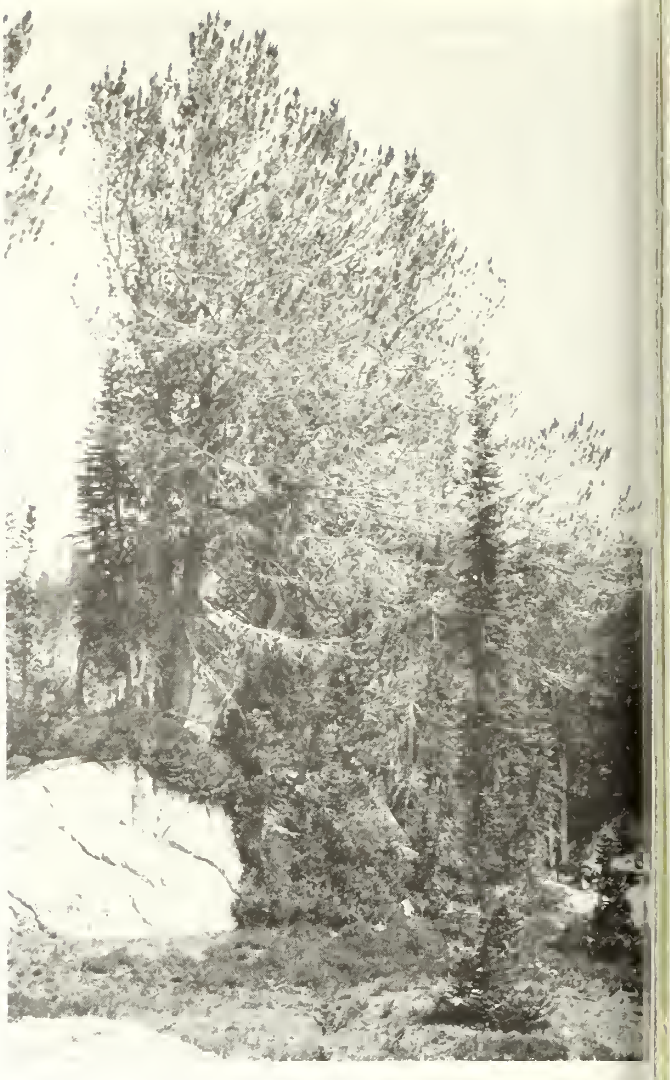

Figure 17.—*Pinus albicaulis-Abies lasiocarpa* stand located near Moccasin Lake. The most abundant undergrowth species are *Vaccinium scoparium*, *Juncus parryi*, and *Carex* sp.

Pinus contorta/Calamagrostis rubescens (PICO/CARU)

Description.—This type is most common on flat benches below 6,000 ft (1 800 m), although it occasionall occurs on other topographic positions and at higher elevations.

The overstory is usually a dense stand of polelike *Pinus contorta* (fig. 18), with widely scattered *Pseudotsuga menziesii* and *Larix occidentalis* individuals. In some of these stands *Pinus contorta* is the only species regenerating; in others *Abies lasiocarpa* is the most abundant seedling. Apparently, *Abies lasiocarpa* is the potential climax tree species in some stands while *Pinus contorta* may be capable of perpetuating itself in others. *Pseudotsuga menziesii* seldom establishes seedlings in these stands, suggesting that very few of these stands are successional to *Pseudotsuga*.

igure 18.—Pole-sized trees are charcteristic of most *Pinus contorta* tands, such as this representative of he *Pinus contorta/Calamagrostis ubescens* community type.

The undergrowth is dominated strongly by *Calamarostis rubescens*. *Spiraea betulifolia* and *Arnica cordiolia* are the only other species found in more than 50 ercent of the stands.

Management implications.—Implications are similar to hose for the *PSME/CARU* type, except that these dense tands do not seem as attractive as the *Pseudotsuga* tands with their well-spaced large trees. They are also ommonly located in areas of cold air accumulation hich makes them less desirable campsite locations. ome type of fire management, other than total suppresion, will be necessary to maintain stands of this type.

Other studies.—Similar vegetation, whether clearly eral or not, has been described in the Blue Mountains of regon (Hall 1973), Idaho (Steele and others 1981), Montana (Pfister and others 1977), northwestern Wyoming (Steele and others 1979, preliminary draft, USDA orest Service, Intermountain Station), and northern Utah Mauk and Henderson 1980, preliminary draft, USDA orest Service, Intermountain Station).

Pinus contorta/Vaccinium membranaceum (PICO/VAME)

Description.—This type occupies midelevation—5,300 to 7,000 ft (1 600 to 2 100 m)—rocky benches, as the *ABLA/VAME* type does, but is more common and widely distributed.

Pinus contorta is the most consistently abundant mature tree, although *Pseudotsuga menziesii* may be locally abundant and *Larix occidentalis* can occasionally be found. *Abies lasiocarpa* is the most abundant seedling in all stands. *Picea engelmannii* and *Pinus contorta* seedlings can also be found in some places.

The undergrowth is less diverse than that associated with an *Abies lasiocarpa* overstory; species richness is less and the predominance of *Vaccinium* is greater. Forb cover, in particular, is quite low and variable. Only *Arnica cordifolia*, *Chimaphila umbellata*, and *Viola orbiculata* were found in more than one of the three stands sampled.

Management implications.—Implications are similar to those of the *ABLA/VAME* type. Perpetuation of these stands will require modification of current fire suppression policies.

Other studies.—Similar seral stands have been described by Hall (1973) in the Blue Mountains of Oregon.

Pinus contorta/Vaccinium scoparium (PICO/VASC)

Description.—This type is common on relatively flat, but rocky sites on granitic substrates, mostly between 6,000 and 7,000 ft (1 800 and 2 100 m). In the study area it is most extensive on the flat valley floor of the West Fork of the Wallowa River below its junction with Lake Creek.

Pinus contorta usually forms extremely dense stands, with many fallen trees on the forest floor. In most of these stands *Abies lasiocarpa* is the most abundant seedling (fig. 19), although *Pinus contorta* is establishing seedlings more frequently than in the other *Pinus contorta* types. The stands in which *P. contorta* exhibits climax behavior are most common on granitic benches where soils are particularly shallow and, therefore, probably droughty and infertile. *Picea engelmannii* is also regenerating frequently in some stands; *Larix occidentalis* can be found scattered through the overstory but is not establishing seedlings.

The undergrowth is sparse and dominated by *Vaccinium scoparium*. Other shrubs are usually absent. Species richness is extremely low. Common associates include *Carex rossii*, *Juncus parryi*, *Oryzopsis exigua*, and *Arnica cordifolia*.

Management implications.—Implications are similar to those of the *ABLA/VASC* type. Perpetuation of these stands will require modification of current fire suppression policies.

Other studies.—Similar vegetation, whether obviously seral or not, has been described in Idaho (Daubenmire and Daubenmire 1968; Steele and others 1981), Montana (Pfister and others 1977), eastern Oregon (Hall 1973), Wyoming (Wirsing and Alexander 1973; Hoffman and Alexander 1976; Steele and others 1979, preliminary draft,

Figure 19.—*Abies lasiocarpa* is the most abundant seedling in this *Pinus contorta/Vaccinium scoparium* stand.

USDA Forest Service, Intermountain Station), and Utah (Mauk and Henderson 1980, preliminary draft, USDA Forest Service, Intermountain Station).

Acer glabrum (ACGL)

Description.—This type occupies the more stable parts of boulder fields below 6,900 ft (2 100 m). It is particularl common on granitics and the Clover Creek greenstone, which produce extensive boulder fields (fig. 20).

Below the *Acer glabrum* layer there commonly is a layer of medium-sized shrubs including *Philadelphus lewisii, Physocarpus malvaceous,* and *Rubus idaeus* var *gracilipes*. Beneath these shrubs are shade-tolerant forbs (e.g., *Galium triflorum, Arenaria macrophylla,* and *Arnica cordifolia*), while more xerophytic species (e.g., *Cystopteris fragilis, Heuchera cylindrica,* and *Penstemon venustus*) inhabit the openings between shrubs.

Management implications.—This type is not suitable for camping, and trail construction requires removal of boulders and surfacing with sand or gravel. Where this has been done, it does provide a highly stable surface, and trails through this type contribute beauty and diversity to the visitor's experience.

Other studies.—No similar types have been described elsewhere.

Figure 20.—*Acer glabrum* shrublands are common on lower elevation boulder slopes.

Alnus sinuata (ALSI)

Description.—This type is found on seepage areas kept free of trees by persistent avalanching. It is most common on granitic rocks between 5,700 and 7,000 ft 1 700 and 2 100 m).

The undergrowth, below the tangle of *Alnus* stems, is characteristically a lush growth of forbs. The most consistently abundant species are *Urtica dioica* var. *lyallii*, *Mertensia paniculata* var. *borealis*, and *Heracleum lanatum*. Total cover is extremely high, as is species richness.

Management implications.—The dense tangle of shrubs makes this type poorly suited for any type of recreational use (fig. 21). Nevertheless it can provide a source of water for people camping on adjacent slopes. Trail deterioration can be a common problem, as a result of trampling impact on moist soils and frequent erosion by debris avalanches. Great care should be taken so that trails cross drainages at right angles and water is not diverted down the trails.

Other studies.—Similar vegetation has been described n the Cascade Mountains of Oregon and Washington Franklin and Dyrness 1973) and in eastern Washington and northern Idaho (Daubenmire and Daubenmire 1968). Hall (1973) describes a similar type, dominated by *Alnus ncana*, in the Blue Mountains of eastern Oregon.

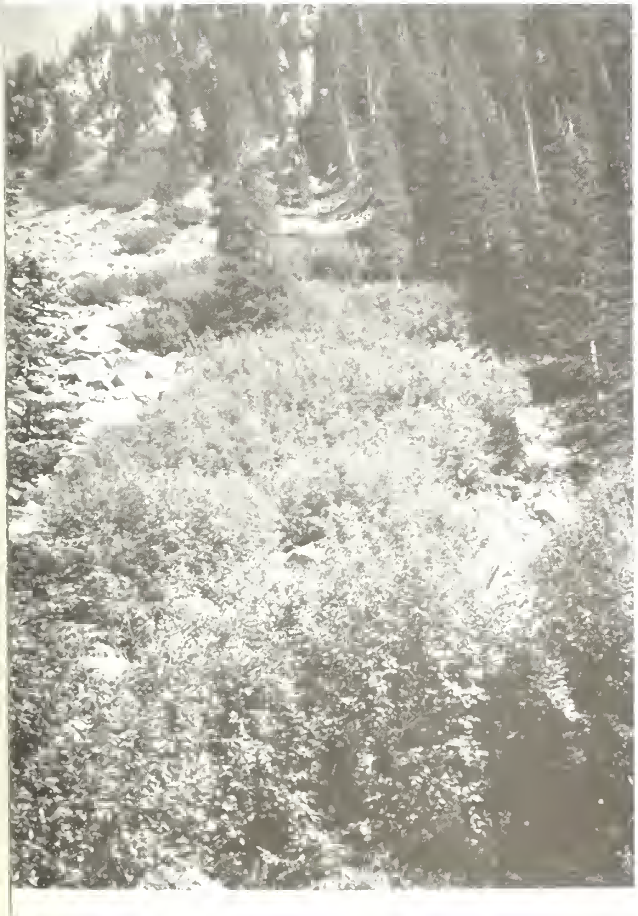

Figure 21.—*Alnus sinuata* shrublands often provide a source of water on dry lopes.

Cercocarpus ledifolius (CELE)

Description.—This type is largely confined to highly exposed, rocky bluffs and south slopes below 7,000 ft (2 100 m). In the study area, it is seldom found on granitic rocks and is particularly conspicuous on calcareous rocks and the Clover Creek greenstones.

Cercocarpus ledifolius creates a prominent layer about 10 ft (3 m) above the ground, which may also include some *Juniperus scopulorum*. The most abundant ground cover species is usually *Agropyron spicatum*. Consistent associates include *Symphoricarpos oreophilus*, *Berberis repens*, *Achillea millefolium*, and *Phacelia hastata* var. *leucophylla*.

Management implications.—This is an attractive and relatively durable type for trails, although construction may be difficult. It is usually too steep and rocky for camping. Rehabilitation would be difficult due to droughty conditions.

Other studies.—Similar vegetation has been described in the Blue Mountains of eastern Oregon (Hall 1973), Idaho (Scheldt and Tisdale 1970), and western Montana (Mueggler and Stewart 1980).

Avalanche Slopes

Description.—Distinctive grassland communities are found on colluvial fans at the base of avalanche paths in the major valley bottoms. These are primarily found below 7,000 ft (2 100 m). Composition varies with rock type and distance from water.

On granitic rocks, these grasslands are usually dominated by *Carex hoodii*, *Elymus glaucus*, and *Bromus carinatus* (fig. 22). Forb cover is dense and diverse, particularly close to watercourses. *Mertensia paniculata* var. *borealis*, *Urtica dioica* var. *lyallii*, and *Agastache urticifolia* are especially common.

On calcareous rocks, *Stipa occidentalis* is the most abundant graminoid, although *Agropyron caninum* var. *majus*, *Agropyron spicatum*, and *Carex geyeri* may be locally abundant. Shrubs, such as *Potentilla fruticosa*, *Symphoricarpos albus*, and *Berberis repens*, are more common than on the granitics.

Communities on other rock types often combine features of these two rather distinct types. Below 5,300 ft (1 600 m), particularly on the Clover Creek greenstone, *Symphoricarpos albus* is prominent.

Management implications.—This type is generally a durable and attractive location for trails and campsites (fig. 23). It offers the best views in the valley bottoms. The graminoid ground cover is relatively resistant to trampling, so that bare areas around campsites are small. Dispersal and rotation of sites is usually preferable to concentration of use. As in all open vegetation types, there is a tendency for people to leave trails. This has resulted in the development of parallel trails in some places. It is also important to insure that seasonal surface drainage is not intercepted by the trail tread. Rehabilitation will probably vary from easy to moderately difficult as soil moisture decreases.

Other studies.—I have found no comparable types described in the literature.

Figure 22.—Abundant tall forbs such as *Mertensia paniculata* and *Heracleum lanatum* characterize the avalanche slope grasslands on granitic substrates.

Figure 23.—Trails through avalanche slope grasslands are usually in good condition. This grassland located along Hurricane Creek has developed on calcareous colluvial material.

High Elevation Grasslands

Description.—This type occurs on dry, exposed ridges and south slopes above 7,000 ft (2 100 m). Such grasslands are considerably more common on the metamorphic rocks than on granitics. Daubenmire and Daubenmire (1968) attribute many of these xerophytic parks to excessive wind transfer of snow from these slopes to the leeward side of the ridges.

Species composition varies with conditions such as rock type and exposure. Although *Festuca viridula* is the most common dominant (fig. 24), *Festuca* grasslands are much more abundant outside of the study area where basalt rock is more widespread. *Carex geyeri* and *Agropyron spicatum* also dominate some of these grasslands, particularly on metamorphic rocks. Shrubs are conspicuously absent among associated species which include *Stipa occidentalis, Carex microptera, Linanthastrum nuttallii, Polygonum phytolaccaefolium,* and *Arenaria aculeata.*

Most of these grasslands were severely overgrazed by sheep in the decades around the turn of the century. Most researchers suggest that originally graminoids were more dominant than today (Sampson 1909; Pickford and Reid 1942; Strickler 1961; Hall 1973). The forb component is considered to be largely an artifact of this period of overgrazing. *Stipa* spp., *Linanthastrum nuttallii, Eriogonum* spp., and *Polygonum phytolaccaefolium,* among others, are indicative of overgrazing. Fair amounts of these species occur in the stands sampled and illustrate the seral nature of the majority of this community type.

Figure 24.—*Festuca viridula* is the most abundant species in this high-elevation grassland.

Management implications.—This type provides a relatively durable location for trails and campsites. Trail grades should be gentle, however, because the deep soils are prone to erosion. Dispersal and rotation of campsites should be encouraged. The availability of campsites, however, is often limited by lack of water and the infrequency of level ground. Rehabilitation will be a slow process and continued grazing by pack stock will prolong recovery from the period of sheep grazing.

Other studies.—Similar vegetation has been described in the Blue Mountains (Hall 1973) and in eastern Washington and northern Idaho (Daubenmire and Daubenmire 1968). *Festuca viridula* grasslands have also been described in rain shadow areas in western Washington (Franklin and Dyrness 1973) and western Oregon (Van Vechten 1960), but the associated species are usually quite different.

Phyllodoce empetriformis (PHEM)

Description.—This type is common between 7,500 and 9,000 ft (2 250 and 2 700 m), on gently concave slopes that are well drained but have a short snow-free period. It is most common on north-facing microtopography in cirque basins. At its lower extremity, it intermingles with subalpine forest and meadow (fig. 25), but also extends above timberline.

The two heathers, *Phyllodoce empetriformis* and *Cassiope mertensiana*, form a consistent low shrub layer. *Phyllodoce* is always more abundant but *Cassiope* increases in abundance with elevation. In some places, *Vaccinium scoparium* is also conspicuous.

Consistent forb associates include *Potentilla flabellifolia*, *Veronica cusickii*, *Erigeron peregrinus* var. *scaposus*, *Ligusticum tenuifolium*, *Antennaria lanata*, and *Castilleja chrysantha*. Graminoids are less abundant than forbs, but *Carex nigricans* and *Luzula hitchcockii* were found in four of the five stands sampled.

Figure 25.—*Phyllodoce empetriformis* communities (foreground) frequently intermingle with *Pinus albicaulis-Abies lasiocarpa* stands and subalpine meadows.

Management implications.—This type is particularly susceptible to damage, because the brittle stems of the heathers are easily broken when trampled. Because the attractiveness of this type encourages leaving the trail for a closer view, campsites and trails should avoid this type as much as possible. Trails through this type also tend to deteriorate, particularly in response to early season use, because the late snowmelt keeps the soil saturated. Although recovery of grasses and forbs should be relatively rapid, recovery of the heathers should be a slow process.

Other studies.—Similar vegetation has been described in western Oregon and Washington (Kuramoto and Bliss 1980; Henderson 1973; Campbell 1973; Douglas and Bliss 1977; del Moral 1979). They also occur, but have not been described, in the Northern Rocky Mountains.

Carex spectabilis (CASP)

Description.—This type occurs most frequently on steep, north slopes, between 7,500 and 9,000 ft (2 250 to 2 700 m), where the snow melts late in the summer. Soils remain saturated for much of the summer and slopes are usually unstable (fig. 26).

Although *Carex spectabilis* is the most abundant species, *Luzula hitchcockii* is consistently conspicuous. Species richness is quite high, but total cover is low (45 percent). The most consistent forb associates are *Antennaria lanata, Aster alpigenus,* and *Veronica cusickii.*

Management implications.—Late snowmelt and unstable slopes make this a poor location for trails or campsites. Saturated soils contribute to a high potential for soil erosion when subjected to heavy use. Usually these sites can be avoided by relocating trails on drier, more stable slopes. The potential for revegetation is probably greater than on some of the drier adjacent sites, such as *PIAL-ABLA* sites, but it will be necessary to guard against continued erosion first.

Other studies.—Plant communities dominated by *Carex spectabilis* have been described in the Olympic Mountains (Kuramoto and Bliss 1970), North Cascades (Douglas and Bliss 1977), and Wenatchee Mountains (del Moral 1979) of Washington. Except for the Wenatchee communities, these occupy very different environments from the Wallowa type, however.

Carex nigricans (CANI)

Description.—This type occurs between 7,500 and 9,000 ft (2 250 and 2 700 m), in poorly drained depressions where snowmelt is late. Although it occurs frequently, it never covers a very large area.

Carex nigricans forms a dense, tough sod that affords little growing space for other plants (fig. 27). *Carex spectabilis* and *Juncus drummondii* var. *subtriflorus* are consistent graminoid associates. The most consistently abundant forbs are *Antennaria alpina, Erigeron peregrinus* var. *scaposus, Potentilla flabellifolia, Veronica cusickii,* and *Viola adunca* var. *bellidifolia.* Total cover is high (79 percent), but species richness is relatively low.

Figure 26.—*Carex spectabilis* communities occupy steep, north slopes close to timberline, such as this slope along the trail between Moccasin Lake and Glacier Pass. Trail deterioration is a common problem in this community type.

Figure 27.—The dense *Carex nigricans* sod in this small depression near Glacier Lake is occasionally interrupted by other species such as *Antennaria alpina,* the light-colored forb in the foreground.

Management implications.—This type provides a good location for campsites, provided that use occurs after soils drain. Although impacts are highly visible, impacted areas are usually small (fig. 28) because *Carex nigricans* is resistant to trampling. In all but the most heavily used areas, impacts at high elevations could probably be reduced by encouraging dispersed, infrequent camping on *CANI* meadows. Campers should be careful not to leave fire scars and should dispose of their wastes in adjacent *PIAL-ABLA* forests. *Carex nigricans* has also been successfully used to revegetate recreation sites. Trails are subject to deterioration if used when soils are still saturated, but they are less prone to disturbance than adjacent *PHEM* and *CASP* sites. Where possible, trails in this landscape should be located on rocky, *PIAL-ABLA* sites.

Other studies.—Similar vegetation has been described throughout the Pacific Northwest, north to southern Alaska (see Douglas and Bliss 1977 for references), and south to Colorado (Cox 1933).

Bare Rock and Fell-field

Description.—A wide variety of species and vegetation types occur at the highest elevations in the study area. Vegetation varies with rock type and geomorphic type, from bare rock to fell-fields and talus slopes (fig. 29). The five stands sampled include a broad range of this variability. Wiry graminoids and cushion and matted forbs are most abundant. The species most consistently present are *Trisetum spicatum*, *Aster alpigenus*, and *Ivesia gordonii*. *Dryas octopetala* var. *hookeriana* may be locally dominant. Total cover is usually low.

Management implications.—Although many of these communities are relatively resistant to trampling damage, many are not and recovery is an extremely slow process in all types. Willard and Marr (1971) estimated that recovery of similar communities in Colorado could take as long as 1,000 years. Therefore, recreational use in these types should not be encouraged. Where use is heavy, such as on the climb to the top of Eagle Cap, trails should be constructed and hikers should be encouraged to stay on the trail.

Krummholz[5]

Description.—Toward the upper limits of tree growth, trees exhibit a stunted, wind-shorn growth form. Depending upon slope, aspect, and substrate this type can occur at varied elevations. For example, meter-high *Pinus albicaulis* survive above 9,500 ft (2 850 m) on the gentle, granitic, south slope of Eagle Cap. On the calcareous rocks, *Pinus flexilis* is the major krummholz tree species, but is seldom found above 7,000 ft (2 100 m) in the study area. *Abies lasiocarpa* is the other common krummholz tree species. Although it is not found at elevations as high as *Pinus albicaulis*, it is more prevalent than *Pinus* on talus slopes.

Figure 28.—The minimal amount of vegetation loss on this well-developed campsite is characteristic of campsites located in the damage-resistant *Carex nigricans* community type.

Figure 29.—The short stature of the plants growing on this fell-field above Ice Lake is characteristic of high-elevation sites.

Of the various understory species, the most consistently common include *Ribes montigenum*, *Juniperus communis*, *Vaccinium scoparium*, *Polemonium pulcherrimum*, *Valeriana sitchensis*, and *Thalictrum occidentale*.

Management implications.—While this type is a good location for trails, the susceptible ground cover, paucity of downed wood, and slow recovery rates makes it a poor choice for campsites. These sites are often windy, which encourages campers to construct shelters from the wind.

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[5] The following community types were observed but not sampled, either because of their limited extent or their great variability.

Populus tremuloides (POTR)

Description.—This type is occasionally found below 6,000 ft (1 800 m), usually on boulder slopes which appear to be more stable and moist than those occupied by the *Acer glabrum* type (fig. 30). Both types occur in close proximity but usually remain separated. Associates of *Populus* are varied but usually consist of species from both the *Acer glabrum* and *Alnus sinuata* types (for example, *Galium triflorum, Arnica cordifolia, Urtica dioica* var. *lyallii,* and *Rubus parviflorus*).

Management implications.—Trails and campsites should not be constructed in this type because people carve their initials in the trees. The trees are thin-barked and extremely susceptible to damage (Hinds 1976). This type is highly scenic, however, so trails might be routed around these types but within viewing distance.

Artemisia tridentata (ARTR)

This uncommon type occurs sporadically over a wide elevational range. It is most common on south slopes on the metamorphic rocks. The dominant shrub, *Artemisia tridentata* var. *vaseyana,* is usually associated with an abundant graminoid such as *Agropyron spicatum, Carex geyeri,* or *Festuca viridula. Berberis repens, Achillea millefolium, Eriogonum heracleoides,* and *Hieracium albertinum* are also frequently encountered.

Subalpine Meadows

Description.—These meadows are common between 7,000 and 8,000 ft (2 100 and 2 400 m) in depressions carved by the glaciers. They commonly occur adjacent to lakes or on the sites of former lakes that have been filled with alluvium and organic material (fig. 31). They are perennially moist, with some parts inundated for most of the year. Although they are seldom all present in one area, the following zones can be delimited:

1. At low elevations (below 7,200 ft [2 160 m]) *Carex rostrata* is usually the most abundant species in standing water.
2. Elsewhere, *Eleocharis pauciflora* is the most abundant species in standing water.
3. *Carex scopulorum* dominates sites surrounding standing water, which are always wet but rarely inundated.
4. *Allium validum* often dominates soils further removed from standing water, but below seepage areas. A distinctive group of forbs is common in this and the following zone. It consists of *Veronica cusickii, Ligusticum tenuifolium, Viola adunca* var. *bellidifolia, Castilleja chrysantha, Senecio cymbalarioides, Erigeron peregrinus* var. *scaposus, Potentilla flabellifolia, Dodecatheon alpinum,* and *Pedicularis groenlandica.*
5. Drier parts of the meadow may be dominated by the previously mentioned forbs, with or without *Deschampsia caespitosa,* which is often thought to have been the dominant in meadows of this type under pristine conditions.
6. Before entering forest there is often a zone dominated by *Kalmia microphylla, Gaultheria humifusa,* and *Vaccinium caespitosum.*

Figure 30.—*Populus tremuloides* stands usually occupy bouldery sites and occasionally occupy other disturbed situations.

Figure 31.—Subalpine meadow adjacent to Little Frazier Lake, elevation 7,500 ft. The north slope in the background has *Phyllodoce empetriformis* communities around the base and krummholz above.

Management implications.—The vegetation of these meadows is not as fragile as many people have thought (fig. 32). Vegetation change in campsites and along trails is usually less than in adjacent forested types (Cole 1981). Nevertheless, trail erosion can be a severe problem due to perennially moist and uniformly fine-textured soils. Sets of parallel, deep, narrow trails are common in these meadows (fig. 33). Trampling by pack stock can be particularly damaging. Moreover, impacts are highly visible and these meadows are one of the prime scenic resources of the area. Recovery rates vary from rapid, in the moister types, to moderate. Even on drier sites they are generally more rapid than in the forests.

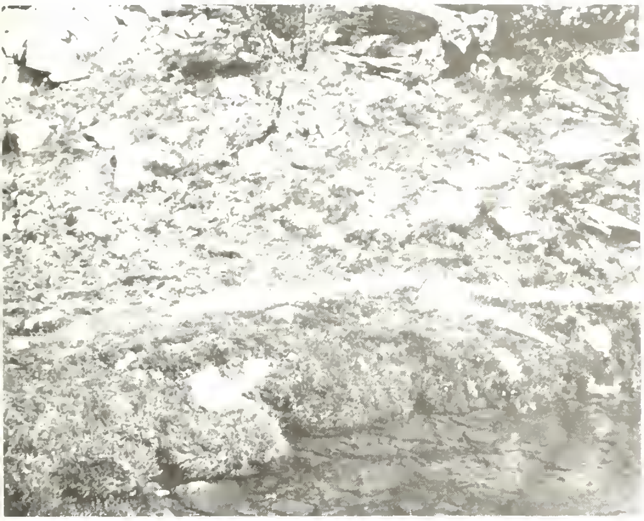

Figure 32.—Trail along the shore of Glacier Lake is quite evident where the ground cover consists of *Vaccinium scoparium*. The trail disappears when t enters subalpine meadow on the left, llustrating the relative resistance of his community type.

GENERAL DISTRIBUTION OF COMMUNITY TYPES

The distributional patterns of forested community types are broadly similar on the noncalcareous rock types. *Pseudotsuga menziesii* is the most common tree species on lower elevation slopes, although *Pinus ponderosa*, *Pinus contorta*, and *Larix occidentalis* may be locally abundant. Community types with *Physocarpus malvaceous* and *Calamagrostis rubescens* understories are the most common, with *C. rubescens* types on smooth sloping benches, and *P. malvaceous* types on the boulder-strewn slopes that alternate with these benches. The *Thalictrum occidentale* type occurs on some north-facing slopes and *Agropyron spicatum* types occur on some south-facing slopes, especially on the nongranitic rocks.

Adjacent valley bottoms are most frequently populated by *Abies grandis* (below 5,300 ft [1 600 m]), *Picea engelmannii*, or *Pinus contorta*. *Abies lasiocarpa* is usually the most abundant seedling. *Pinus contorta* appears to be capable of self-perpetuation in some stands, particularly on dry, shallow granitic soils. This situation appears similar to that in the Canadian Rockies, where LaRoi and Hnatiuk (1980) report *P. contorta* may be "an edaphic climax on certain dry, poor sites in the lower subalpine." *Thalictrum occidentale* and *Vaccinium scoparium* are the most abundant understory types, although *Vaccinium membranaceum* may be abundant on some rough, rocky sites.

Above 7,000 ft (2 100 m), *Abies lasiocarpa* dominates stands in valley bottoms, on lower slopes, and on upper north-facing slopes. *Pinus contorta* and *Picea engelmannii* are associates in some locales. The *Vaccinium scoparium* understory type occurs throughout these forests, extending to lower elevations in valley bottoms, usually in conjunction with *Pinus contorta*. The *Pinus albicaulis-Abies lasiocarpa* type dominates high elevation rocky ridges and south-facing slopes.

igure 33.—Multiple trails are common n the fine-textured, perennially moist oils of subalpine meadows. As many s six parallel trails can be distinuished in this photograph.

Despite these general similarities, the relative importance of several community types differs between granitic and noncalcareous metamorphic rocks. *Pinus contorta* forms monospecific stands over much of the midelevation forest, but almost exclusively on granitic substrates. Most of the stands occur on flat, rocky benches, where soils are poorly developed and where cold air often collects. *Vaccinium scoparium* and, less frequently, *Vaccinium membranaceum* are the most common understory types.

Pseudotsuga menziesii occurs on granitic rocks, but is much more common on the metamorphics where it extends to higher elevations and occupies more varied topographic sites. *Calamagrostis rubescens, Physocarpus malvaceous,* and *Agropyron spicatum* understory types are more common than understories dominated by ericads. Similar differences in the distribution of tree species have been noted by Despain (1973) in the Bighorn Mountains of Wyoming.

On calcareous rocks, altitudinal zonation is less well developed, largely because forests seldom extend above 7,000 ft (2 100 m) (fig. 3). *Picea engelmannii* is the most abundant tree species in the valley bottoms, although *Abies lasiocarpa* is a frequent associate above 6,000 ft (1 800 m). *Thalictrum occidentale* is the most common understory type in these forests. *Pseudotsuga menziesii,* usually in conjunction with the *Berberis repens* understory type, occurs locally in valley bottoms, but this c.t. is most characteristic of lower slopes. *Calamagrostis rubescens* types can also be found on slopes above the valley bottom, while *Pinus flexilis* dominates the steep, rocky upper slopes.

Two other coniferous tree species are occasionally encountered in the Wallowa Mountains. *Juniperus scopulorum* is locally common on xeric sites, particularly on calcareous rocks. *Tsuga mertensiana*, although infrequently noted in the Wallowa Mountains, is a rare associate of *Abies lasiocarpa* on some north-facing slopes at about 7,000 ft (2 100 m), elsewhere in the Wallowas. I found no *Tsuga* in the study area.

The nonforested community types at lower elevations are usually found on boulder slopes, steep south-facing slopes, and avalanche paths. *Acer glabrum* and, less frequently, *Populus tremuloides* types are most common on boulder slopes. The *Cercocarpus ledifolius* type is most common on steep, rocky south-facing slopes, particularly on nongranitic rock types. Various communities, classified under avalanche slope types, and the *Alnus sinuata* type occur on avalanche slopes, with the *Alnus* most common around seeps.

In the subalpine zone, 7,000 to 8,000 ft (2 100 to 2 400 m), meadows are interspersed with forest, occupying depressional areas which are perennially moist. At higher elevations alpine types are widespread. The *Carex nigricans* type occurs in depressional areas with late snowmelt. *Carex spectabilis* types are common on adjacent slopes with late snowmelt and on unstable gravelly substrates. *Phyllodoce empetriformis* occupies warmer slopes with earlier snowmelt, usually with a more southerly aspect. Grassland communities, most frequently dominated by *Festuca viridula,* occur on the warmest and driest exposures and are most common on substrates other than granite. Bare rock and fell-field communities occupy the highest ridgetops and other highly exposed sites.

CONCLUSIONS

As emphasized in the introduction, this classification system is a preliminary one. It is presented here for two reasons—to provide species data and descriptions of common plant community types in an area which has been largely neglected in the literature and to provide brief management suggestions for major community types. In the future this system should be refined and expanded to include the entire Wallowa Mountains. Ideally, it should be developed into a habitat type classification system that stratifies land according to site potential. Maps based on habitat types have the advantage of changing less over time. A careful documentation of all existing vegetation types, regardless of their successional status, should supplement the habitat type classification, however.

Several of the types described above need additional work. Of the coniferous forest types, those with *Berberis repens, Thalictrum occidentale,* and *Vaccinium scoparium* ground covers occupy broad environmental spectra and could probably be subdivided on the basis of indicator species. The *Berberis repens* type also needs to be more adequately delimited from other types. Additional nonconiferous types could be identified, and some of the environmentally grouped types, such as high elevation grasslands, could be floristically defined (for example *Festuca viridula* type).

With this stratification, observation of and research into impact problems could be organized by habitat type. As information accumulates it should be possible to relocate trails on durable types, close campsites on fragile sites, avoid sensitive wildlife habitat, direct pack stock to productive but durable grazing areas, and adapt a rehabilitation program to the specific needs of a damaged site. Management actions could incorporate an ever-increasing understanding of site differences.

Furthermore, the baseline data on existing vegetation types, such as the stand data provided here, will be increasingly valuable as a measure of conditions in the 1970's. It can be used to monitor changes in conditions over time and to evaluate the success of management programs, such as a natural fire policy, designed to perpetuate natural conditions.

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APPENDIXES

APPENDIX 1— KEY TO MAJOR COMMUNITY TYPES

Key to Coniferous Forest Types

1. Trees stunted, generally not more than 16 ft (5 m) tall	Krummholz
1. Not as above	2
2. *Pinus flexilis* dominant or co-dominant in overstory	*PIFL*
2. Not as above	3
3. *Pinus albicaulis* dominant or co-dominant in overstory	*PIAL-ABLA*
3. Not as above	4
4. *Abies grandis* dominant or co-dominant in overstory	*ABGR/THOC*
4. Not as above	5
5. *Abies lasiocarpa* or *Picea engelmannii* dominant in overstory	6
5. Not as above	8
6. *Vaccinium membranaceum* cover greater than 10 percent	*ABLA/VAME*
6. Not as above	7
7. *Vaccinium scoparium* dominant in undergrowth	*ABLA/VASC*
7. Not as above, *Thalictrum occidentale*, *Arnica cordifolia*, or *Pyrola secunda* dominant in undergrowth	*ABLA/THOC*
8. *Pinus contorta* dominant in overstory	9
8. Not as above	11
9. *Calamagrostis rubescens* dominant in undergrowth	*PICO/CARU*
9. Not as above	10
10. *Vaccinium membranaceum* dominant in undergrowth	*PICO/VAME*
10. Not as above, *Vaccinium scoparium* abundant	*PICO/VASC*
11. *Agropyron spicatum* dominant in undergrowth	*PSME/AGSP*
11. Not as above	12
12. *Physocarpus malvaceous* dominant in undergrowth	*PSME/PHMA*
12. Not as above	13
13. *Calamagrostis rubescens* dominant in undergrowth	*PSME/CARU*
13. Not as above	14
14. *Thalictrum occidentale* dominant in undergrowth	*PSME/THOC*
14. *Thalictrum occidentale* less abundant than *Berberis repens, Spiraea betulifolia, Symphoricarpos albus,* or *S. oreophilus*	*PSME/BERE*

Key to Nonconiferous Types

1. Dominants are shrubs or broadleaf trees greater than 3 ft (1 m) tall	2
1. Not as above	7
2. *Cercocarpus ledifolius* abundant	*CELE*
2. Not as above	3
3. *Populus tremuloides* dominant	*POTR*
3. Not as above	4
4. *Acer glabrum* dominant	*ACGL*
4. Not as above	5
5. *Artemisia tridentata* abundant	*ARTR*
5. Not as above	6
6. *Alnus sinuata* abundant	*ALSI*
6. Not as above	Undifferentiated type
7. Community occurs on avalanche slopes	Avalanche slopes
7. Not as above	8
8. *Phyllodoce empetriformis* dominant	*PHEM*
8. Not as above	9
9. *Carex spectabilis* dominant	*CASP*
9. Not as above	10
10. *Carex nigricans* dominant	*CANI*
10. Not as above	11
11. Graminoids dominant, elevation greater than 7,000 ft (2 100 m)	12
11. Not as above	13
12. Community occupies xeric exposures; *Agropyron spicatum, Carex geyeri,* or *Festuca viridula* abundant	High elevation grasslands
12. Community occupies mesic or hydric sites	Subalpine meadows
13. Community occurs on bare rock or fell-field; elevation greater than 7,900 ft (2 400 m)	Bare rock and fell-field
13. Not as above	Undifferentiated type

APPENDIX 2 —
BASIC DATA ON COMMUNITY TYPES

Table 1.—Dynamic status of tree species as interpreted from sample stand data C = major climax, c = minor climax, S = major seral, s = minor seral, ( ) = in certain areas of the type, a = accidentals

Community type	*Pinus ponderosa*	*Pseudotsuga menziesii*	*Larix occidentalis*	*Abies grandis*	*Abies lasiocarpa*	*Picea engelmannii*	*Pinus albicaulis*	*Pinus contorta*	*Juniperus scopulorum*	*Pinus flexilis*
PSME/AGSP	S	C	—	—	—	—	—	—	—	
PSME/PHMA	a	C	s	a	a	a	—	a	—	-
PSME/CARU	s	(C)	S	—	(C)	s	a	s	a	(s*)
PSME/THOC	—	S	S	—	C	S*	—	—	(s)	—
PSME/BERE	a	C	—	a	(c)	(c)	—	—	s*	—
PIFL	—	c	—	—	—	—	—	—	c	C
ABGR/THOC	—	s	s	C	(c)	(s*)	—	—	—	—
ABLA/THOC	a	s	s	—	C	C*	a	s	—	—
ABLA/VAME	—	s	s	—	C	S*	—	s	—	—
ABLA/VASC	—	—	—	—	C	S*	(c)	s	—	-
PIAL-ABLA	—	—	—	—	C	s	C	—	—	—
PICO/CARU	—	s	s	—	C	s	—	S*	—	—
PICO/VAME	—	s	s	—	C	s	—	S	—	—
PICO/VASC	—	—	s	—	C	S*	—	S*	—	—

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*Status difficult to determine. May be climax in some places

Table 2.—Tree population structure by community type. Mean number of trees by species per 200 m^2 macroplot and stems/ha

Community type	No. of stands sampled	Mean no. of trees per 200 m^2 macroplot — Diameter (at breast height) classes in dm											Total
		<0.2	.2-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	>9	
PSME/AGSP	2												
Pipo		—	—	—	—	0.5	—	—	—	—	1.0	—	1.5
Psme		3.5	0.5	2.0	1.0	.5	1.0	—	—	—	—	—	8.5
Stems/ha		*175*	*25*	*100*	*50*	*50*	*50*	—	—	—	*50*	—	*500*
PSME/PHMA	6												
Pipo		—	—	—	—	—	0.2	—	—	—	—	—	0.2
Psme		2.8	5.3	3.0	2.0	1.3	1.7	0.7	0.2	—	0.2	—	17.2
Laoc		—	—	.2	.5	.5	—	—	—	—	—	—	1.2
Abgr		.2	—	.7	—	—	—	—	—	—	—	—	.9
Abla		—	.8	—	—	—	.2	—	—	—	—	—	1.0
Pien		—	.2	.5	—	—	—	—	—	—	—	—	.7
Pico		—	—	—	.2	—	—	—	—	—	—	—	.2
Stems/ha		*150*	*315*	*220*	*135*	*90*	*105*	*35*	*10*	—	*10*	—	*1 070*
PSME/CARU	8												
Pipo		—	—	—	—	—	0.3	0.3	0.1	0.5	—	—	1.2
Psme		3.3	2.1	1.6	1.6	2.5	1.5	.8	.6	.1	0.1	—	14.2
Laoc		—	—	.3	—	.4	.5	.1	.6	.1	—	—	2.0
Abla		9.4	1.0	.6	.3	.1	.1	—	—	—	—	—	11.5
Pien		1.0	—	.1	.1	—	—	—	—	—	—	—	1.2
Pial		—	—	.1	—	—	—	—	—	—	—	—	.1
Pico		.4	.3	.3	.6	.1	—	—	—	—	—	—	1.7
Jusc		.1	—	—	—	—	—	—	—	—	—	—	.1
Pifl		.1	.1	.1	—	.1	—	—	—	—	—	—	.4
Stems/ha		*715*	*175*	*155*	*130*	*160*	*120*	*60*	*65*	*35*	*5*	—	*1 620*
PSME/THOC	4												
Psme		.8	0.3	0.3	1.3	0.5	2.3	3.0	0.3	0.3	—	—	9.1
Laoc		—	—	—	—	.3	.5	1.5	1.0	—	—	—	3.3
Abla		9.3	2.8	1.3	.3	—	—	—	—	—	—	—	13.7
Pien		4.0	1.3	.3	.3	—	—	—	—	—	—	—	5.9
Jusc		.3	.8	—	—	—	—	—	—	—	—	—	1.1
Stems/ha		*720*	*260*	*95*	*95*	*40*	*140*	*225*	*65*	*15*	—	—	*1 655*
PSME/BERE	3												
Pipo		—	—	—	—	—	—	—	—	0.3	—	—	0.3
Psme		2.7	5.0	3.7	3.3	3.3	1.3	0.7	—	—	—	—	20.0
Abgr		—	.3	—	—	—	—	—	—	—	—	—	.3
Abla		.7	—	—	—	—	—	—	—	—	—	—	.7
Pien		.7	.3	1.7	.7	—	—	—	—	—	—	—	3.4
Jusc		4.0	1.7	1.0	—	—	—	—	—	—	—	—	6.7
Stems/ha		*405*	*365*	*320*	*200*	*165*	*65*	*35*	—	*15*	—	—	*1 570*
PIFL	2												
Psme		—	0.5	0.5	0.5	0.5	—	—	—	—	—	—	2.0
Jusc		4.0	1.0	—	.5	—	—	—	—	—	—	—	5.5
Pifl		2.0	1.0	.5	1.0	1.0	0.5	1.0	—	—	—	—	7.0
Stems/ha		*300*	*125*	*50*	*100*	*75*	*25*	*50*	—	—	—	—	*725*
ABGR/THOC	3												
Psme		—	—	—	—	—	1.3	0.3	—	—	—	—	1.6
Laoc		1.3	—	—	—	0.7	0.3	.7	0.3	—	—	—	3.3
Abgr		4.7	6.7	14.3	2.0	1.3	1.3	.3	—	—	—	—	30.6
Abla		1.3	.3	.3	.7	—	—	—	—	—	—	—	2.6
Pien		2.7	4.0	3.3	—	—	—	—	—	—	—	—	10.0
Stems/ha		*500*	*550*	*895*	*135*	*100*	*145*	*65*	*15*	—	—	—	*2 405*

(con.)

Table 2. (con.)

Community type	No. of stands sampled	Mean no. of trees per 200 m^2 macroplot											
		Diameter (at breast height) classes in dm											
		<0.2	.2-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	>9	Total
ABLA/THOC	18												
Pipo		—	—	—	—	—	+	—	—	—	—	—	+
Psme		0.1	0.1	0.3	+	0.3	0.2	0.4	+	0.1	+	—	1.5
Laoc		—	—	+	—	.2	.4	+	0.2	+	+	0.1	.9
Abla		51.7	12.4	7.0	3.3	1.7	.4	.2	+	—	—	—	76.7
Pien		3.4	1.5	2.6	1.2	1.6	1.7	.9	+	+	0.1	+	13.0
Pial		—	—	.1	.2	.1	—	—	—	—	—	—	.4
Pico		.3	—	.4	.5	.4	—	—	—	—	—	—	1.6
Stems/ha		*2 775*	*700*	*520*	*260*	*215*	*135*	*75*	*10*	*5*	*5*	*5*	*4 705*
ABLA/VAME	3												
Psme		—	0.3	—	—	0.7	1.3	—	—	—	—	—	2.3
Laoc		—	—	—	—	—	—	0.3	—	—	—	—	.3
Abla		12.7	6.7	6.0	2.3	1.3	—	—	—	—	—	—	29.0
Pien		8.7	3.0	1.3	1.0	2.7	0.3	—	—	—	—	—	17.0
Pico		—	—	—	1.0	.3	—	—	—	—	—	—	1.3
Stems/ha		*1 070*	*500*	*365*	*215*	*250*	*80*	*15*	—	—	—	—	*2 495*
ABLA/VASC	19												
Abla		41.3	10.4	5.4	4.2	2.3	0.5	0.1	—	—	—	—	64.2
Pien		2.9	.8	1.3	1.4	1.9	.6	.2	0.2	0.1	—	—	9.4
Pial		1.7	.5	—	.1	.1	.2	+	+	—	+	+	2.6
Pico		1.2	.3	.4	.8	.1	—	—	—	—	—	—	2.8
Stems/ha		*2 355*	*600*	*355*	*325*	*220*	*65*	*15*	*10*	*5*	+	+	*3 950*
PIAL/ABLA	10												
Abla		31.0	12.2	6.0	1.2	0.4	0.3	—	—	—	—	—	51.1
Pien		.5	.5	—	.3	—	—	—	—	—	—	—	1.3
Pial		14.8	5.1	3.5	2.4	1.9	0.6	—	—	0.1	0.1	0.1	28.6
Stems/ha		*2 315*	*890*	*475*	*195*	*115*	*45*	—	—	*5*	*5*	*5*	*4 050*
PICO/CARU	4												
Laoc		—	—	—	0.3	—	0.3	—	—	—	—	—	0.6
Psme		—	0.5	0.3	—	—	—	0.3	—	—	—	—	1.1
Abla		7.0	1.0	1.7	—	—	—	—	—	—	—	—	9.7
Pien		1.3	—	—	—	—	—	—	—	—	—	—	1.3
Pico		17.8	26.0	9.3	11.5	.5	.3	—	—	—	—	—	65.4
Stems/ha		*1 305*	*1 375*	*565*	*590*	*25*	*30*	*15*	—	—	—	—	*3 905*
PICO/VAME	3												
Laoc		—	—	—	0.3	—	—	0.3	—	—	—	—	0.6
Psme		1.3	—	—	—	—	0.3	1.0	—	—	—	—	2.6
Abla		37.3	8.3	0.7	—	—	—	—	—	—	—	—	46.3
Pien		3.7	1.3	—	0.7	—	—	—	—	—	—	—	5.7
Pico		1.7	.3	9.0	5.3	0.3	—	—	—	—	—	—	16.6
Stems/ha		*2 200*	*495*	*485*	*315*	*15*	*15*	*65*	—	—	—	—	*3 590*
PICO/VASC	5												
Laoc		—	—	—	—	—	0.8	0.2	—	—	—	—	1.0
Abla		52.0	8.4	2.0	1.2	—	0.2	—	—	—	—	—	63.8
Pien		10.0	1.6	0.8	—	—	—	—	—	—	—	—	12.4
Pial		1.0	—	—	—	—	—	—	—	—	—	—	1.0
Pico		22.6	18.8	11.8	5.2	1.2	—	—	—	—	—	—	59.6
Stems/ha		*4 280*	*1 440*	*730*	*320*	*60*	*50*	*10*	—	—	—	—	*6 890*

Table 2.—Tree population structure by community type. Mean number of trees by species per 200 m² macroplot and stems/ha

Community type	No. of stands sampled	Mean no. of trees per 200 m² macroplot											Total
		Diameter (at breast height) classes in dm											
		<0.2	.2-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	>9	
PSME/AGSP	2												
Pipo		—	—	—	—	0.5	—	—	—	—	1.0	—	1.5
Psme		3.5	0.5	2.0	1.0	.5	1.0	—	—	—	—	—	8.5
Stems/ha		*175*	*25*	*100*	*50*	*50*	*50*	—	—	—	*50*	—	*500*
PSME/PHMA	6												
Pipo		—	—	—	—	—	0.2	—	—	—	—	—	0.2
Psme		2.8	5.3	3.0	2.0	1.3	1.7	0.7	0.2	—	0.2	—	17.2
Laoc		—	—	.2	.5	.5	—	—	—	—	—	—	1.2
Abgr		.2	—	.7	—	—	—	—	—	—	—	—	.9
Abla		—	.8	—	—	—	.2	—	—	—	—	—	1.0
Pien		—	.2	.5	—	—	—	—	—	—	—	—	.7
Pico		—	—	—	.2	—	—	—	—	—	—	—	.2
Stems/ha		*150*	*315*	*220*	*135*	*90*	*105*	*35*	*10*	—	*10*	—	*1 070*
PSME/CARU	8												
Pipo		—	—	—	—	—	0.3	0.3	0.1	0.5	—	—	1.2
Psme		3.3	2.1	1.6	1.6	2.5	1.5	.8	.6	.1	0.1	—	14.2
Laoc		—	—	.3	—	.4	.5	.1	.6	.1	—	—	2.0
Abla		9.4	1.0	.6	.3	.1	.1	—	—	—	—	—	11.5
Pien		1.0	—	.1	.1	—	—	—	—	—	—	—	1.2
Pial		—	—	.1	—	—	—	—	—	—	—	—	.1
Pico		.4	.3	.3	.6	.1	—	—	—	—	—	—	1.7
Jusc		.1	—	—	—	—	—	—	—	—	—	—	.1
Pifl		.1	.1	.1	—	.1	—	—	—	—	—	—	.4
Stems/ha		*715*	*175*	*155*	*130*	*160*	*120*	*60*	*65*	*35*	*5*	—	*1 620*
PSME/THOC	4												
Psme		.8	0.3	0.3	1.3	0.5	2.3	3.0	0.3	0.3	—	—	9.1
Laoc		—	—	—	—	.3	.5	1.5	1.0	—	—	—	3.3
Abla		9.3	2.8	1.3	.3	—	—	—	—	—	—	—	13.7
Pien		4.0	1.3	.3	.3	—	—	—	—	—	—	—	5.9
Jusc		.3	.8	—	—	—	—	—	—	—	—	—	1.1
Stems/ha		*720*	*260*	*95*	*95*	*40*	*140*	*225*	*65*	*15*	—	—	*1 655*
PSME/BERE	3												
Pipo		—	—	—	—	—	—	—	—	0.3	—	—	0.3
Psme		2.7	5.0	3.7	3.3	3.3	1.3	0.7	—	—	—	—	20.0
Abgr		—	.3	—	—	—	—	—	—	—	—	—	.3
Abla		.7	—	—	—	—	—	—	—	—	—	—	.7
Pien		.7	.3	1.7	.7	—	—	—	—	—	—	—	3.4
Jusc		4.0	1.7	1.0	—	—	—	—	—	—	—	—	6.7
Stems/ha		*405*	*365*	*320*	*200*	*165*	*65*	*35*	—	*15*	—	—	*1 570*
PIFL	2												
Psme		—	0.5	0.5	0.5	0.5	—	—	—	—	—	—	2.0
Jusc		4.0	1.0	—	.5	—	—	—	—	—	—	—	5.5
Pifl		2.0	1.0	.5	1.0	1.0	0.5	1.0	—	—	—	—	7.0
Stems/ha		*300*	*125*	*50*	*100*	*75*	*25*	*50*	—	—	—	—	*725*
ABGR/THOC	3												
Psme		—	—	—	—	—	1.3	0.3	—	—	—	—	1.6
Laoc		1.3	—	—	—	0.7	0.3	.7	0.3	—	—	—	3.3
Abgr		4.7	6.7	14.3	2.0	1.3	1.3	.3	—	—	—	—	30.6
Abla		1.3	.3	.3	.7	—	—	—	—	—	—	—	2.6
Pien		2.7	4.0	3.3	—	—	—	—	—	—	—	—	10.0
Stems/ha		*500*	*550*	*895*	*135*	*100*	*145*	*65*	*15*	—	—	—	*2 405*

(con.)

able 2. (con.)

Community type	No. of stands sampled	Mean no. of trees per 200 m^2 macroplot Diameter (at breast height) classes in dm <0.2	.2-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	>9	Total
BLA/THOC	18												
Pipo		—	—	—	—	—	+	—					+
Psme		0.1	0.1	0.3	+	0.3	0.2	0.4	+	0.1	+	—	1.5
Laoc		—	—	+	—	.2	.4	+	0.2	+	+	0.1	.9
Abla		51.7	12.4	7.0	3.3	1.7	.4	.2	+		—	—	76.7
Pien		3.4	1.5	2.6	1.2	1.6	1.7	.9	+	+	0.1	+	13.0
Pial		—	—	.1	.2	.1	—	—	—	—			.4
Pico		.3	—	.4	.5	.4	—	—	—	—	—	—	1.6
Stems/ha		*2 775*	*700*	*520*	*260*	*215*	*135*	*75*	*10*	*5*	*5*	*5*	*4 705*
BLA/VAME	3												
Psme		—	0.3	—	—	0.7	1.3	—	—	—		—	2.3
Laoc		—	—	—	—	—	—	0.3	—	—	—	—	.3
Abla		12.7	6.7	6.0	2.3	1.3	—	—	—	—		—	29.0
Pien		8.7	3.0	1.3	1.0	2.7	0.3	—	—		—	—	17.0
Pico		—	—	—	1.0	.3	—	—	—		—	—	1.3
Stems/ha		*1 070*	*500*	*365*	*215*	*250*	*80*	*15*	—	—	—	—	*2 495*
BLA/VASC	19												
Abla		41.3	10.4	5.4	4.2	2.3	0.5	0.1	—	—	—	—	64.2
Pien		2.9	.8	1.3	1.4	1.9	.6	.2	0.2	0.1	—	—	9.4
Pial		1.7	.5	—	.1	.1	.2	+	+	—	+	+	2.6
Pico		1.2	.3	.4	.8	.1	—	—	—	—	—	—	2.8
Stems/ha		*2 355*	*600*	*355*	*325*	*220*	*65*	*15*	*10*	*5*	+	+	*3 950*
IAL/ABLA	10												
Abla		31.0	12.2	6.0	1.2	0.4	0.3	—	—	—	—	—	51.1
Pien		.5	.5	—	.3	—	—	—	—	—		—	1.3
Pial		14.8	5.1	3.5	2.4	1.9	0.6	—	—	0.1	0.1	0.1	28.6
Stems/ha		*2 315*	*890*	*475*	*195*	*115*	*45*	—	—	*5*	*5*	*5*	*4 050*
ICO/CARU	4												
Laoc		—	—	—	0.3	—	0.3	—	—	—	—	—	0.6
Psme		—	0.5	0.3	—	—	—	0.3	—	—	—	—	1.1
Abla		7.0	1.0	1.7	—	—	—	—	—	—	—	—	9.7
Pien		1.3	—	—	—	—	—	—	—	—	—	—	1.3
Pico		17.8	26.0	9.3	11.5	.5	.3	—	—	—	—	—	65.4
Stems/ha		*1 305*	*1 375*	*565*	*590*	*25*	*30*	*15*	—	—	—	—	*3 905*
ICO/VAME	3												
Laoc		—	—	—	0.3	—	—	0.3	—	—	—	—	0.6
Psme		1.3	—	—	—	—	0.3	1.0	—	—	—	—	2.6
Abla		37.3	8.3	0.7	—	—	—	—	—	—	—	—	46.3
Pien		3.7	1.3	—	0.7	—	—	—	—	—	—	—	5.7
Pico		1.7	.3	9.0	5.3	0.3		—	—	—	—	—	16.6
Stems/ha		*2 200*	*495*	*485*	*315*	*15*	*15*	*65*	—	—	—	—	*3 590*
ICO/VASC	5												
Laoc		—	—	—	—	—	0.8	0.2	—				1.0
Abla		52.0	8.4	2.0	1.2	—	0.2	—	—	—		—	63.8
Pien		10.0	1.6	0.8	—	—	—	—	—	—		—	12.4
Pial		1.0	—	—	—	—	—	—	—	—	—	—	1.0
Pico		22.6	18.8	11.8	5.2	1.2	—	—	—	—	—		59.6
Stems/ha		*4 280*	*1 440*	*730*	*320*	*60*	*50*	*10*	—	—	—	—	*6 890*

SPECIES	ABLA/THOC															
Stand number	4	6	8	25	54	9	124	15	83	39	127	29	85	137	51	126
Township and section	3S35	4S9	3S33	4S5	3S33	3S33	4S19	4S7	4S25	4S30	4S30	4S19	4S25	5S6	3S22	4S30
Range	44E	44E	44E	45E	44E	44E	45E	45E	44E	45E	45E	45E	44E	45E	44E	45E
Elevation	2180	1920	1830	1620	1810	1880	1770	2160	1850	1800	1830	1800	1890	1980	1650	1830
Azimuth (degrees)	85	290	280	280	275	285	300	110	280	285	290	270	185	350	120	210
Slope (percent)	5	20	40	10	45	30	25	40	10	25	20	10	25	15	10	5
Rock type	mb	l	l	gr	mb	l	gr	l	gr	gr	gr	gr	gr	gr	mb	gr
SHRUBS AND SUBSHRUBS																
Acer glabrum	—	—	7(2)	—	1(4)	—	—	—	—	—	—	1(+)	—	—	3(1)	—
Amelanchier alnifolia	—	—	—	—	—	—	2(1)	—	—	—	—	—	—	—	—	—
Berberis repens	—	—	—	2(+)	—	—	—	—	—	—	—	—	2(1)	—	—	—
Clematis columbiana	—	—	—	1(+)	1(+)	—	—	—	—	—	—	—	—	—	2(1)	—
Linnaea borealis	—	—	—	—	2(1)	4(8)	—	—	—	—	—	—	—	—	—	—
Lonicera involucrata	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—	1(1)	—
Lonicera utahensis	—	1(+)	2(1)	—	—	—	—	1(+)	—	—	—	—	—	—	—	1(1)
Pachistima myrsinites	—	—	—	—	—	—	4(1)	—	—	—	—	—	—	—	—	—
Ribes lacustre	—	2(6)	—	1(+)	—	—	—	—	1(+)	1(+)	—	—	—	—	1(+)	1(+)
Ribes viscosissimum	—	—	1(2)	—	—	—	—	—	—	—	—	—	—	—	—	—
Spiraea betulifolia	—	—	—	—	—	—	1(+)	—	—	—	—	2(1)	2(1)	—	—	—
Symphoricarpos albus	—	1(+)	6(3)	—	—	1(+)	—	—	—	—	—	—	—	—	—	—
Symphoricarpos oreophilus	—	—	—	—	1(+)	—	—	—	—	—	—	—	—	—	—	—
Vaccinium membranaceum	—	—	—	4(7)	—	—	4(3)	—	—	—	—	—	—	3(1)	—	—
Vaccinium scoparium	—	—	—	—	1(+)	2(1)	4(2)	5(5)	—	1(+)	—	1(+)	—	—	—	3(1)
GRAMINOIDS																
Bromus vulgaris	—	—	—	4(3)	—	—	—	—	—	3(1)	—	—	—	—	—	—
Calamagrostis rubescens	—	—	—	4(1)	—	—	4(5)	—	—	—	—	—	1(+)	—	—	—
Carex geyeri	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—	—	—
Carex rossii	—	—	—	—	—	—	—	—	4(1)	—	—	—	—	—	—	4(2)
FORBS																
Achillea millefolium	—	1(+)	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Actaea rubra	—	—	—	1(+)	1(+)	—	—	—	—	—	—	—	—	—	—	—
Anemone oregana	—	—	—	1(+)	—	—	8(3)	—	7(3)	5(1)	—	1(+)	—	—	—	—
Aquilegia flavescens	—	2(1)	—	—	2(1)	—	—	—	—	—	—	—	—	—	1(+)	—
Arenaria macrophylla	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	2(1)	6(4)
Arnica cordifolia	10(9)	2(2)	1(+)	8(2)	—	—	4(1)	7(10)	8(10)	7(8)	9(7)	6(2)	4(2)	1(2)	—	—
Aster conspicuus	—	1(+)	5(4)	4(1)	2(1)	2(1)	—	—	—	—	—	1(1)	—	—	—	—
Chimaphila umbellata	1(+)	—	1(+)	2(1)	2(+)	6(3)	2(1)	—	1(1)	—	3(1)	—	1(+)	1(+)	1(+)	—
Disporum trachycarpum	—	—	—	1(+)	—	—	—	—	—	—	—	—	—	—	1(+)	—
Fragaria vesca	—	3(1)	2(2)	1(+)	1(+)	1(+)	3(2)	2(2)	—	—	—	—	—	—	—	—
Fragaria virginiana	—	—	—	—	—	—	—	—	2(1)	2(1)	—	2(+)	—	—	—	—
Galium triflorum	—	4(1)	—	2(1)	—	—	—	1(+)	—	1(+)	—	—	—	—	5(2)	—
Goodyera oblongifolia	—	—	1(+)	—	3(1)	1(+)	2(1)	1(+)	—	3(1)	—	—	—	—	1(+)	—
Hieracium albiflorum	—	—	—	—	—	—	—	—	3(1)	—	—	—	—	—	—	—
Listera caurina	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	1(+)	—
Mertensia paniculata	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—
Osmorhiza chilensis	—	—	—	1(+)	—	1(+)	3(1)	1(+)	1(+)	2(1)	6(2)	—	1(+)	—	6(2)	—
Polemonium pulcherrimum	3(1)	—	1(2)	—	—	—	—	1(2)	—	—	—	—	—	—	—	3(1)
Pyrola chlorantha	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2(+)	—
Pyrola secunda	2(1)	3(1)	—	4(1)	8(2)	6(2)	10(4)	—	—	5(2)	7(4)	3(1)	4(1)	7(5)	7(3)	5(5)
Pyrola uniflora	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2(1)	—
Smilacina stellata	—	—	—	1(2)	—	—	—	—	—	—	—	—	—	—	—	—
Streptopus amplexifolius	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1(+)
Thalictrum occidentale	9(33)	10(27)	8(17)	7(15)	7(13)	10(10)	9(9)	6(7)	—	3(2)	7(6)	2(2)	—	3(3)	3(1)	2(1)
Tiarella trifoliata	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—
Valeriana sitchensis	—	4(1)	1(+)	—	—	—	—	3(2)	—	—	—	—	—	—	—	—
Veratrum viride	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—	—
Viola adunca	—	2(1)	7(2)	—	1(+)	6(3)	1(+)	3(1)	—	—	—	1(+)	—	—	3(1)	—
Viola glabella	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—
Viola orbiculata	—	—	—	6(1)	8(2)	—	9(3)	—	2(1)	6(2)	3(1)	4(1)	1(+)	—	—	7(3)

(con.)

Table 3. (con.)

SPECIES	ABLA/VAME			ABLA/VASC												
Stand number	60	27	123	81	72	69	1	93	82	79	80	74	71	94	130	78
Township and section	3S32	4S7	4S7	4S26	4S26	4S24	4S27	4S21	4S22	4S23	4S23	4S27	4S24	4S34	5S6	4S23
Range	44E	45E	45E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E	45E	44E
Elevation	2040	1740	1710	2160	2190	2130	2250	2200	2220	2280	2250	2230	2130	2280	2100	2310
Azimuth (degrees)	360	290	310	190	20	340	130	30	50	350	40	350	50	150	160	280
Slope (percent)	25	25	15	5	20	30	5	50	30	15	10	10	20	20	5	30
Rock type	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr
SHRUBS AND SUBSHRUBS																
Alnus sinuata	—	—	1(4)	—	—	—	—	—	—	—	—	—	—	—	—	—
Amelanchier alnifolia	—	1(1)	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Cassiope mertensiana	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—
Gaultheria humifusa	—	—	—	3(5)	—	—	1(2)	1(+)	—	—	—	—	—	—	—	—
Ledum glandulosum	3(1)	—	—	8(33)	6(14)	7(10)	3(9)	—	2(1)	—	—	2(3)	1(4)	—	—	—
Lonicera utahensis	—	—	—	2(1)	2(1)	1(1)	—	—	—	1(+)	1(+)	—	—	—	—	—
Pachistima myrsinites	—	4(1)	3(2)	—	—	—	—	—	—	—	—	—	—	—	—	—
Phyllodoce empetriformis	—	—	—	—	2(1)	1(2)	7(10)	9(21)	7(18)	8(18)	7(8)	7(7)	5(6)	—	1(1)	—
Ribes lacustre	—	1(1)	1(+)	—	—	—	—	—	—	—	—	—	—	—	—	—
Sorbus sitchensis	—	1(+)	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Spiraea betulifolia	—	4(2)	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Vaccinium membranaceum	9(37)	9(36)	10(19)	—	—	—	—	—	—	—	—	—	1(+)	—	—	—
Vaccinium scoparium	3(1)	6(6)	—	10(25)	10(30)	10(39)	10(39)	10(34)	10(28)	10(17)	9(16)	10(25)	10(39)	10(14)	10(20)	8(6)
GRAMINOIDS																
Bromus vulgaris	—	2(1)	7(2)	—	—	—	—	—	—	—	—	—	—	—	—	—
Calamagrostis rubescens	—	5(5)	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Carex geyeri	—	—	2(1)	2(1)	—	—	—	—	—	—	—	—	—	—	—	—
Carex rossii	—	—	—	—	—	—	—	1(+)	5(2)	—	2(1)	—	—	7(2)	5(2)	2(1)
Festuca viridula	—	—	—	—	—	—	—	—	—	—	—	—	—	1(1)	1(+)	—
Juncus parryi	—	—	—	—	—	—	—	—	2(1)	—	1(+)	—	—	7(3)	1(+)	—
Luzula campestris	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—
Luzula hitchcockii	—	—	—	—	3(1)	—	—	9(17)	—	—	2(1)	5(7)	3(2)	—	—	—
Muhlenbergia filiformis	—	—	—	1(+)	—	—	—	—	—	—	—	—	—	—	—	—
Oryzopsis exigua	—	—	—	—	—	—	—	—	—	—	—	—	—	1(+)	—	—
Poa sp.	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—
FORBS																
Allium validum	—	—	—	3(1)	—	—	1(+)	—	—	—	—	—	—	—	—	—
Anaphalis margaritacea	—	—	—	4(2)	—	—	—	—	—	—	—	—	—	—	—	—
Anemone oregana	—	—	7(2)	—	—	—	—	—	—	—	—	—	—	—	—	—
Antennaria lanata	—	—	—	—	—	—	2(1)	5(3)	4(2)	3(1)	6(2)	—	—	—	2(1)	—
Arenaria aculeata	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1(+)	—
Arenaria macrophylla	—	1(+)	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Arnica cordifolia	4(1)	9(5)	8(5)	—	—	2(1)	—	—	—	—	—	—	2(1)	—	—	—
Arnica mollis	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—	—	—
Aster conspicuus	—	3(1)	2(1)	—	—	—	—	—	—	—	—	—	—	—	—	—
Chimaphila umbellata	—	—	1(+)	—	—	—	—	—	—	—	—	—	—	—	—	—
Dodecatheon alpinum	—	—	—	—	—	—	2(1)	—	—	—	—	—	—	—	—	—
Epilobium angustifolium	—	—	—	2(1)	—	—	—	—	—	—	—	—	—	—	—	—
Erigeron peregrinus	—	—	—	4(2)	—	—	—	1(+)	1(+)	1(+)	5(2)	—	—	—	—	—
Fragaria vesca	—	2(1)	1(+)	—	—	—	—	—	—	—	—	—	—	—	—	—
Galium triflorum	—	3(1)	5(2)	—	—	—	—	—	—	—	—	—	—	—	—	—
Goodyera oblongifolia	1(+)	—	1(+)	—	—	—	—	—	—	—	—	—	—	—	—	—
Hieracium albiflorum	—	—	1(+)	—	—	2(1)	—	—	—	—	3(1)	—	1(+)	—	—	—
Hieracium gracile	—	—	—	—	—	1(+)	—	4(2)	1(+)	—	3(1)	—	—	—	—	—
Hypericum formosum	—	—	—	3(1)	—	—	—	—	—	—	—	—	—	—	—	—
Ligusticum tenuifolium	—	—	—	1(+)	1(+)	—	2(1)	—	—	—	—	1(+)	—	—	—	—
Listera caurina	1(+)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Lupinus polyphyllus	—	—	—	1(1)	—	—	—	—	—	—	—	—	—	—	—	—
Osmorhiza chilensis	4(1)	5(1)	1(+)	—	—	—	—	—	—	—	—	—	—	—	—	—
Pedicularis racemosa	—	—	—	4(2)	2(1)	—	—	—	—	—	—	1(+)	—	—	1(+)	—
Polemonium pulcherrimum	1(1)	—	—	—	—	—	1(+)	—	—	—	1(+)	—	2(1)	—	1(+)	—
Polygonum phytolaccaefolium	—	—	—	—	—	—	—	—	—	—	—	—	—	3(2)	—	—
Potentilla flabellifolia	—	—	—	—	—	—	2(1)	—	—	—	—	—	—	—	—	—
Pyrola secunda	4(1)	1(+)	9(5)	—	—	—	—	—	—	—	—	—	—	—	—	—
Ranunculus alismaefolius	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—	—	—
Thalictrum occidentale	8(20)	6(15)	9(6)	—	—	—	—	—	—	—	—	—	—	—	—	—
Valeriana sitchensis	4(1)	—	—	10(5)	1(+)	2(1)	—	—	—	—	4(1)	—	—	—	—	—
Veratrum viride	1(+)	—	—	4(1)	—	—	—	—	—	—	—	—	—	—	1(+)	—
Veronica cusickii	—	—	—	3(1)	—	—	2(1)	2(1)	—	2(1)	4(2)	—	—	—	1(+)	—
Viola adunca	—	3(1)	—	2(1)	—	—	—	—	—	—	—	—	—	—	—	—
Viola orbiculata	8(2)	5(2)	9(4)	—	—	—	—	—	—	—	—	—	—	—	—	—

(con.)

Table 3. (con.)

SPECIES	ABLA/THOC															
Stand number	4	6	8	25	54	9	124	15	83	39	127	29	85	137	51	126
Township and section	3S35	4S9	3S33	4S5	3S33	3S33	4S19	4S7	4S25	4S30	4S30	4S19	4S25	5S6	3S22	4S30
Range	44E	44E	44E	45E	44E	44E	45E	45E	44E	45E	45E	45E	44E	45E	44E	45E
Elevation	2180	1920	1830	1620	1810	1880	1770	2160	1850	1800	1830	1800	1890	1980	1650	1830
Azimuth (degrees)	85	290	280	280	275	285	300	110	280	285	290	270	185	350	120	210
Slope (percent)	5	20	40	10	45	30	25	40	10	25	20	10	25	15	10	5
Rock type	mb	l	l	gr	mb	l	gr	l	gr	gr	gr	gr	gr	gr	mb	gr
SHRUBS AND SUBSHRUBS																
Acer glabrum	—	—	7(2)	—	1(4)	—	—	—	—	—	—	1(+)	—	—	3(1)	—
Amelanchier alnifolia	—	—	—	—	—	—	2(1)	—	—	—	—	—	—	—	—	—
Berberis repens	—	—	—	2(+)	—	—	—	—	—	—	—	—	2(1)	—	—	—
Clematis columbiana	—	—	—	1(+)	1(+)	—	—	—	—	—	—	—	—	—	2(1)	—
Linnaea borealis	—	—	—	—	2(1)	4(8)	—	—	—	—	—	—	—	—	—	—
Lonicera involucrata	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—	1(1)	—
Lonicera utahensis	—	1(+)	2(1)	—	—	—	—	1(+)	—	—	—	—	—	—	—	1(1)
Pachistima myrsinites	—	—	—	—	—	—	4(1)	—	—	—	—	—	—	—	—	—
Ribes lacustre	—	2(6)	—	1(+)	—	—	—	—	1(+)	1(+)	—	—	—	—	1(+)	1(+)
Ribes viscosissimum	—	—	1(2)	—	—	—	—	—	—	—	—	—	—	—	—	—
Spiraea betulifolia	—	—	—	—	—	—	1(+)	—	—	—	—	2(1)	2(1)	—	—	—
Symphoricarpos albus	—	1(+)	6(3)	—	—	1(+)	—	—	—	—	—	—	—	—	—	—
Symphoricarpos oreophilus	—	—	—	—	1(+)	—	—	—	—	—	—	—	—	—	—	—
Vaccinium membranaceum	—	—	—	4(7)	—	—	4(3)	—	—	—	—	—	—	3(1)	—	—
Vaccinium scoparium	—	—	—	—	1(+)	2(1)	4(2)	5(5)	—	1(+)	—	1(+)	—	—	—	3(1)
GRAMINOIDS																
Bromus vulgaris	—	—	—	4(3)	—	—	—	—	—	3(1)	—	—	—	—	—	—
Calamagrostis rubescens	—	—	—	4(1)	—	—	4(5)	—	—	—	—	—	1(+)	—	—	—
Carex geyeri	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—	—	—
Carex rossii	—	—	—	—	—	—	—	—	4(1)	—	—	—	—	—	—	4(2)
FORBS																
Achillea millefolium	—	1(+)	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Actaea rubra	—	—	—	1(+)	1(+)	—	—	—	—	—	—	—	—	—	—	—
Anemone oregana	—	—	—	1(+)	—	—	8(3)	—	7(3)	5(1)	—	1(+)	—	—	—	—
Aquilegia flavescens	—	2(1)	—	—	2(1)	—	—	—	—	—	—	—	—	—	1(+)	—
Arenaria macrophylla	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	2(1)	6(4)
Arnica cordifolia	10(9)	2(2)	1(+)	8(2)	—	—	4(1)	7(10)	8(10)	7(8)	9(7)	6(2)	4(2)	1(2)	—	—
Aster conspicuus	—	1(+)	5(4)	4(1)	2(1)	2(1)	—	—	—	—	—	1(1)	—	—	—	—
Chimaphila umbellata	1(+)	—	1(+)	2(1)	2(+)	6(3)	2(1)	—	1(1)	—	3(1)	—	1(+)	1(+)	1(+)	—
Disporum trachycarpum	—	—	—	1(+)	—	—	—	—	—	—	—	—	—	—	1(+)	—
Fragaria vesca	—	3(1)	2(2)	1(+)	1(+)	1(+)	3(2)	2(2)	—	—	—	—	—	—	—	—
Fragaria virginiana	—	—	—	—	—	—	—	—	2(1)	2(1)	—	2(+)	—	—	—	—
Galium triflorum	—	4(1)	—	2(1)	—	—	—	1(+)	—	1(+)	—	—	—	—	5(2)	—
Goodyera oblongifolia	—	—	1(+)	—	3(1)	1(+)	2(1)	1(+)	—	3(1)	—	—	—	—	1(+)	—
Hieracium albiflorum	—	—	—	—	—	—	—	—	3(1)	—	—	—	—	—	—	—
Listera caurina	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	1(+)	—
Mertensia paniculata	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—
Osmorhiza chilensis	—	—	—	1(+)	—	1(+)	3(1)	1(+)	1(+)	2(1)	6(2)	—	1(+)	—	6(2)	—
Polemonium pulcherrimum	3(1)	—	1(2)	—	—	—	—	1(2)	—	—	—	—	—	—	—	3(1)
Pyrola chlorantha	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2(+)	—
Pyrola secunda	2(1)	3(1)	—	4(1)	8(2)	6(2)	10(4)	—	—	5(2)	7(4)	3(1)	4(1)	7(5)	7(3)	5(5)
Pyrola uniflora	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2(1)	—
Smilacina stellata	—	—	—	1(2)	—	—	—	—	—	—	—	—	—	—	—	—
Streptopus amplexifolius	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1(+)
Thalictrum occidentale	9(33)	10(27)	8(17)	7(15)	7(13)	10(10)	9(9)	6(7)	—	3(2)	7(6)	2(2)	—	3(3)	3(1)	2(1)
Tiarella trifoliata	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—
Valeriana sitchensis	—	4(1)	1(+)	—	—	—	—	3(2)	—	—	—	—	—	—	—	—
Veratrum viride	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—	—
Viola adunca	—	2(1)	7(2)	—	1(+)	6(3)	1(+)	3(1)	—	—	—	1(+)	—	—	3(1)	—
Viola glabella	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—
Viola orbiculata	—	—	—	6(1)	8(2)	—	9(3)	—	2(1)	6(2)	3(1)	4(1)	1(+)	—	—	7(3)

(con.)

Table 3. (con.)

SPECIES	ABLA/VAME			ABLA/VASC												
Stand number	60	27	123	81	72	69	1	93	82	79	80	74	71	94	130	78
Township and section	3S32	4S7	4S7	4S26	4S26	4S24	4S27	4S21	4S22	4S23	4S23	4S27	4S24	4S34	5S6	4S23
Range	44E	45E	45E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E	45E	44E
Elevation	2040	1740	1710	2160	2190	2130	2250	2200	2220	2280	2250	2230	2130	2280	2100	2310
Azimuth (degrees)	360	290	310	190	20	340	130	30	50	350	40	350	50	50	160	280
Slope (percent)	25	25	15	5	20	30	5	50	30	15	10	10	20	20	5	30
Rock type	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr
SHRUBS AND SUBSHRUBS																
Alnus sinuata	—		1(4)													
Amelanchier alnifolia	—	1(1)	—	—		—	—	—								
Cassiope mertensiana	—	—	—	—	—	—	—	—	1(+)							
Gaultheria humifusa	—	—	—	3(5)	—	—	1(2)	1(+)								
Ledum glandulosum	3(1)	—		8(33)	6(14)	7(10)	3(9)		2(1)			2(3)	1(4)			
Lonicera utahensis	—	—	—	2(1)	2(1)	1(1)	—			1(+)	1(+)			—		
Pachistima myrsinites	—	4(1)	3(2)	—	—	—	—			—			—			
Phyllodoce empetriformis	—	—	—	—	2(1)	1(2)	7(10)	9(21)	7(18)	8(18)	7(8)	7(7)	5(6)		1(1)	
Ribes lacustre	—	1(1)	1(+)	—	—	—	—	—	—	—	—	—				
Sorbus sitchensis	—	1(+)	—	—	—	—	—	—	—	—		—		—		
Spiraea betulifolia	—	4(2)	—	—	—	—	—	—	—	—						
Vaccinium membranaceum	9(37)	9(36)	10(19)	—	—	—							1(+)			
Vaccinium scoparium	3(1)	6(6)	—	10(25)	10(30)	10(39)	10(39)	10(34)	10(28)	10(17)	9(16)	10(25)	10(39)	10(14)	[illegible]	8(6)
GRAMINOIDS																
Bromus vulgaris	—	2(1)	7(2)		—		—	—	—	—					—	—
Calamagrostis rubescens	—	5(5)	—		—	—	—	—	—	—		—	—	—	—	—
Carex geyeri	—	—	2(1)	2(1)	—	—	—	—		—	—	—	—	—		
Carex rossii	—	—	—	—	—	—		1(+)	5(2)		2(1)			7(2)	5(2)	[illegible]
Festuca viridula	—	—	—	—		—	—	—	—	—	—	—		1(1)	1(+)	—
Juncus parryi	—	—	—	—	—	—	—	—	2(1)	—	1(+)	—	—	7(3)	1(+)	
Luzula campestris	—	—	—	—	—	—	—	—	1(+)			—	—			
Luzula hitchcockii	—	—	—	—	3(1)	—		9(17)			2(1)	5(7)	3(2)		—	—
Muhlenbergia filiformis	—	—	—	1(+)	—	—	—	—	—	—		—	—	—	—	—
Oryzopsis exigua	—	—	—	—	—	—	—	—	—	—		—	—	1(+)	—	—
Poa sp.	—	—	—	—	—	—	—	—	1(+)							
FORBS																
Allium validum	—	—	—	3(1)	—	—	1(+)	—	—	—	—	—				
Anaphalis margaritacea	—	—	—	4(2)	—	—	—	—								
Anemone oregana	—	—	7(2)	—	—	—	—	—	—	—	—			—	—	
Antennaria lanata	—	—	—	—	—	—	2(1)	5(3)	4(2)	3(1)	6(2)	—			2(1)	
Arenaria aculeata	—	—	—	—	—	—	—	—		—	—				1(+)	
Arenaria macrophylla	—	1(+)	—	—	—	—	—		—	—				—	—	
Arnica cordifolia	4(1)	9(5)	8(5)	—	—	2(1)		—	—	—	—	—	2(1)	—	—	
Arnica mollis	—	—	—	—	—	—	1(+)	—	—		—	—	—			
Aster conspicuus	—	3(1)	2(1)	—	—	—	—	—	—	—						
Chimaphila umbellata	—	—	1(+)	—		—	—		—	—	—					
Dodecatheon alpinum	—	—	—	—	—	—	2(1)	—	—	—	—	—				
Epilobium angustifolium	—	—	—	2(1)	—	—	—	—	—	—			—			
Erigeron peregrinus	—	—	—	4(2)		—	—	1(+)	1(+)	1(+)	5(2)					
Fragaria vesca	—	2(1)	1(+)	—	—	—	—	—			—		—	—	—	
Galium triflorum	—	3(1)	5(2)	—	—	—	—	—	—	—			—			
Goodyera oblongifolia	1(+)	—	1(+)	—	—	—	—	—								
Hieracium albiflorum	—	—	1(+)	—	—	2(1)		—			3(1)	—	1(+)			
Hieracium gracile	—	—	—	—	—	1(+)	—	4(2)	1(+)	—	3(1)	—	—			
Hypericum formosum	—	—	—	3(1)	—	—	—		—	—						
Ligusticum tenuifolium	—	—	—	1(+)	1(+)	—	2(1)		—			1(+)				
Listera caurina	1(+)	—	—	—	—	—	—	—			—		—			
Lupinus polyphyllus	—	—	—	1(1)	—	—	—	—				—				
Osmorhiza chilensis	4(1)	5(1)	1(+)	—	—	—	—									
Pedicularis racemosa	—	—	—	4(2)	2(1)	—						1(+)	—		1	
Polemonium pulcherrimum	1(1)	—		—	—	—	1(+)	—			1(+)		2(1)		1(+)	
Polygonum phytolaccaefolium	—	—	—	—	—	—	—			—	—			[illegible]		
Potentilla flabellifolia	—	—	—	—	—		2(1)									
Pyrola secunda	4(1)	1(+)	9(5)	—		—		—	—						—	
Ranunculus alismaefolius	—	—	—	—	—	—	1(+)	—	—							
Thalictrum occidentale	8(20)	6(15)	9(6)	—	—		—	—								
Valeriana sitchensis	4(1)	—	—	10(5)	1(+)	2(1)					4(1)					
Veratrum viride	1(+)	—	—	4(1)	—	—	—				—				1	
Veronica cusickii	—	—	—	3(1)	—	—	2(1)	2(1)		2(1)	4(2)				1(+)	
Viola adunca	—	3(1)		2(1)	—	—										
Viola orbiculata	8(2)	5(2)	9(4)	—	—		—									

Table 3. (con.)

SPECIES	ABLA/VASC						PIAL-ABLA									
Stand number	75	77	10	2	76	34	5	73	133	119	18	96	95	97	17	16
Township and section	4S23	4S23	3S33	4S28	4S23	4S25	4S21	4S27	5S1	4S12	4S11	4S35	4S34	5S1	4S11	4S11
Range	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E
Elevation	2160	2280	1830	2160	2220	1830	2280	2310	2220	2340	2400	2460	2250	2520	2410	2370
Azimuth (degrees)	320	260	290	320	220	0	330	130	195	105	280	310	190	220	205	185
Slope (percent)	25	20	15	20	25	0	40	30	30	25	45	30	40	45	35	35
Rock type	gr	gr	l	gr	gr	gr	gr	gr	gr	h	gr	gr	gr	gr	l	h
SHRUBS AND SUBSHRUBS																
Berberis repens	—	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—
Gaultheria humifusa	—	—	—	1(+)	—	—	—	—	—	—	—	—	—	—	—	—
Juniperus communis	—	—	—	—	—	—	—	—	3(8)	—	—	—	—	—	2(10)	2(7)
Ledum glandulosum	—	—	—	—	—	4(3)	—	—	—	—	—	—	—	—	—	—
Linnaea borealis	—	—	2(2)	—	—	2(1)	—	—	—	—	—	—	—	—	—	—
Lonicera utahensis	—	—	—	—	—	—	—	—	1(1)	—	—	—	—	—	—	—
Penstemon fruticosus	—	—	—	—	—	—	—	—	2(1)	—	—	—	2(1)	—	5(3)	3(1)
Phyllodoce empetriformis	—	—	—	3(2)	—	—	3(8)	—	—	—	—	—	—	—	—	—
Potentilla fruticosa	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2(2)	—
Ribes lacustre	—	—	—	—	—	1(+)	—	—	—	—	—	—	—	—	—	—
Ribes montigenum	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—
Vaccinium scoparium	9(29)	10(41)	10(36)	10(32)	10(20)	8(18)	8(31)	10(24)	10(25)	10(25)	7(12)	9(11)	4(8)	3(5)	1(+)	—
GRAMINOIDS																
Bromus vulgaris	—	—	—	—	—	1(+)	—	—	—	—	—	—	—	—	—	—
Carex geyeri	—	—	—	—	1(4)	—	—	—	—	—	2(1)	1(+)	1(+)	—	7(2)	6(2)
Carex rossii	3(1)	—	—	—	3(1)	—	—	2(1)	5(2)	6(2)	—	6(2)	5(3)	1(1)	—	—
Carex spectabilis	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—
Festuca viridula	—	—	—	1(+)	—	—	—	—	—	2(1)	—	—	1(+)	6(4)	2(1)	—
Juncus parryi	—	1(+)	—	—	—	—	—	—	—	1(1)	1(+)	4(3)	—	4(5)	—	—
Oryzopsis exigua	—	—	—	—	—	—	—	—	2(1)	—	—	2(1)	7(4)	—	—	—
Poa gracillima	—	—	—	—	—	—	—	—	—	—	—	1(+)	—	3(1)	—	—
Poa nervosa	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—
Sitanion hystrix	—	—	—	—	—	—	—	—	—	—	—	—	—	—	4(1)	—
Stipa occidentalis	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1(+)
Trisetum spicatum	—	—	—	—	—	—	—	—	—	—	—	—	—	1(+)	—	—
FORBS																
Achillea millefolium	—	—	—	—	—	—	—	—	3(1)	1(+)	—	—	—	—	3(1)	1(+)
Anaphalis margaritacea	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—
Antennaria alpina	—	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—
Antennaria lanata	—	—	—	2(1)	—	—	—	—	1(+)	—	—	—	—	—	—	—
Arenaria aculeata	—	—	—	—	—	—	—	—	—	3(2)	—	3(1)	5(3)	—	—	1(+)
Arenaria macrophylla	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—
Arnica cordifolia	—	—	—	5(9)	7(4)	8(2)	—	—	5(2)	10(11)	6(3)	—	—	3(1)	—	4(1)
Arnica latifolia	—	—	—	—	—	—	—	—	2(1)	—	—	—	—	—	—	—
Arnica mollis	—	—	—	2(1)	—	—	—	—	—	—	—	—	—	—	—	—
Aster conspicuus	—	—	3(2)	—	—	—	—	—	—	—	—	—	—	—	—	—
Castilleja miniata	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2(1)
Catilleja rhexifolia	—	—	—	1(+)	—	—	—	—	—	—	—	—	—	—	—	—
Chimaphila umbellata	—	—	1(2)	—	—	2(+)	—	—	—	1(+)	—	—	—	—	—	—
Epilobium angustifolium	—	—	1(+)	—	—	—	—	—	4(2)	1(+)	—	1(+)	—	—	—	3(1)
Erigeron peregrinus	—	3(1)	—	3(1)	—	—	—	—	—	1(+)	—	—	—	—	—	—
Eriogonum flavum	—	—	—	—	—	—	—	—	—	—	—	2(1)	—	—	1(+)	—
Fragaria vesca	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2(1)
Fragaria virginiana	—	—	1(+)	—	—	—	—	—	—	—	—	—	—	—	—	—
Goodyera oblongifolia	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—
Hieracium albertinum	—	—	—	—	—	—	—	—	2(1)	—	1(+)	—	—	—	—	—
Hieracium albiflorum	—	—	1(+)	—	8(2)	—	—	—	—	—	—	—	—	—	—	—
Hieracium gracile	1(+)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Linanthastrum nuttallii	—	—	—	—	1(+)	—	—	—	—	5(2)	—	4(2)	—	—	4(2)	8(5)
Listera caurina	—	—	—	—	—	2(1)	—	—	—	—	—	—	—	—	—	—
Osmorhiza chilensis	—	—	—	—	—	2(1)	—	—	—	—	—	—	—	—	—	—
Pedicularis contorta	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	1(+)	—
Pedicularis racemosa	—	1(1)	—	3(2)	—	—	—	—	—	—	—	—	—	—	—	—
Penstemon globosus	—	—	—	—	—	—	—	—	—	—	—	2(1)	—	—	—	—
Polemonium pulcherrimum	—	—	—	—	—	1(+)	—	—	1(+)	1(1)	—	—	—	1(+)	—	—
Polygonum phytolaccaefolium	—	—	—	—	—	—	—	—	—	—	—	4(1)	—	—	—	1(+)
Potentilla glandulosa	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—	—
Pyrola secunda	—	—	1(+)	—	—	3(1)	—	—	—	—	—	—	—	—	—	—
Solidago multiradiata	—	—	—	—	—	—	—	—	—	3(1)	5(1)	—	—	—	—	7(3)
Spraguea umbellata	—	—	—	—	—	—	—	—	—	1(+)	—	—	—	—	—	—
Thalictrum occidentale	—	—	2(2)	—	1(+)	6(1)	—	—	—	—	—	—	—	—	—	—
Valeriana sitchensis	—	—	—	1(+)	1(+)	1(+)	—	—	2(2)	—	—	—	—	—	—	—
Veratrum viride	—	—	—	—	—	—	—	—	—	3(2)	—	—	—	—	—	—
Viola orbiculata	—	—	5(1)	—	—	6(2)	—	—	—	—	—	—	—	—	—	—

(con.)

Table 3. (con.)

SPECIES	PICO/CARU				PICO/VAME			PICO/VASC				
Stand number	23	59	24	35	100	61	26	30	31	33	70	68
Township and section	3S29	3S32	3S32	4S25	4S7	3S33	4S7	4S19	4S19	4S25	4S24	4S24
Range	45E	44E	45E	44E	45E	44E	45E	45E	45E	44E	44E	44E
Elevation	1490	2250	1500	1800	1740	2010	1680	1800	1830	1850	2160	2130
Azimuth (degrees)	55	180	270	175	280	60	100	260	120	320	195	150
Slope (percent)	20	45	15	20	30	20	20	15	10	5	25	20
Rock type	cc	l	cc	gr	gr	gr	gr	gr	gr	gr	gr	gr
SHRUBS AND SUBSHRUBS												
Acer glabrum	—	—	1(+)	—	1(1)		—					
Amelanchier alnifolia	—	—	—		2(5)							
Berberis repens	—	2(1)	—	6(2)	1(+)	—		[illegible]	[illegible]			
Lonicera utahensis	—	—	—	—	—	—	1(+)					
Pachistima myrsinites	—	—	—	—	4(1)		1(+)					
Ribes lacustre	—	—	—	—	1(+)	—	—					
Rosa gymnocarpa	1(+)	—	—	—	—	—	—		—			
Spiraea betulifolia	6(3)	—	2(1)	8(2)	7(4)		1(+)	6(4)				
Symphoricarpos albus	6(1)	—	—									
Vaccinium membranaceum	—	—	8(7)	2(1)	10(61)	10(48)	10(35)	—	—	[illegible]	—	—
Vaccinium scoparium	—	—	—	6(3)	—	3(2)	2(6)	10(32)	10(29)	[illegible]	[illegible]	[illegible]
GRAMINOIDS												
Bromus vulgaris	—	—	—	—	6(2)				—			
Calamagrostis rubescens	19(50)	10(48)	10(32)	9(23)	—	—	4(1)	1(1)				
Carex geyeri	—	2(1)	—	—	6(4)	—						
Carex rossii	—	—	—	—	—		—	2(1)	—	2(2)	[illegible]	[illegible]
Elymus glaucus	—	—	—	—	1(+)	—	—	—	—	—		—
Juncus parryi	—	—	—	—	—	—	—	—	—		1(1)	[illegible]
Oryzopsis exigua	—	—	—	—	—	—	—		—		[illegible]	[illegible]
FORBS												
Anaphalis margaritacea	—	2(1)	—	—	—	—	—	—			—	
Anemone sp.	2(+)	—	6(2)	—	—	—	—		2(1)			—
Arenaria aculeata	—	—	—	—	—	—	—	—	—	—	[illegible]	[illegible]
Arenaria macrophylla	—	—	—	—	2(1)		—	1(+)				
Arnica cordifolia	10(12)	—	2(1)	6(2)	1(+)	3(1)	—	10(5)	4(1)	[illegible]	6(2)	[illegible]
Astragalus canadensis	—	1(+)	2(1)	—	—	—	—	—	—	—		
Aster conspicuus	2(+)	1(+)	—	—	2(1)	—	—	—	—	—		
Chimaphila umbellata	1(+)	—	2(1)	—	1(+)	—	7(4)	—	4(1)	1(+)		
Epilobium angustifolium	—	3(1)	—	—	—	—	—					
Fragaria vesca	—	5(3)	—	—	6(3)	—	—		—			
Fragaria virginiana	9(5)	—	—	2(2)	1(+)	—	—	1(+)				
Galium triflorum	—	—	—	—	2(1)		—	—				
Galium sp.	1(+)	—	—	—	—		—		—	—	—	
Goodyera oblongifolia	—	—	—	—	—	—	1(+)	—	—	—	—	
Hieracium albertinum	—	8(2)	—	4(1)	—	—	—	—	—	—		
Hieracium albiflorum	—	—	—	—	—				3(1)			[illegible]
Osmorhiza chilensis	2(+)	—	—	—	5(2)		—	—				
Polygonum phytolaccaefolium	—	—	—	—	—	—	—	—			[illegible]	[illegible]
Pyrola secunda	—	—	—	—	2(1)	—						
Smilacina stellata	1(+)	—	—	—	—					—		
Thalictrum occidentale	7(6)	—	—	—	6(7)		—	—	—	—	—	
Valeriana sitchensis	—	—	—	—	—	—		—	—		[illegible]	
Viola adunca	—	2(1)	—	—	2(1)	—						
Viola orbiculata	—	—	—	—	9(4)		5(1)		[illegible]			

Table 3. (con.)

SPECIES	PHEM					CASP					CANI		
Stand number	134	110	132	116	148	105	108	131	113	112	111	115	118
Township and section	5S6	4S11	5S12	4S12	4S11	4S11	4S11	5S12	4S12	4S11	4S11	4S12	4S12
Range	45E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E
Elevation	2190	2530	2250	2400	2460	2640	2670	2250	2400	2530	2520	2400	2430
Azimuth (degrees)	60	30	5	60	150	65	360	10	50	15	30	100	90
Slope (percent)	5	20	25	15	30	45	35	40	30	50	5	5	5
Rock type	gr	gr	gr	gr	gr	l	l	gr	l	gr	gr	gr	gr
SHRUBS AND SUBSHRUBS													
Cassiope mertensiana	—	6(4)	5(4)	6(6)	1(1	—	2(1)	—	—	—	—	—	—
Gaultheria humifusa	—	—	6(6)	—	1(2)	—	—	—	—	—	—	—	—
Kalmia microphylla	—	1(+)	6(2)	—	—	—	—	—	—	—	1(+)	—	—
Phyllodoce empetriformis	10(46)	10(39)	10(33)	9(33)	9(28)	—	—	—	—	—	—	2(2)	—
Phyllodoce glanduliflora	—	—	—	—	—	—	1(+)	—	—	—	—	—	—
Salix cascadensis	—	—	—	—	—	4(5)	3(2)	—	—	—	—	—	—
Vaccinium caespitosum	—	—	2(1)	—	—	—	—	—	—	—	—	—	—
Vaccinium scoparium	—	—	2(2)	1(+)	9(15)	—	—	—	—	—	—	—	—
GRAMINOIDS													
Carex nigricans	8(8)	6(3)	5(2)	3(4)	—	2(1)	—	—	1(+)	—	10(66)	10(58)	10(56)
Carex rossii	—	—	—	1(+)	2(1)	—	—	—	1(+)	—	—	—	—
Carex spectabilis	1(+)	1(+)	—	2(1)	—	9(30)	9(21)	9(21)	9(17)	9(16)	1(+)	2(1)	3(5)
Juncus drummondii	—	2(1)	2(1)	1(+)	—	—	6(4)	3(1)	2(1)	—	3(1)	5(6)	3(4)
Juncus parryi	—	—	—	3(2)	9(8)	—	—	—	1(+)	—	—	—	—
Luzula hitchcockii	—	5(4)	9(6)	1(+)	1(+)	6(2)	5(7)	9(11)	6(5)	8(9)	—	—	—
Luzula spicata	—	—	—	—	—	2(1)	1(+)	—	—	—	—	—	—
Muhlenbergia filiformis	4(1)	—	—	—	—	—	—	—	—	—	—	2(1)	2(2)
Phleum alpinum	1(+)	—	3(1)	—	—	4(1)	—	1(+)	—	—	—	—	2(1)
Poa alpina	—	1(+)	1(+)	—	—	—	—	—	—	1(+)	—	—	—
Trisetum spicatum	—	—	—	—	—	2(1)	1(+)	—	—	—	—	—	—
FORBS													
Achillea millefolium	—	—	—	—	—	—	—	1(+)	—	—	—	—	—
Allium validum	—	—	5(2)	—	—	—	—	—	—	—	—	—	—
Antennaria alpina	—	—	—	1(+)	—	5(2)	—	—	—	—	4(1)	2(1)	1(1)
Antennaria lanata	5(2)	7(2)	2(+)	6(3)	9(7)	1(+)	2(1)	—	8(7)	7(6)	1(+)	—	2(1)
Arabis lyallii	—	—	—	—	—	—	2(1)	2(1)	2(1)	1(+)	—	—	1(+)
Arenaria aculeata	—	—	—	1(+)	—	—	—	1(+)	—	1(+)	—	—	—
Arenaria obtusiloba	—	—	—	—	—	—	1(2)	—	—	—	—	—	—
Arnica latifolia	—	—	—	—	—	—	—	6(2)	—	1(+)	—	—	—
Arnica mollis	—	—	—	—	1(+)	1(1)	—	1(+)	—	—	—	—	—
Aster alpigenus	—	1(+)	—	6(4)	—	2(1)	—	1(+)	4(1)	2(1)	—	1(+)	1(+)
Astragalus alpinus	—	—	—	—	—	4(1)	—	—	—	—	—	—	—
Castilleja chrysantha	3(1)	6(2)	1(+)	5(1)	2(1)	—	—	—	—	—	1(+)	—	—
Castilleja rhexifolia	—	—	—	—	3(1)	—	—	—	—	—	—	—	—
Castilleja rubida	—	—	—	—	—	—	—	—	2(+)	—	—	—	—
Dodecatheon alpinum	—	—	—	—	—	3(1)	—	—	—	—	—	—	—
Epilobium alpinum	—	—	—	—	—	—	—	—	—	—	—	—	1(+)
Erigeron peregrinus	8(4)	5(2)	5(2)	3(1)	8(4)	8(5)	—	—	1(+)	—	2(1)	3(1)	4(1)
Happlopappus lyallii	—	—	—	—	—	—	—	—	—	4(1)	—	—	—
Hieracium gracile	1(+)	1(+)	3(1)	9(4)	—	—	1(+)	—	5(1)	—	—	—	—
Lewisia pygmaea	—	1(+)	—	—	—	—	—	—	—	—	—	—	—
Ligusticum tenuifolium	3(1)	10(8)	6(2)	5(1)	8(3)	9(5)	—	—	—	—	4(1)	—	6(2)
Oxyria digyna	—	—	—	—	—	—	—	3(1)	—	—	—	—	—
Parnassia fimbriata	—	—	4(1)	—	—	—	—	—	—	—	—	—	—
Pedicularis contorta	—	—	—	—	—	2(1)	—	—	—	—	—	—	—
Potentilla diversifolia	—	—	—	—	—	—	—	—	—	2(1)	—	—	—
Potentilla flabellifolia	9(7)	4(2)	10(6)	—	1(+)	—	—	—	—	—	9(5)	1(+)	1(2)
Ranunculus eschscholtzii	—	—	—	—	—	—	—	3(1)	3(1)	—	—	—	—
Saxifraga bronchialis	—	—	—	—	—	—	1(+)	—	—	1(+)	—	—	—
Saxifraga occidentalis	—	—	—	—	—	3(1)	1(+)	—	—	—	—	—	—
Sedum stenopetalum	—	—	—	2(+)	—	1(+)	2(+)	—	1(+)	—	—	—	—
Senecio cymbalarioides	—	—	5(2)	—	—	5(2)	—	—	—	—	—	—	—
Sibbaldia procumbens	7(3)	—	—	2(+)	—	1(+)	3(1)	—	2(1)	—	—	5(4)	2(+)
Thalictrum occidentale	—	—	—	—	—	—	—	1(+)	—	—	—	—	—
Veronica cusickii	6(2)	9(3)	7(3)	9(5)	8(3)	5(2)	—	3(1)	10(10)	8(2)	3(1)	6(2)	5(5)
Viola adunca	—	—	4(2)	—	2(1)	5(2)	—	—	—	—	2(1)	1(+)	4(2)

(con.

Table 3. (con.)

SPECIES	Fell-field and bare rock				
Stand number	103	104	107	106	109
Township and section	4S11	4S11	4S11	4S11	4S11
Range	44E	44E	44E	44E	44E
Elevation	2640	2670	2760	2700	2580
Azimuth (degrees)	120	115	230	20	180
Slope (percent)	5	20	5	45	30
Rock type	mb	mb	l	l	gr
SHRUBS AND SUBSHRUBS					
Potentilla fruticosa	1(6)	1(2)	—	—	—
Salix arctica	—	—	1(+)	—	—
Salix cascadensis	—	—	2(+)	5(10)	—
GRAMINOIDS					
Carex scirpoidea	—	—	6(8)	—	—
Carex spectabilis	—	—	6(5)	—	3(1)
Oryzopsis exigua	—	—	—	—	3(1)
Poa alpina	2(1)	—	—	—	—
Sitanion hystrix	5(3)	1(+)	—	—	—
Trisetum spicatum	10(5)	1(+)	2(1)	2(1)	—
FORBS					
Achillea millefolium	5(3)	1(+)	—	—	—
Agoseris glauca	5(3)	—	—	—	—
Anemone multifida	1(+)	—	—	—	—
Antennaria alpina	—	—	—	—	4(3)
Antennaria lanata	—	—	6(5)	—	1(+)
Arabis lyallii	—	—	—	—	1(+)
Arenaria aculeata	—	—	—	—	5(3)
Aster alpigenus	2(1)	1(+)	2(1)	—	5(3)
Astragalus alpinus	5(8)	—	1(+)	—	—
Castilleja rubida	—	—	—	1(+)	—
Delphinium nuttallianum	4(1)	—	—	—	—
Dryas octopetala	—	5(10)	—	9(19)	—
Erigeron chrysopsida	4(1)	4(1)	—	—	—
Eriogonum flavum	5(3)	—	—	—	1(+)
Eriogonum ovalifolium	—	—	—	—	1(+)
Eritrichium nanum	—	—	—	1(+)	—
Erysimum asperum	3(1)	—	—	—	—
Ivesia gordonii	—	3(2)	1(+)	1(+)	9(8)
Lewisia pygmaea	—	—	4(1)	—	—
Linum perenne	9(3)	3(1)	—	—	—
Oxytropis campestris	—	2(1)	—	1(+)	—
Pedicularis contorta	1(+)	—	3(1)	2(1)	—
Phacelia hastata	3(1)	—	—	—	—
Phlox caespitosa	—	4(4)	—	2(1)	5(4)
Sedum stenopetalum	4(1)	—	—	—	—
Senecio streptanthifolius	10(6)	—	—	—	—
Silene acaulis	—	—	2(1)	2(1)	—
Solidago multiradiata	2(1)	2(+)	—	1(+)	—
FERNS AND FERN ALLIES					
Selaginella wallacei	—	—	—	—	4(2)

Table 3. (con.)

SPECIES	PHEM					CASP					CANI		
Stand number	134	110	132	116	148	105	108	131	113	112	111	115	118
Township and section	5S6	4S11	5S12	4S12	4S11	4S11	4S11	5S12	4S12	4S11	4S11	4S12	4S12
Range	45E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E	44E
Elevation	2190	2530	2250	2400	2460	2640	2670	2250	2400	2530	2520	2400	2430
Azimuth (degrees)	60	30	5	60	150	65	360	10	50	15	30	100	90
Slope (percent)	5	20	25	15	30	45	35	40	30	50	5	5	5
Rock type	gr	gr	gr	gr	gr	l	l	gr	l	gr	gr	gr	gr
SHRUBS AND SUBSHRUBS													
Cassiope mertensiana	—	6(4)	5(4)	6(6)	1(1	—	2(1)	—	—	—	—	—	—
Gaultheria humifusa	—	—	6(6)	—	1(2)	—	—	—	—	—	—	—	—
Kalmia microphylla	—	1(+)	6(2)	—	—	—	—	—	—	—	1(+)	—	—
Phyllodoce empetriformis	10(46)	10(39)	10(33)	9(33)	9(28)	—	—	—	—	—	—	2(2)	—
Phyllodoce glanduliflora	—	—	—	—	—	—	1(+)	—	—	—	—	—	—
Salix cascadensis	—	—	—	—	—	4(5)	3(2)	—	—	—	—	—	—
Vaccinium caespitosum	—	—	2(1)	—	—	—	—	—	—	—	—	—	—
Vaccinium scoparium	—	—	2(2)	1(+)	9(15)	—	—	—	—	—	—	—	—
GRAMINOIDS													
Carex nigricans	8(8)	6(3)	5(2)	3(4)	—	2(1)	—	—	1(+)	—	10(66)	10(58)	10(56)
Carex rossii	—	—	—	1(+)	2(1)	—	—	—	1(+)	—	—	—	—
Carex spectabilis	1(+)	1(+)	—	2(1)	—	9(30)	9(21)	9(21)	9(17)	9(16)	1(+)	2(1)	3(5)
Juncus drummondii	—	2(1)	2(1)	1(+)	—	—	6(4)	3(1)	2(1)	—	3(1)	5(6)	3(4)
Juncus parryi	—	—	—	3(2)	9(8)	—	—	—	1(+)	—	—	—	—
Luzula hitchcockii	—	5(4)	9(6)	1(+)	1(+)	6(2)	5(7)	9(11)	6(5)	8(9)	—	—	—
Luzula spicata	—	—	—	—	—	2(1)	1(+)	—	—	—	—	—	—
Muhlenbergia filiformis	4(1)	—	—	—	—	—	—	—	—	—	—	2(1)	2(2)
Phleum alpinum	1(+)	—	3(1)	—	—	4(1)	—	1(+)	—	—	—	—	2(1)
Poa alpina	—	1(+)	1(+)	—	—	—	—	—	—	1(+)	—	—	—
Trisetum spicatum	—	—	—	—	—	2(1)	1(+)	—	—	—	—	—	—
FORBS													
Achillea millefolium	—	—	—	—	—	—	—	1(+)	—	—	—	—	—
Allium validum	—	—	5(2)	—	—	—	—	—	—	—	—	—	—
Antennaria alpina	—	—	—	1(+)	—	5(2)	—	—	—	—	4(1)	2(1)	1(1)
Antennaria lanata	5(2)	7(2)	2(+)	6(3)	9(7)	1(+)	2(1)	—	8(7)	7(6)	1(+)	—	2(1)
Arabis lyallii	—	—	—	—	—	—	2(1)	2(1)	2(1)	1(+)	—	—	1(+)
Arenaria aculeata	—	—	—	1(+)	—	—	—	1(+)	—	1(+)	—	—	—
Arenaria obtusiloba	—	—	—	—	—	—	1(2)	—	—	—	—	—	—
Arnica latifolia	—	—	—	—	—	—	—	6(2)	—	1(+)	—	—	—
Arnica mollis	—	—	—	—	1(+)	1(1)	—	1(+)	—	—	—	—	—
Aster alpigenus	—	1(+)	—	6(4)	—	2(1)	—	1(+)	4(1)	2(1)	—	1(+)	1(+)
Astragalus alpinus	—	—	—	—	—	4(1)	—	—	—	—	—	—	—
Castilleja chrysantha	3(1)	6(2)	1(+)	5(1)	2(1)	—	—	—	—	—	1(+)	—	—
Castilleja rhexifolia	—	—	—	—	3(1)	—	—	—	—	—	—	—	—
Castilleja rubida	—	—	—	—	—	—	—	—	2(+)	—	—	—	—
Dodecatheon alpinum	—	—	—	—	—	3(1)	—	—	—	—	—	—	—
Epilobium alpinum	—	—	—	—	—	—	—	—	—	—	—	—	1(+
Erigeron peregrinus	8(4)	5(2)	5(2)	3(1)	8(4)	8(5)	—	—	1(+)	—	2(1)	3(1)	4(1)
Happlopappus lyallii	—	—	—	—	—	—	—	—	—	4(1)	—	—	—
Hieracium gracile	1(+)	1(+)	3(1)	9(4)	—	—	1(+)	—	5(1)	—	—	—	—
Lewisia pygmaea	—	1(+)	—	—	—	—	—	—	—	—	—	—	—
Ligusticum tenuifolium	3(1)	10(8)	6(2)	5(1)	8(3)	9(5)	—	—	—	—	4(1)	—	6(2)
Oxyria digyna	—	—	—	—	—	—	—	3(1)	—	—	—	—	—
Parnassia fimbriata	—	—	4(1)	—	—	—	—	—	—	—	—	—	—
Pedicularis contorta	—	—	—	—	—	2(1)	—	—	—	—	—	—	—
Potentilla diversifolia	—	—	—	—	—	—	—	—	—	2(1)	—	—	—
Potentilla flabellifolia	9(7)	4(2)	10(6)	—	1(+)	—	—	—	—	—	9(5)	1(+)	1(2)
Ranunculus eschscholtzii	—	—	—	—	—	—	—	3(1)	3(1)	—	—	—	—
Saxifraga bronchialis	—	—	—	—	—	—	1(+)	—	—	1(+)	—	—	—
Saxifraga occidentalis	—	—	—	—	—	3(1)	1(+)	—	—	—	—	—	—
Sedum stenopetalum	—	—	—	2(+)	—	1(+)	2(+)	—	1(+)	—	—	—	—
Senecio cymbalarioides	—	—	5(2)	—	—	5(2)	—	—	—	—	—	—	—
Sibbaldia procumbens	7(3)	—	—	2(+)	—	1(+)	3(1)	—	2(1)	—	—	5(4)	2(+
Thalictrum occidentale	—	—	—	—	—	—	—	1(+)	—	—	—	—	—
Veronica cusickii	6(2)	9(3)	7(3)	9(5)	8(3)	5(2)	—	3(1)	10(10)	8(2)	3(1)	6(2)	5(5)
Viola adunca	—	—	4(2)	—	2(1)	5(2)	—	—	—	—	2(1)	1(+)	4(2)

(cc

Table 3. (con.)

SPECIES	Fell-field and bare rock				
Stand number	103	104	107	106	109
Township and section	4S11	4S11	4S11	4S11	4S11
Range	44E	44E	44E	44E	44E
Elevation	2640	2670	2760	2700	2580
Azimuth (degrees)	120	115	230	20	180
Slope (percent)	5	20	5	45	30
Rock type	mb	mb	l	l	gr
SHRUBS AND SUBSHRUBS					
Potentilla fruticosa	1(6)	1(5)			
Salix arctica	—	—	1(+)		
Salix cascadensis	—	—	2(+)	[illegible]	
GRAMINOIDS					
Carex scirpoidea	—	—	6(6)		
Carex spectabilis	—		6(5)		[illegible]
Oryzopsis exigua	—	—			[illegible]
Poa alpina	2(1)				
Sitanion hystrix	5(3)	1(+)			
Trisetum spicatum	10(5)	1(+)	2(1)	[illegible]	
FORBS					
Achillea millefolium	5(3)	1(+)			
Agoseris glauca	5(3)	—			
Anemone multifida	1(+)	—		—	
Antennaria alpina	—	—	—	—	[illegible]
Antennaria lanata	—	—	6(5)	—	[illegible]
Arabis lyallii	—				[illegible]
Arenaria aculeata	—	—			—
Aster alpigenus	2(1)	1(+)	2(1)		[illegible]
Astragalus alpinus	5(8)	—	1(+)		
Castilleja rubida	—	—	—	1(+)	
Delphinium nuttallianum	4(1)	—	—	—	—
Dryas octopetala	—	5(10)		9(19)	
Erigeron chrysopsida	4(1)	4(1)			
Eriogonum flavum	5(3)	—	—		[illegible]
Eriogonum ovalifolium	—	—			[illegible]
Eritrichium nanum	—	—		1(+)	
Erysimum asperum	3(1)	—	—	—	—
Ivesia gordonii	—	3(2)	1(+)	1(+)	[illegible]
Lewisia pygmaea	—	—	4(1)	—	
Linum perenne	9(3)	3(1)	—		
Oxytropis campestris	—	2(1)		1(+)	
Pedicularis contorta	1(+)	—	3(1)	2(1)	
Phacelia hastata	3(1)	—			
Phlox caespitosa	—	4(4)		2(1)	[illegible]
Sedum stenopetalum	4(1)	—	—	—	—
Senecio streptanthifolius	10(6)	—	—	—	
Silene acaulis	—	—	2(1)	2(1)	
Solidago multiradiata	2(1)	2(+)		1(+)	
FERNS AND FERN ALLIES					
Selaginella wallacei	—	—	—		[illegible]

Table 4.—Selected characteristics of each community type

Characteristic	PSME/ AGSP	PSME/ PHMA	PSME/ CARU	PSME/ THOC	PSME/ BERE	PIFL	ABGR/ THOC	ABLA/ THOC	ABLA/ VAME	ABLA/ VASC	PIAL/ ABLA	PICO/ CARU
Mean shrub cover (percent)	5	59	6	9	26	10	12	3	37	36	18	5
Mean graminoid cover (percent)	31	5	35	5	3	2	5	1	3	2	4	38
Mean forb cover (percent)	19	12	16	47	21	5	23	27	26	5	6	10
Mean total cover (percent)	55	76	57	61	50	17	40	31	66	43	28	53
Total No. shrub species	5	15	9	12	9	7	8	15	9	8	8	7
Total No. graminoid species	6	3	3	2	3	5	2	5	3	10	11	2
Total No. forb species	19	17	25	30	30	18	16	36	18	32	26	15
Total No. vascular species	30	35	37	44	42	30	26	56	30	50	45	24
Mean No. vascular species per 10 m^2 (species richness)	19	14	12	21	22	17	16	12	17	9	10	10

	PICO/ VAME	PICO/ VASC	ACGL	ALSI	Avalanche slope	CELE	High grass	PHEM	CASP	CANI	Fell-field
Mean shrub cover (percent)	54	26	49	91	17	50	2	44	2	1	4
Mean graminoid cover (percent)	2	3	+	1	31	13	26	9	30	67	5
Mean forb cover (percent)	9	3	8	50	33	8	30	20	13	11	21
Mean total cover (percent)	65	32	60	142	81	71	58	73	45	79	30
Total No. shrub species	9	4	6	3	12	11	4	6	3	2	3
Total No. graminoid species	4	4	1	1	9	3	16	9	10	5	6
Total No. forb species	13	10	10	13	35	21	41	19	28	12	28
Total No. vascular species	26	18	18	17	57	35	61	34	41	19	38
Mean No. vascular species per 10 m^2 (species richness)	11	7	18	17	18	18	18	18	16	13	13

Cole, David N.
1982. Vegetation of two drainages in Eagle Cap Wilderness, Wallowa Mountains, Oregon. USDA For. Serv. Res. Pap. INT-288. 42 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Describes plant communities in two drainages of the Eagle Cap Wilderness, Wallowa Mountains, Oreg. Compositional data and implications for wilderness management are provided for 14 coniferous forest types and nine other community types. Four additional plant communities are described, but were not sampled.

KEYWORDS: wilderness management, plant communities, Oregon, Wallowa Mountains

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**Intermountain
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Experiment Station
Ogden, UT 84401**

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June 1982

A Reexamination of Fire Spread in Free-Burning Porous Fuel Beds

Ralph A. Wilson, Jr.

RESEARCH SUMMARY

The original assumption (made by Rothermel in his 1972 paper—A Mathematical Model for Predicting Fire Spread in Wildland Fuels) that the reaction intensity in the combustion zone is linear with loading is experimentally supported within the fuel sizes, loadings, and packing ratios commonly encountered in wildland fuels; further confirmation is needed in light loadings of the fine fuels.

Rothermel's empirical relations for the propagating flux ratio are judged to be adequate for their current use, though perhaps they underestimate the propagating flux in heavy loads of fine fuels. New evidence is presented to physically relate the propagating flux ratio to the optical density ($\sigma\beta$) of the fuel bed. Again, further development is needed.

Experimental difficulties in rigorous determination of reaction zone size remain unsolved. Thus, physical interpretation of reaction intensities should be made with caution. Similarly, the causes and consequences of the optimum packing ratio should be interpreted with caution; for example (in the author's opinion), the idea that reaction intensity is limited by oxygen supply (in draft) at heavier packing ratios is premature and has been overemphasized.

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NTRODUCTION

A mathematical model for fire in wildland fuels Rothermel 1972) is the basis of several forest fire nanagement systems. During development of the model, Rothermel found it necessary to make several assumpions about the effects of fuel geometry and fuel noisture upon combustion. The experimental work decribed here was initiated to examine these assumptions nd to extend the data base beyond the range of Rothermel's early work. The interactions between fuel noisture, load, depth, packing ratio, and fuel particle size re of primary concern, because some combinations of hese variables represent fuel arrays that will not support ire. We consider only the no-wind and zero-slope case.

Analysis of data from more than 250 experimental fires ndicates clearly that additional data (probably 100 fires) re needed before definitive corrections can be made to he fire model equations. Although the results presented iere are preliminary and tentative, some of the original ssumptions are confirmed: the original functional form of the spread equations is retained for the geometric ariables (σ, β, δ, w_o, etc.) while the numerical coefficients re reevaluated; a simplified fuel moisture-damping oefficient is proposed; a separate probability function is ntroduced to predict extinguishment. Reaction and ritique are solicited.

PRELIMINARY DISCUSSION

Following the lead of Frandsen (1971), Rothermel (1972) leveloped the basic spread rate equations based on hysical principles. One can begin with the proposition hat the propagating flux (I_p) required to drive a fire is roportional to the heat needed to bring the fuel to gnition ($\rho_b \varepsilon Q_{ig}$):[1]

$$I_p = R(\rho_b \varepsilon Q_{ig}) \qquad (1)$$

vhere the constant of proportionality is the spread rate. R. The preignition term ($\rho_b \varepsilon Q_{ig}$) is experimentally deterined by calorimetric methods and is not considered here. The propagating flux is dependent on the fuel particle size, arrangement, [illegible] variables.

We next postulate that the propagating flux is proportional to the reaction intensity, I_R (the [illegible], released by the fire)

$$I_p = \xi I_R \qquad (2)$$

and assume that ξ is a function of only [illegible] (i.e., the fraction of energy transferred [illegible] function of particle size and packing ratio [illegible]

An important key to Rothermel's [illegible] the concept of independently evaluating [illegible] and I_R so that spread rate can be functionally related [illegible] intensity defined by

$$I_R = -h\,(dw/dt) \qquad (3)$$

Then by a series of definitions and [illegible] the reaction intensity (Rothermel [illegible] a product of mathematically [illegible] functions [illegible] primary independent variables [illegible]

$$I_R = w_n \ldots \eta_M \ldots \qquad (4)$$

In summary, it has been assumed heretofore that:

- The propagation flux, I_p, is [illegible] reaction intensity, I_R.
- The proportionality constant [illegible] fuel particle size and fuel bed packing [illegible]
- I_R is linearly proportional to net [illegible] w_n
- The moisture damping coefficient [illegible] function of fuel moisture [illegible]
- The mineral damping coefficient [illegible] on the silica-free mineral content [illegible] and
- Optimum reaction velocity (the [illegible] fractional dry weight [illegible] zone) is a function of packing ratio [illegible] fuel beds with only one size of fuel particle [illegible]

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[1] [illegible]

Furthermore, the empirical damping coefficients, η_M and η_S, are defined such that

- $\eta_M = 1$ at $M_f = 0$ and
- $\eta_s = 1$ at $S_e = 0$; thus,
- $I_R = w_n h \Gamma'$ properly describes the fire state in the limit of no fuel moisture and no minerals.

As shown below, the experimentally determined reaction intensity, I_R, is dependent on the experimentally determined reaction zone size, and the propagating flux ratio, ξ, is determined as the fraction of I_R that is required to drive the fire at the measured spread rate, R. Thus, any consistent experimental technique for determining the reaction intensity will provide a consistent set of equations for I_R and ξ that will predict the spread rate, R (within the range of experimental applicability). The reaction intensity, however, is also used in applied models to predict other fire phenomena such as total heat release, flame length, scorch height, and fireline intensity. The reaction intensity, per se, is not derived from compensating factors and must represent as accurately as possible what it is purported to be. So, the experimental method of determining reaction zone size and hence reaction intensity must be carefully defined. In specific applications, the experimental method of determining "reaction intensity" may be significant for predicting specific fire phenomena.

FIRE MODEL GEOMETRIC EQUATIONS

Analysis of the geometric variables, σ, β, and δ, are confined to tests of the original fire equations against the expanded data base. The new data are restricted to the case of no wind, zero (level) slope, and a minimum of variation in fuel chemistry.

Rothermel's equations are reduced to a factor-product form for testing against the new data by the following substitutions in equations 27, 36, 37, and 38 of table 1.[2]

$$C_1 = \ln\left(\frac{\rho_p h \eta_S \Gamma'_{max} (1 - S_t)}{100}\right) + A\,(1 - \ln(\beta_{op}))$$

$$C_2 = A + 1$$

$$C_3 = -A/\beta_{op}.$$

A fourth parameter, C_4, is introduced to test the linearity of reaction intensity with loading and note that in the original formulation $C_4 = 1$.

The reaction intensity equation becomes

$$I_R = -h\left(\frac{dw}{dt}\right) = e^{C_1}\,\beta^{C_2}\,e^{C_3\beta}\,\delta^{C_4}\,\eta_M \qquad (5)$$

where the C_i coefficients are dependent on fuel size, σ, alone. Anticipating a linear regression technique, the log transform of equation 5 is:

$$\ln(I_R) = C_1 + C_2 \ln(\beta) + C_3\beta + C_4 \ln(\delta) + \ln(\eta_M). \qquad (6)$$

Note that in the ovendry limit $\eta_M = 1$ (also that in Rothermel's equations $C_4 = 1$). Evaluation of the coefficients by least square error fit and comparison with the original values will test the fire model formulation.

Similarly, the reaction velocity, Γ', becomes

$$\Gamma' = \left(\frac{100\,e^{C_1}}{\rho_p \quad \eta_M \quad \eta_S}\right)\beta^{C_2 - 1} e^{C_3\beta}\,\delta^{C_4 - 1}.$$

The optimum packing ratio β_{op} is defined as the packing ratio at the maximum value of the reaction velocity.

$$\text{Setting} \quad \left.\frac{\partial \Gamma'}{\partial \beta}\right|_{\beta_{op}} = 0$$

we have $\beta_{op} = (1 - C_2)/C_3$

whereby the optimum packing ratio is determined by the regression coefficients C_2 and C_3.

In similar fashion, the propagating flux ratio, ξ, is expressed as:

$$\xi = I_p/I_R = R(\rho_p \varepsilon Q_{ig})\;/\left(-h\frac{dw}{dt}\right).$$

Again substituting coefficients in equation 42 of table 1:

$$d_1 = [0.0792 + 0.37597\,\sigma^{0.5} - \ln(192 + 7.9095\sigma)]$$

$$d_2 = [0.792 + 3.7597\sigma^{0.5}]$$

the propagating flux ratio becomes

$$\xi = \exp\,(d_1 + d_2\beta)$$

or

$$\ln(I_p/I_R) = d_1 + d_2\beta,$$

where d_1 and d_2 are dependent on fuel particle size, σ.

Again, the coefficients, d_i, can be determined from the data and compared to Rothermel's original values.

In addition to the above, we introduce a dimensionless geometric parameter—the product, $\sigma\beta\delta$, which is the total surface area of all fuel particles per unit area of fuel bed. We note that heat transport out of the combustion zone, heat absorption by fuel particles, moisture mass transport into and out of fuels, production of volatile combustion products by pyrolysis, etc., are all related to fuel surface area (further theoretical consideration is beyond the scope of this paper). This product ($\sigma\beta\delta$) is used below in exploration of the limits of combustion.

The product ($\sigma\beta$) has the physical character of a radiation extinction coefficient and is introduced below in speculation concerning the propagating flux ratio.

MOISTURE DAMPING

The empirical form of the moisture damping coefficient, η_M, used by Rothermel is

$$\eta_M = \sum b_n \left(\frac{M_f}{M_X}\right)^n. \qquad (10$$

This arbitrary power series was easily fitted to the limited data available and met the requirements that in the dry fuel limit

---

[2] Note: the factor (in the equation for C_1), 1/100, is due to measurement of fuel bed depth in centimeters rather than meters.

Table 1.—Basic fire spread equations

Equations	Units and dimension	Equations (Rothermel 1972)
$R = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}}$	Rate of spread, m/min	(52)
$I_R = \Gamma' w_n h \eta_M \eta_s$	Reaction intensity, kJ/min·m²	(27)
where:		
$\Gamma' = \Gamma'_{max} (\beta/\beta_{op})^A \exp[A(1 - \beta/\beta_{op})]$	Optimum reaction velocity, min⁻¹	(38)
$\Gamma'_{max} = (0.0591 + 2.926\sigma^{-1.5})^{-1}$	Maximum reaction velocity, min⁻¹	(36)
$\beta_{op} = 0.204\sigma^{-0.8189}$	Optimum packing ratio	(37)
$A = (6.723\sigma^{0.1} - 7.27)^{-1}$		(39)
$\eta_M = 1 - 2.59\left(\frac{M_f}{M_x}\right) + 5.11\left(\frac{M_f}{M_x}\right)^2 - 3.52\left(\frac{M_f}{M_x}\right)^3$	Moisture-damping coefficient	(29)
$\eta_s = 0.174S_e^{-0.19}$	Mineral-damping coefficient	(30)
$\xi = (192 + 7.9095\sigma)^{-1}\exp[(0.792 + 3.760\sigma^{0.5})(\beta + 0.1)]$	Propagating flux ratio	(42)
$\phi_w = C(0.305U)^B \left(\frac{\beta}{\beta_{op}}\right)^{-E}$	Wind coefficient	(47)
$C = 7.47\exp(-0.8711\sigma^{0.55})$		(48)
$B = 0.1599\sigma^{0.54}$		(49)
$E = 0.715\exp(-0.01094\sigma)$		(50)
$w_n = w_o(1 - S_T)$	Net fuel loading, kg/m²	(24)
$\phi_s = 5.275\beta^{-0.3}(\tan\phi)^2$	Slope factor	(51)
$\rho_b = w_o/\delta$	Ovendry bulk density, kg/m³	(40)
$\varepsilon = \exp(-4.528/\sigma)$	Effective heating number	(14)
$Q_{ig} = 581 + 2594M_f$	Heat of preignition, kJ/kg	(12)
$\beta = \frac{\rho_b}{\rho_p}$	Packing ratio	(31)

Input parameters for basic equations

w_o, ovendry fuel loading, kg/m²

δ, fuel depth, m

σ, fuel particle surface-area-to-volume ratio, cm⁻¹

h, fuel particle low heat content, kJ/kg

ρ_p, ovendry particle density, kg/m³

M_f, fuel particle moisture content, $\frac{\text{gm moisture}}{\text{gm ovendry wood}}$

S_T, fuel particle total mineral content, $\frac{\text{gm minerals}}{\text{gm ovendry wood}}$

S_e, fuel particle effective mineral content, $\frac{\text{gm silica-free minerals}}{\text{gm ovendry wood}}$

U, wind velocity at midflame height, m/min

$\tan\phi$, slope, vertical rise/horizontal distance

M_x, moisture content of extinction, dimensionless fraction

$$\eta_M = 1 \text{ at } M_f = 0$$

and at the extinction limit of combustion

$$\eta_M = 0 \text{ at } M_f = M_X.$$

The requirement that the moisture damping function also provides for extinguishment at the marginal limits of burning has not worked satisfactorily in application, primarily because we have been unable to find a consistent rationale for choosing a value of the moisture of extinction, M_X.

An alternative approach suggested here (and supported by analysis below) is to separate extinction from moisture damping. A separate probability function is proposed to predict the marginal burning state of the fire and then, if it will burn, a less complicated form of the damping coefficient is needed to characterize fuel moisture effects.

From among several alternatives, a good fit to the new data is given by

$$\eta_M = \exp(C_5 M_f) \qquad (11)$$

which meets the only requirement that $\eta_M = 1$ at $M_f = 0$ for interpretation of the dry fuel limit in equation 5 above. Then regression equation 6 becomes

$$\ln(I_R) = C_1 + C_2 \ln(\beta) + C_3\beta + C_4 \ln(\delta) + C_5 M_f. \qquad (12)$$

The marginal burning probability function is discussed in the results section below. By this rationale the moisture damping function will characterize the effects of fuel moisture on I_R **of burning fires**; an independent function will predict the probability that it will burn or not burn.

EXPERIMENTAL SETUP

Three size classes of fuel were studied: *Populus* spp. (poplar) excelsior ($\sigma = 81.3 \text{ cm}^{-1}$); ponderosa pine, 1/4-inch-square sticks ($\sigma = 6.30 \text{ cm}^{-1}$); and ponderosa pine, 1/2-inch sticks ($\sigma = 3.5 \text{ cm}^{-1}$).

The fuels used in these experiments were chosen to minimize the effects of physiochemical variations (fuels chosen were high-cellulose, low-ash woods and were milled to precise dimensions). The physiochemical characteristics were determined by standard techniques and are tabulated in table 2.

A series of preliminary fires were burned to establish the range of fire phenomena over the experimental range of interest of fuel moisture and loading. These fires were also used to check out instrumentation and measurement techniques. Preliminary test results are given in appendix table 6.

Table 3 shows the matrix of variables examined. For scheduling and accounting purposes, a group number was assigned to each specific combination of σ, β, and δ such that for each fuel size, data would be obtained for a series of groups

- at one constant fuel depth for all packing ratios;
- at one constant packing ratio for all depths;
- at least one constant load for all depths; and,
- within practical limits, loadings and packing would be duplicated for the different fuel sizes.

Within each group (σ, β, δ), fires were burned at various fuel moisture contents from near ovendry up to $M_f = 0.30$. The moisture saturation limit of wood fiber is approximately 30 percent of the ovendry wood weight and is the upper limit of woody fuels ability to absorb moisture from the atmosphere without immersion in liquid water.

Fuels were prepared for a series of burns at a given fuel moisture content by conditioning at controlled temperature and relative humidity for 3 to 10 days, depending on fuel size and target fuel moisture. Prior to conditioning of the excelsior, the dry weight load corrected for storage equilibrium moisture content (EMC) for each burn was measured out into baskets. To construct the fuel bed, excelsior from the conditioning basket was spread uniformly over the bed, fluffed to 2 or 3 times the planned fuel depth to remove tightly packed concentrations, and lightly and uniformly pressed down to the final fuel depth (fig. 1A, B). Extraneous vertical strands above the bed surface were then clipped. Packing ratio for excelsior was calculated from $\beta = w_o / \rho\delta$.

The first 10 burns were loaded heavily (assuming $\rho = 32 \text{ lb/ft}^3$) before density measurements were completed from fuel samples.

For the larger pine fuels (1/4- and 1/2-inch-square sticks), the packing ratio was controlled directly by constructing each horizontal layer (4 or 2 layers per inch of depth, respectively) with the planned (solid volume/total volume) ratio (figs. 2, 3).

Raw data were collected by an automatic digital system (fig. 4) consisting of a programmable controller, clock, 80-channel scanner, digital multimeter, thermocouple reference junctions, digital weighing system, 35 mm camera, and associated interfaces and sensors. (Manual data acquisition consisted of visual measurements of the flame depth and flame height, a photograph of the fuel bed prior to ignition, and a tailing edge view of the fire.)

Table 2.—Physiochemical characteristics of fuels

Fuel	Surface/volume (σ), cm^{-1}	Particle density (ρ_p), kg/m^3	Heat of combustion (h), kJ/kg	Total mineral content (S_T), fraction	Effective mineral content (S_e), fraction
Excelsior (poplar)	81.3	466	17 550	0.00347	0.00322
1/4-inch sticks (ponderosa pine)	6.30	442	19 660	.00238	.00224
1/2-inch sticks (ponderosa pine)	3.15	444	19 163	.00367	.00322

Table 3.—Fuel loading matrix. First number is the I.D. index to identify a group of burns (series of fuel moistures) with constant loading and geometry. Second number is the (ovendry) fuel load in kg/m²

Fuel bed depth (cm)	Surface volume σ(cm^{-1})	Packing ratio, β						
		0.005	0.01	0.02	0.04	0.08	0.16	0.32
1.27	81.3		3. 0.050	*	9, 0.201			
	6.3							
	3.15							
2.54	81.3	1, 0.050	4, .101	8, 0.201	10, .402	11, 0.804		
	6.3				16, .448	20, .895	22, 1.790	
	3.15					27, .895		33, 3.580
5.08	81.3		5, .201	*	*			
	6.3		*	13, .448	17, .895	21, 1.790	23, 3.580	
	3.15					28, 1.790	31, 3.580	
10.16	81.3	2, .201	6, .402					
	6.3			14, .895	18, 1.790			
	3.15		*	24, .895	25, 1.790	29, 3.580	32, 7.161	34. 14.322
20.32	81.3		7, .804	*				
	6.3		12, .895	15, 1.790	19, 3.580			
	3.15				26, 3.580	30, 7.161		

*Indicated individual special purpose fires: to test the low moisture limit versus packing, etc. (labeled Group #0 in appendix table 5).

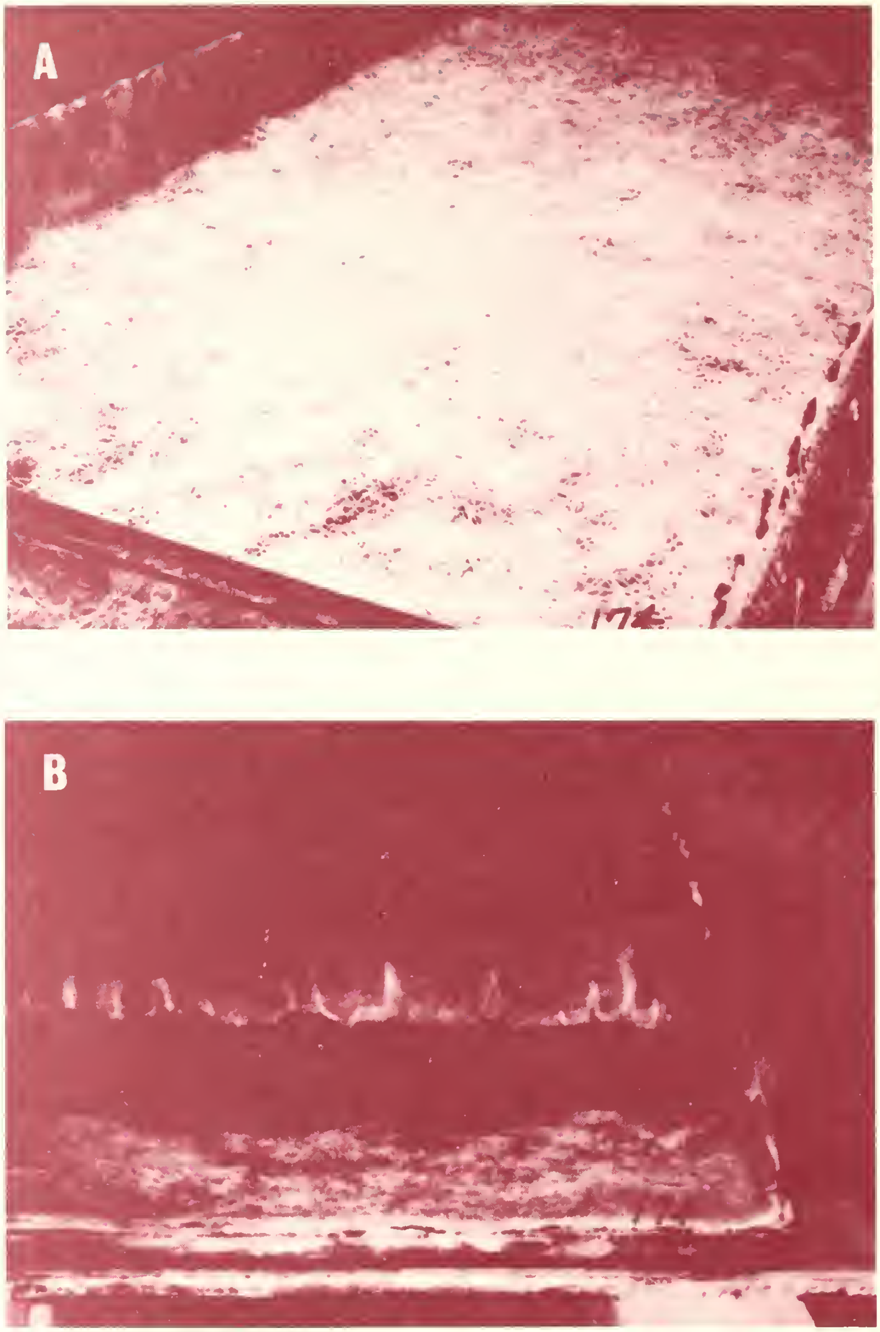

Figure 1.—Excelsior fuel bed for burn No. 174(A) and trailing edge view of the fire (B). $\sigma = 81.3\ \text{cm}^{-1}$, $\beta = 0.04$, $\delta = 1.27$ cm, $w_o = 0.201\ \text{kg/m}^2$, $M_f = 0.103$, $R = 0.269$ m/min, and MBI = 0.6.

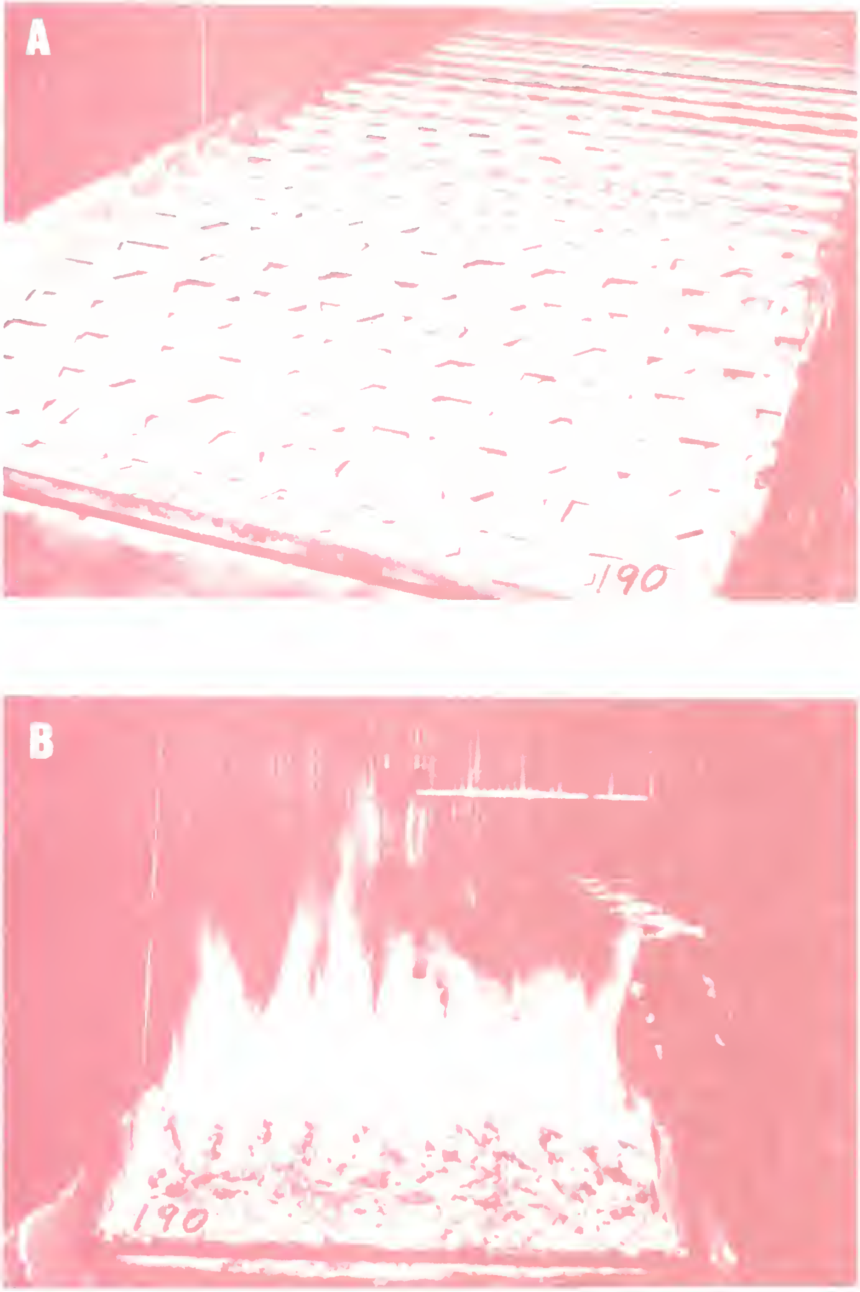

Figure 2.—Preburn 1/2-inch-square-stick fuel bed (A) and trailing edge view of fire (B) Burn No 190. $\sigma = 3.15$ cm^{-1}, $\beta = 0.16$, $\delta = 10.16$ cm, $w = 7.16$ kg/m^2, $M_f = 0.165$, $R = 0.50$ m/min and MBI = 1.0

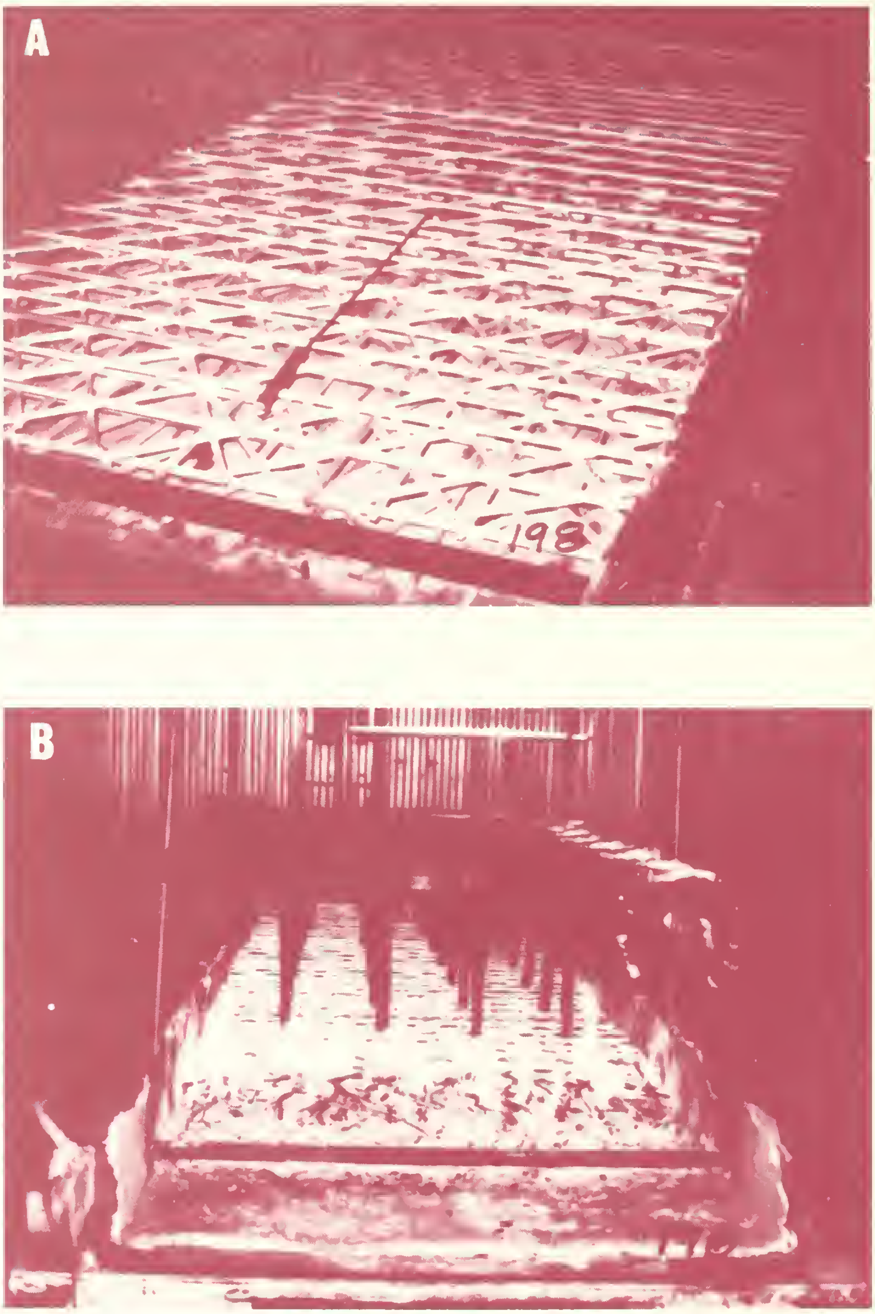

Figure 3.—Preburn 1/4-inch-square-stick fuel bed (A) and trailing edge view of fire (B). Burn No. 198. $\sigma = 6.30$ cm^{-1}, $\beta = 0.08$, $\delta = 5.08$ cm, $w_o = 1.790$ $\mathrm{kg/m}^2$, $M_f = 0.181$, $R = 0.039$ m/min, and $\mathrm{MBI} = 0.9$.

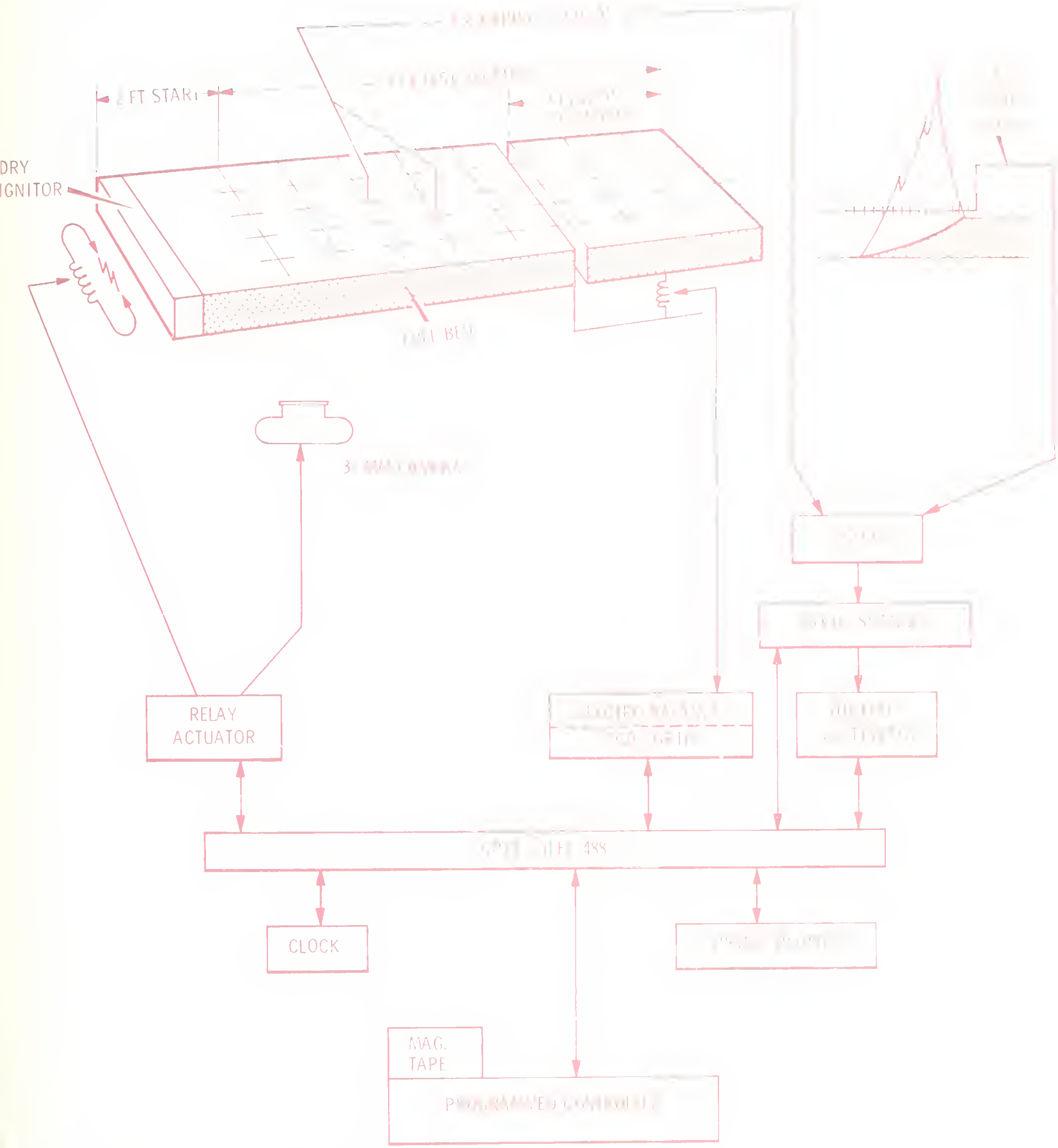

Figure 4.—Schematic of experimental instrumentation

Immediately prior to ignition, fuel bed samples were bottled and sealed for later determination of fuel moisture by xylene distillation. Temperature and relative humidity in the combustion chamber were controlled at approximate conditions for the desired EMC during construction of the fuel bed and for the duration of the test fire.

Spread Rate

The measurement of spread rate was straightforward. A 9 row by 4 column (fig. 4) array of type K (Cr/Al) thermocouples was suspended 2 to 3 cm above the fuel bed surface on a spacing of 17.8 cm (7 in) between columns and 30.48 cm (1 ft) between rows. The TC's voltage was monitored at 1.5 to 2 s cyclic rate. When the thermal EMF exceeded 10 mv threshold (set to 5 mv for low-intensity fires) indicating arrival of the flame front, the clock time, T (i,j), was recorded for each thermocouple (identified by the jth row and ith column). The spread rate, R, was calculated by least squares fit to the equation

$$T = t_o + \left(\frac{1}{R}\right)X$$

where

T is elapsed time and X is distance burned (fig. 5).

Reaction Intensity

Reaction intensity is defined as $I_R = -h\,(dw/dt)$. The heat of combustion, h, was measured for each lot of fuel by oxygen bomb determination (table 2). The mass loss, dm/dt (fig. 6), was calculated from weight and time measurements recorded as the fires progressed over the last three feet of the fuel bed (fig. 4). The unit area weight loss rate, dw/dt, is the raw mass loss rate divided by the combustion zone area. The area of the combustion zone is determined by the width of the fuel bed and the flame depth discussed below. The weight loss rates (listed in column 13 of appendix table 5, are further corrected for fuel moisture by $1/(1 + M_f)$ where M_f is the fractional fuel moisture from the xylene distillation determinations.

Flame Depth/Residence Time

Rothermel (1972) defines reaction time, τ_R, as the "time taken for the fire front to travel a distance equivalent to the depth of one reaction zone." Reaction zone, here called flame depth (D_f), has never been precisely defined, much less the definition standardized.

It is left to the experimentalist to define this reaction/combustion/flame zone depth by his specific measurement technique.[3] Further difficulty is encountered in measuring the area of the combustion zone (by whatever methods including the present), because of its large inherent variance compared to other parameters.

Anderson (1964) and Rothermel and Anderson (1966) calculated the horizontal combustion zone depth, D_f, by measuring the residence time, t, that accrued while embedded thermocouples remained above a threshold temperature as the fire passed at a speed, R. Then $D_f = tR$. Rothermel (1972) measured a similar residence time from the weight loss curves as the combustion zone passed over the leading edge of the weighing platform.

In the tests reported here, the combustion zone depth is the horizontal distance from the leading to trailing edge of the base of the flame. Flame depth was measured by two direct methods; occasionally these results were checked with results using Rothermel's method when data and burning conditions were deemed appropriate (fig. 7A)—i.e., when no observable burnout existed and the burning fuel did not collapse onto nor bridge the weighing platform during transition of the combustion zone.

The primary experimental measurement of flame depth (listed in column 15 of appendix tables 5, 6) is the direct measurement (meter stick) of the distance from leading to trailing edge of the flames. Eight such measurements were taken manually and averaged for each fire (inset fig. 7B).

In addition, several flame probes were constructed of linear arrays of thermocouples for immersion in the flame 1 to 2 cm above the fuel bed (fig. 4). The thermocouple temperature profiles were measured coincident with the eight manual measurements of flame depth (fig. 7B). In the example shown (burn number 141), flame depth, D_f, is calculated:

$$D_f = (\Sigma\overline{\Delta T_i}\,\overline{\Delta X_i})/\overline{\Delta T}_{max}.$$

Flame depths measured in this manner are consistently 15 to 25 percent larger than the manual measurements and invariably smaller than those calculated by the weight loss technique.

The thermocouple probes were incapable of resolving flame depths, smaller than 5 to 6 cm (less than two intervals between thermocouples) or of measuring large zones when the flame depth approached the maximum length of the probe.

We subjectively observed, during the burning and analysis of these fires, that our experimental methods (Rothermel 1972; Anderson 1964; and present studies) may overestimate the combustion zone area that contributes to propagation of the leading edge of the fire. This is particularly likely to happen in heavy fuel loadings where the trailing edge burnout is not in a position to contribute heat flux to driving the fire.

These efforts to measure the total heat release of the combustion zone may provide (in most cases) adequate empirical relations for estimating flame lengths and other fire effects. But the empirical calculation of a gross "propagating flux ratio" masks the physical process by which the propagating heat flux drives the fire. It should be possible to define or experimentally determine a characteristic path length through (or flame depth into) the combustion zone beyond which little or no heat flux can reach the unburned fuel and by which fire propagation could be physically described, namely, by a balance of driving heat flux and preignition heating.

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[3] The author fully appreciates the following view expressed by F. A. Albini (private communication 1981): "The problem here is that the idealization of the spreading fire as exhibiting two distinct event boundaries, one marking the onset of flaming combustion and one its termination, is not a wholly accurate one. We seek to preserve this idealization of the process for its power as a modeling concept, leaving the experimentalist the ill-defined task of fixing an operational definition of its measurement."

Figure 5.—Plotted data for rate of spread for burn No. 141

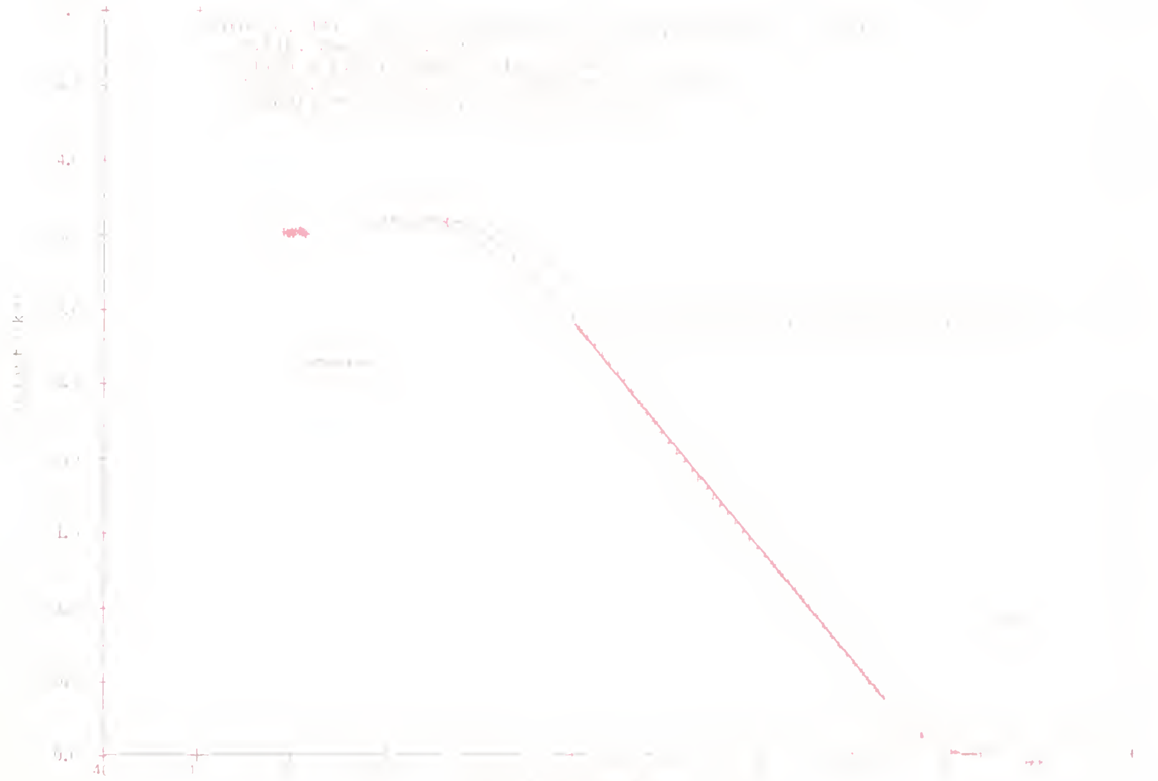
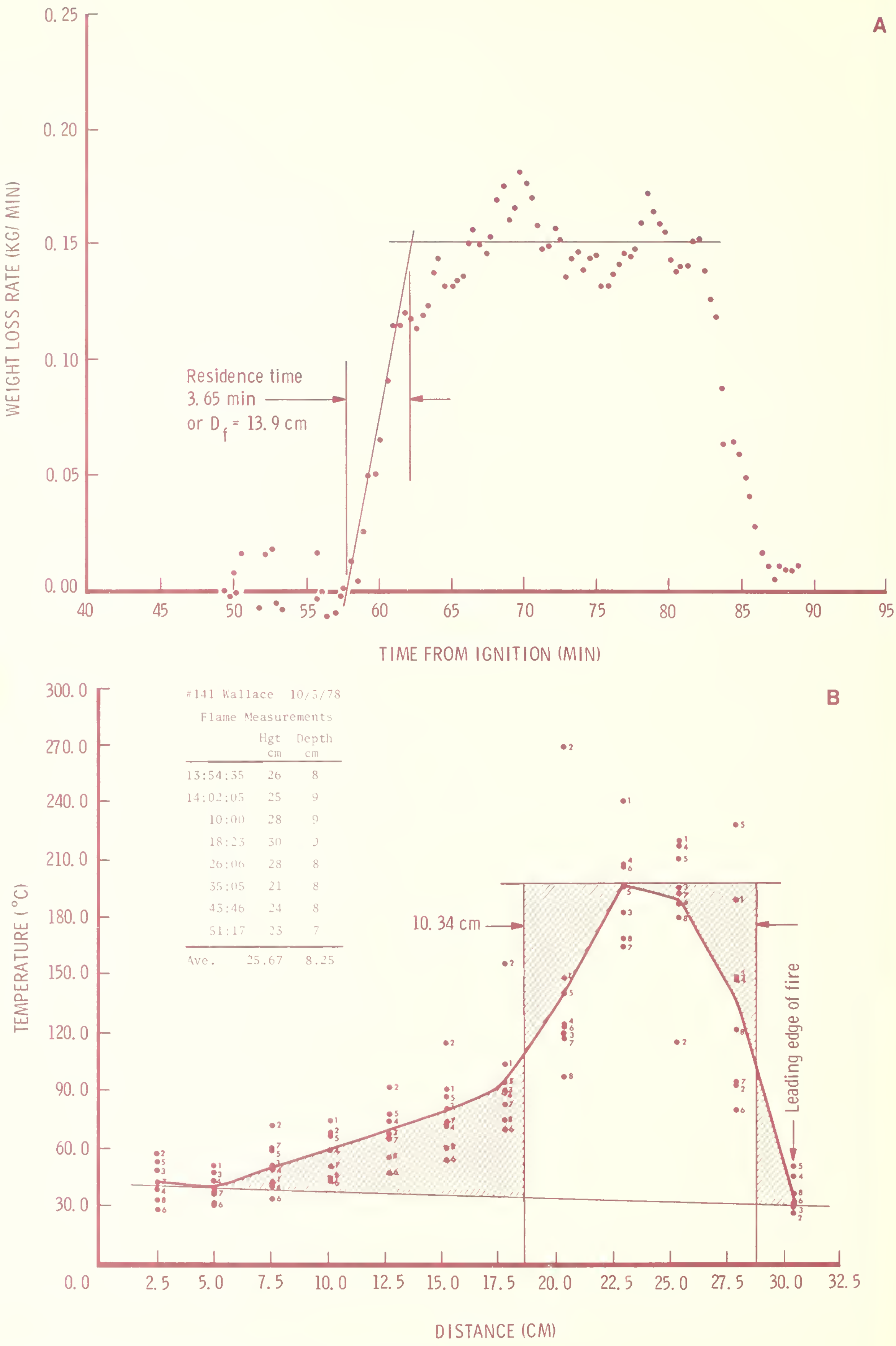


Figure 6.—Plotted data for mass loss rate for burn No. 141



#141 Wallace 10/3/78

Flame Measurements

	Hgt cm	Depth cm
13:54:35	26	8
14:02:05	25	9
10:00	28	9
18:23	30	9
26:06	28	8
35:05	21	8
43:46	24	8
51:17	23	7
Ave.	25.67	8.25

Figure 7.—Combustion zone depth from plotted weight loss rate (A) and from flame probe temperature profile (B) for burn No. 141.

This concept of an effective combustion zone depth might also be extended to eventually include the effects of wind on the fire.

Flame Height

Flame heights are not required in this analysis but are recorded here to facilitate associated fire modeling studies. Visual/manual measurements of flame height (H_f) column 14, appendix tables 5 and 6, were made simultaneously with the flame depth measurements (8 observations for each fire). These are the observer's estimate of the spacial and temporal average flame height across the flame zone for several (5 to 10) seconds. The flame height measurement is particularly prone to observer bias. The individual "official" experimental observer making the H_f and D_f measurements was changed at burn number 61. In addition, periodically one or two (of six individuals) were asked to make simultaneous independent H_f and D_f measurements. A linear bias factor was calculated by least square regression routine with a dummy variable for each observer for each of the eight observers; the resulting H_f (and D_f) measurements listed in appendix tables 5 and 6 are normalized to the H_f (D_f) estimate of the average observer.

Another precautionary note concerns data taken of flames by photography—particularly by cameras with automatic exposure adjustments. It is obvious, but sometimes forgotten, that the dimensions of flames in photographs are very much dependent on the camera exposure settings. Longer exposures show higher peak flame tips and wider flame bases than do shorter exposures. Flame photographs were taken coincidently with the eight measurements of each fire, but were found to be unusable for numerical data on flame size. Nevertheless, the photos proved valuable for estimating the general state of combustion.

Index of Marginal Burning

It became evident during the study that the effect of fuel moisture on burning rate followed a regular pattern, dependent primarily on fuel size class and moisture content. The trend was monotone and regular except that the moisture content at which the fires became erratic or went out varied widely and unpredictably. Thus an arbitrary "Marginal Burning Index" (MBI) was constructed with values between −1 and 1 to indicate each fire's proximity to extinction. Fires that went out (self-extinguished) were given an MBI equal to the negative value of the fraction of unburned fuel bed length; a fire that burned out 1 ft into the 10-ft-long conditioned fuel bed was given MBI = −0.9, one that burned out at 4 ft had MBI = −0.6, and so on. Secondly, the self-sustaining fires were given an MBI value equal to the fraction of bed width, with flame based attached to the combustion zone as measured on the end view photos (fig. 1). These MBI values are in column 16 of appendix tables 5 and 6.

DISCUSSION OF RESULTS

The study plan was designed so that we could partition the data and examine each independent variable, holding all others constant. Because additional data are to be acquired, only a [illegible] preliminary result is presented here.

The statistical bias possibly introduced by the log transforms was examined briefly [illegible] then ignored. That is, for

$y = I_R$, [illegible] $_M$, etc

under some conditions the expectation value

$\langle y \rangle = \exp(\langle \ln y \rangle + S^2/2)$

where from the linear regression (eqs. 6 and 12)

$\langle \ln y \rangle = \sum C X$

and $S^2_{\ln y}$ is the variance of ln y.

In the following discussion the expectation values $\langle y \rangle$ (or predictions, y) are estimated by neglecting the transform bias, thus

$\langle y \rangle = \exp(\langle \ln y \rangle)$

Reaction Intensity, Reaction Velocity

The self-sustaining fires were partitioned by fuel size class, σ, then multiple linear regressions performed on the log transformed form of equation 6 (equation 12)

$$\ln(I_R) = C_1 + C_2 \ln(\beta) + C_3 \sigma + C_4 \ln(\sigma) + C_5 M_f \quad (13)$$

The regression coefficients are listed in table 4. For comparison, the equivalent coefficients of Rothermel's (1972) formulas are also listed. The standard error associated with each coefficient is included in parentheses and the standard error and r^2 of each regression is also listed.

The apparently constant value of C_1 for all three sizes of fuel needs further confirmation and analysis. From Rothermel's limited data, values for this parameter increased with increasing fuel particle size (smaller surface/volume, σ). On cursory examination of equation 5 (taking liberty against formal rigor), as the packing ratio nears its optimum value, $(1 - C_2)/C_3$, the reaction intensity I_R = [illegible]. The new results imply that the reaction intensity per unit mass of dry fuel at the optimum packing may be a constant,[4] independent of fuel size or that a free burning fire may be correctly modeled by a burning rate (mass loss) that is proportional to the total fuel surface area (per unit area of bed)—thus providing a mechanism for handling fuel beds of mixed fuel sizes (note also that if the above proves true, then [illegible] may be determined from **stationary** crib fires with much better experimental accuracy). This sketchy speculation will be examined and studied further with test fires of fuels in the intermediate sizes, 10 < σ < 50 cm[illegible]

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[4] The results [illegible]

The C_4 coefficient is very close to unity for the two larger fuel sizes and reinforces Rothermel's assumption that the reaction intensity is linear with fuel loading. In the fine fuel (excelsior, $\sigma = 81.3\ \text{cm}^{-1}$) the fractional value of C_4 (0.65) indicates a weaker dependence (of I_R on loading) at these loadings and packing ratios. The study was designed to have similar loadings and packing ratios for all fuel sizes within the physical limits of packing the fine fuels. In many of the fires in fine fuels the trailing edge of the combustion zone was not in position to contribute to driving the leading edge of the fire particularly in the deeper, heavier fuel beds—having the effect of decreasing the dependence of reaction intensity on loading.

We plan to extend the fine fuel data base to lighter loadings in the near future. This extension will include loadings near 20 gm per square meter and packing ratios of 0.0005, which approach the light loading limits found in forest litter and grass fields.

In figure 8 A, B, and C, the reaction intensity curves and data (corrected to $M_f = 0$) are plotted and compared with those of Rothermel (1972). For ease of comparison the weighted averages of data at each packing ratio are shown.

In figure 9 A, B, and C, the reaction velocity is similarly compared. The above remarks concerning the fine excelsior fuels are again apparent; in addition, we note that Rothermel forced the reaction velocity curve (for the fine fuels) through the origin by heuristic argument to obtain a maximum Γ' and β_{op}. Figure 9 B and C, show significant differences in the old and new maxima of the reaction velocity curves for the larger fuel sizes. These are the maxima that determine the optimum packing ratios, β_{op}. A review of both the old and new raw data indicates that Rothermel's mass loss rates tend to level off with heavier loading (larger β) and, more importantly, his residence time (or flame depth) increased significantly with larger packing ratios (see discussion of flame depth measurements above).

Lacking data for light loading in the fine fuels, it is premature to draw new conclusions. Also, data are needed in the intermediate size fuels ($10 < \sigma < 50\ \text{cm}^{-1}$) before definitive improvements are made in the present fire equations.

Propagating Flux Ratio

The regression coefficients, d_i, for the propagating flux ratio, ξ, (equation 9), are included in table 4. The regression curves, data, and Rothermel's original curves are compared in figure 10 A, B, and C. Although the coefficients in the empirical regression equations differ considerably, the original Rothermel curves are still reasonable approximations—with the possible exception of underestimating the propagation intensity in the fine fuels.

The data shown in figure 10 suggest that a linear form of ξ (rather than the exponential) may be a better approximation. The best least squares fit of several alternative forms (each including all experimental fires) is

$$\xi = 0.017 - 0.317\,\beta + 0.1119\,(\sigma\beta)$$

with $r^2 = 0.91$, standard error $= 0.048$; the standard error associated with the coefficient (0.1119) of the product $(\sigma\beta)$ is 0.0026.

The product $(\sigma\beta)$ has the physical interpretation of a radiation extinction coefficient for the fuel bed. Its significance as a parameter in the propagation intensity is supported here. Tests of this relationship will be extended by experimental data in the intermediate size fuels ($10 < \sigma < 50\ \text{cm}^{-1}$).

Fuel Moisture

We may interpret $(-1/C_5)$ as a characteristic fuel moisture, M_σ, dependent on fuel particle size (surface/volume ratio):

$$\eta_M = \exp(C_5 M_f) = \exp(-M_f/M_\sigma).$$

The characteristic moisture M_σ is, then, the fuel moisture at which the reaction intensity falls to 1/e of its value at $M_f = 0$. It can be argued heuristically that M_σ must approach a constant value in the fine fuel limit (σ large) and that M_σ should have a small positive value for very large fuels (σ small) and that it must fit the $1/C_5$ values in table 4; then

$$M_\sigma = 1/(2 + 2.4\exp(-0.179\sigma))$$

empirically described the relation of M_σ to fuel particle size, σ, for σ expressed in cm^{-1}. Observe parenthetically that the factor 0.179 (cm) in the equation above is a characteristic "fuel particle surface depth" associated with fuel moisture and fire propagation, and that it is comparable to Frandsen's (1973) depth coefficient (1/138 ft = 0.22 cm) in his effective heating equation.

The function M_σ is plotted in figure 11. This curve again demonstrates the need for confirming experimental data for fuels in the range of $10 < \sigma < 50\ \text{cm}^{-1}$ (fuel particles of 1/8-, 1/16-, and 1/32-inch thickness) near the knee of the M_σ curve.

Figure 12 is a plot of the moisture-damping curve with the confidence bands for each of the three fuel particle sizes. The bands are calculated from the standard error of the coefficient C_5 alone and are given here at the 67 percent confidence level, which is ± one standard error (Draper and Smith 1966).

The curve fit (fig. 12) includes all fires (however broken up, erratic, or marginal) that did not go out.

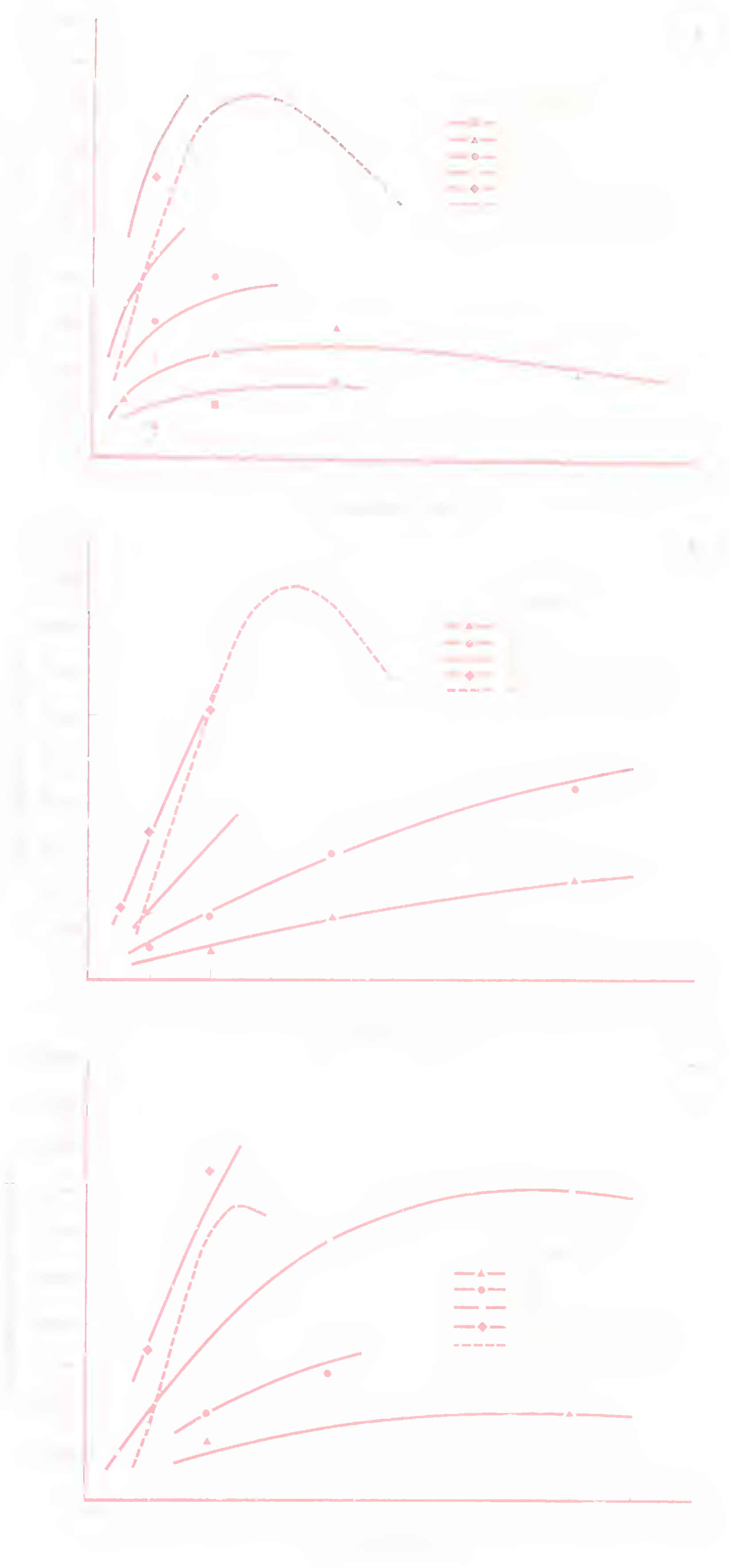

Figure 8.—Reaction intensities for excelsior (A), 1/4-inch fuels (B), 1/2-inch fuels (C)

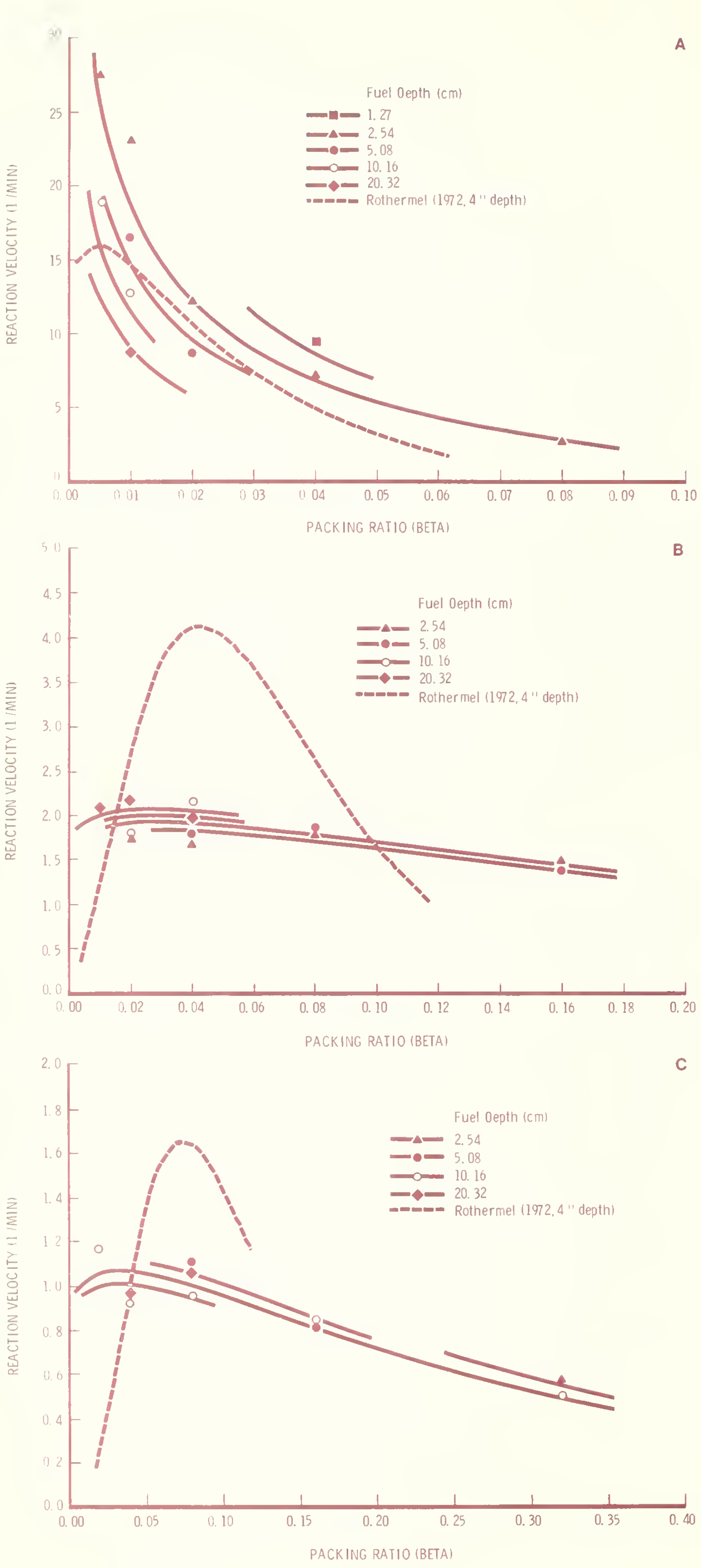

Figure 9.—Reaction velocities for excelsior (A), 1/4-inch fuels (B), 1/2-inch fuels (C).

Figure 10.—Propagating flux ratio for excelsior (A), 1/4-inch fuels (B), 1/2-inch fuels (C)

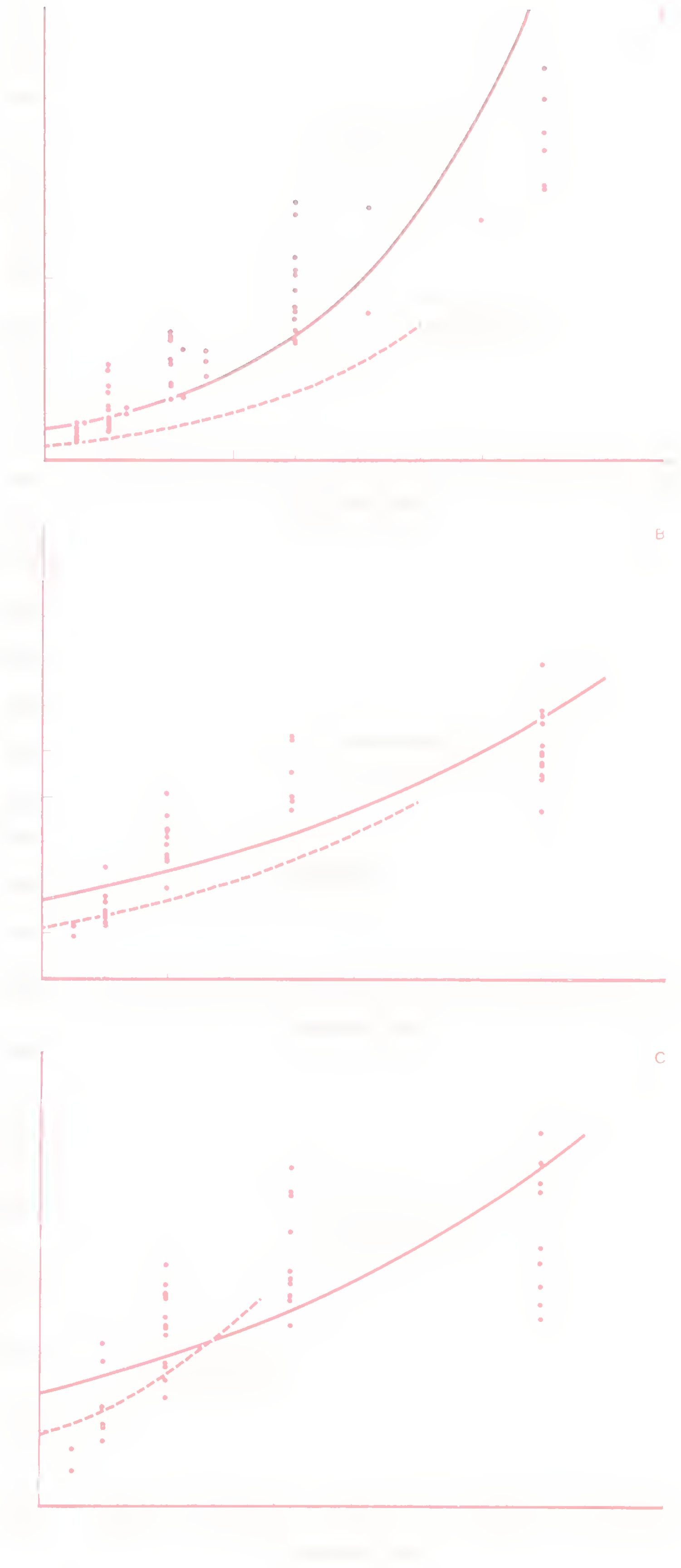

Table 4.—Regression coefficients

Coefficients	σ = 81.3 cm^{-1} New value	Standard error	Old value[1]	σ = 6.3 cm^{-1} New value	Standard error	Old value[1]	σ = 3.15 cm^{-1} New value	Standard error	Old value[1]
C_1	11.985		14.95	11.81		20.70	11.542		23.91
C_2	.574	(0.088)	1.27	1.104	(0.076)	3.075	1.143	(0.090)	4.591
C_3	-14.85	(3.32)	-49.29	-3.432	(1.03)	-45.93	-3.828	(.66)	-45.06
C_4	.652	(.035)	1.000	1.053	(.038)	1.000	.923	(.048)	1.000
C_5	-1.969	(.17)		-2.735	(.250)		-3.570	(.335)	
r^2	.82			.95			.92		
SE	.25			.128			.156		
β_{op}	(—)		.0056	.030		.045	.037		.080
d_1	-2.633		-3.258	-4.032		-4.465	-4.183		-4.633
d_2	34.07	(2.02)	34.69	7.336	(.819)	10.23	3.413	(.644)	7.465
r^2	.75			.62			.39		

[1] Equivalent value calculated from Rothermel (1972).

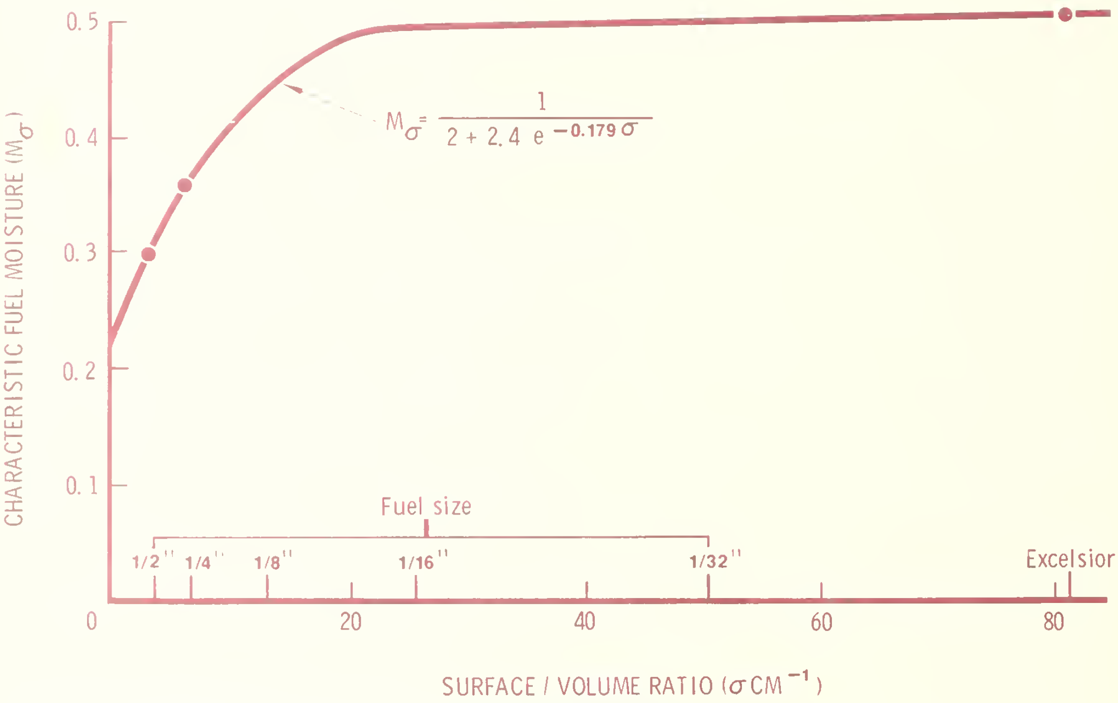

Figure 11.—Fuel moisture characteristic of fuel particle size.

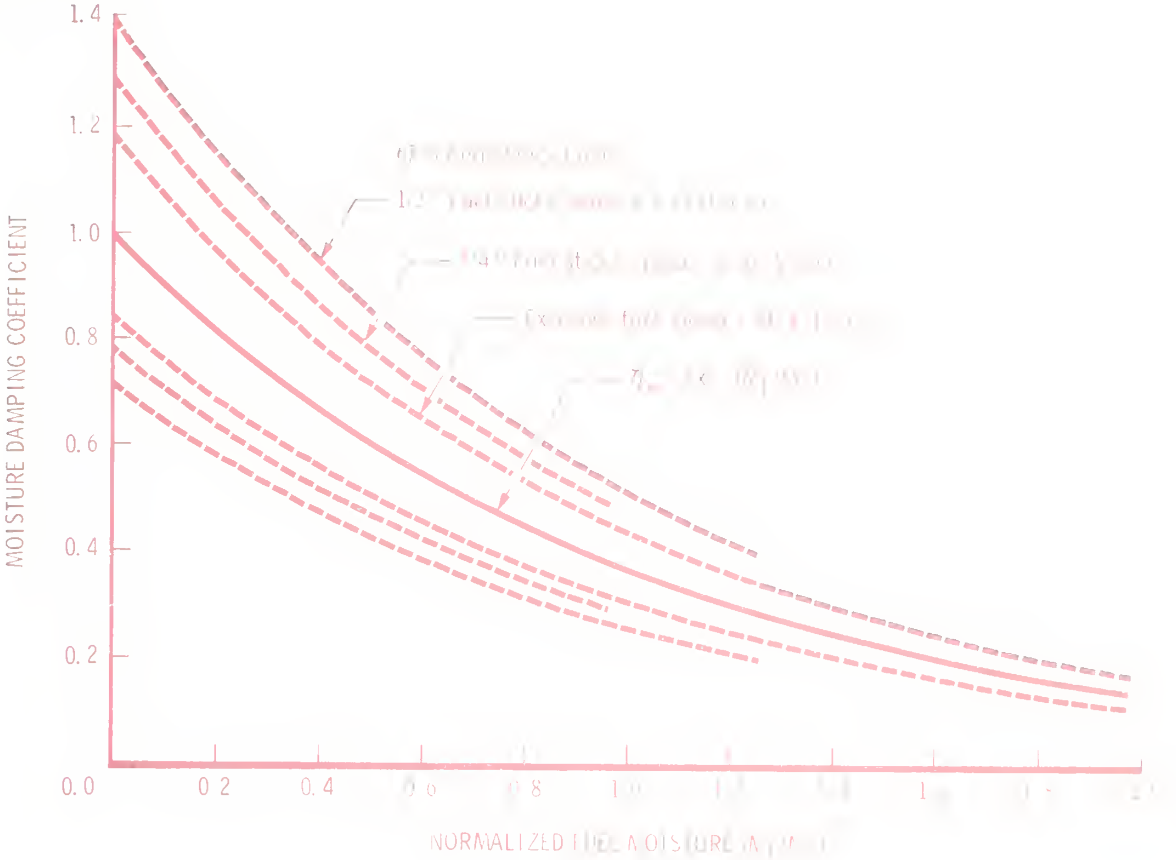

Figure 12.—Moisture-damping coefficient with expected error at 67 percent confidence level (± one standard error of the coefficient C_5).

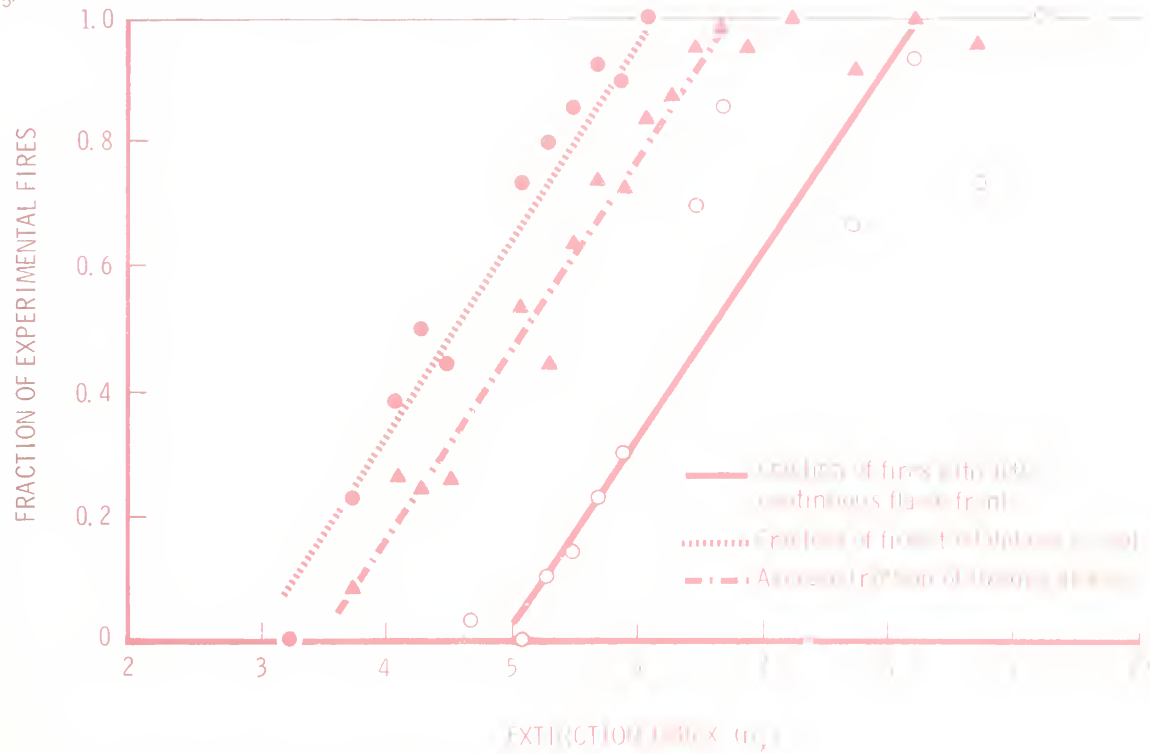

Figure 13.—Probable fire states near extinction

Extinction

As indicated above, the product $\sigma\beta\delta$ is the total fuel particle surface area per unit area of fuel bed. One might expect, as surface area of fuel decreases, that fires will be more difficult to burn and, conversely, as the fuel surface area becomes large, fires will burn more easily and burn at higher fuel moisture. Indeed, as the experimental burning progressed, a predictive rule-of-thumb was developed—fires will not burn if the fuel moisture exceeds:

$$M_f \geq (\ln (2\ \sigma\beta\delta))/4,$$

or if

$$\sigma\beta\delta \leq \exp (4M_f)/2.$$

From this subjective observation and iterative review of the experimental data, a family of curves,

$$\sigma\beta\delta = 2^{(k/2-3)}\exp(-kM_f) \quad \text{for } 0 < k < 20$$

was developed that partition the experimental fires at relatively constant MBI (see Marginal Burning Index above). Thus, an extinction index, n_x, is defined:

$$n_x = \frac{\ln (8\ \sigma\beta\delta)}{M_f + \ln \sqrt{2}} \tag{15}$$

as a predictive indicator of marginal burning. Large values of n_x indicate greater likelihood of good burning; small values, poorer burning. The experimental data, MBI, is compared with n_x in figure 13. The index, n_x, was calculated for each fire; values ranged from 2.56 to 13.56. The number of fires was counted within successive increments of n_x, and classified (1) as a "no burn" with zero flame; (2) by the fraction of flaming fire front (described above), or (3) as a "steady state" fire with 100 percent continuous flame front. The average fraction of flaming front was calculated (for the class 2 fires) within each increment of n_x. Thus, the left most curve of figure 13 represents a probability, P_o, that fires may burn (not go out).

$$P_o = -0.885 + 0.3077\ n_x, \quad (2.875 \leq n_x \leq 6.125). \tag{16}$$

The central curve,

$$P_m = -1.077 + 0.3077\ n_x, \quad (3.5 \leq n_x \leq 6.75), \tag{17}$$

represents the average fraction of fireline aflame; and the right-hand curve,

$$P_{ss} = -1.538 + 0.3077\ n_x, \quad (5 \leq n_x \leq 8.25), \tag{18}$$

is the probability of steady state burning (full, continuous flame front). Fuels will not burn if $n_x < 2.87$; if $n_x > 8.25$, then fires will burn well with a hot, continuous flame front.

Analysis of extinction lacks the rigor that will come later along with more definitive data; however, two points are illustrated; first, that the conditions of marginal burning are experimentally managable and not completely unpredictable (ref. the M_x rationale problem); second, the fuel moisture-surface area relationship provides a mechanism whereby the marginal limits of burning are conditional on fuel loading and particle size as well as fuel moisture content.

SUMMARY

The original assumption that the reaction intensity in the combustion zone is linear with loading is experimentally supported within the fuel sizes, loadings, and packing ratios commonly encountered in wildland fuels; further confirmation is needed in light loadings of the fine fuels.

Rothermel's empirical relations for the propagating flux ratio are judged adequate for current use, though perhaps they underestimate the propagating flux in heavy loads of fine fuels. New evidence is found to physically relate the propagating flux ratio to the optical density ($\sigma\beta$) of the fuel bed. Again, further development is needed.

Experimental difficulties in rigorous determination of reaction zone size remain unsolved. Thus, physical interpretation of reaction intensities should be made with caution. Similarly, the causes and consequences of the optimum packing ratio should be interpreted with caution; for example (in the author's opinion) the widely held idea that reaction intensity is limited by oxygen supply (indraft) at heavier packing ratios is premature and has been overemphasized.

Confirmation is also needed for the hypothesis formed above that the heat release rate (reaction intensity) per unit of mass loading is constant—independent of fuel size. Heretofore, very little experimental evidence was available concerning the relative weighting factors for the several size classes found in wildland fuels. If confirmed, the rationale is that in free-burning fires, the burning mass loss rate will be proportional to the total fuel surface area per unit area of fuel bed.

The marginal limit of self-sustained burning is a function of the fuel surface area as well as fuel moisture content. Thus, an independent function is proposed (for further investigation) as a predictive indicator of marginal burning. The form of the moisture-damping coefficient is much simplified by thus removing the requirement that it provide for the fire extinction limit. After removal of the extinction requirement from the fuel moisture-damping coefficient, it is apparent that the functional relation between moisture damping and fuel particle size becomes tractable.

Additional experimental data are needed in the intermediate fuel sizes and in the light loading limits of fine fuels before definitive conclusions can be made.

An extension of the study in the light and intermediate fuels is underway.

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APPENDIX - TABULATED EXPERIMENTAL DATA

In the following [illegible] the [illegible] (left to right) order are: 1) [illegible] fire number, 2) [illegible], 3) group number, 4, 5, 6) ambient [illegible] of [illegible] chamber, 7) fuel moisture, 8) surface-to-volume ratio of fuel particles, 9) packing ratio, 10) [illegible] bed depth, 11) initial ovendry loading, 12) [illegible], 13) dry mass loss rate (3 ft wide bed), 14) average flame height, 15) average flame depth, 16) index of flame continuity.

Table 5.-- Experemental fire data.

File #	Burn #	Grp #	Temp C*	RH %	EMC (frac)	Mf (frac)	Sigma (1/cm)	Beta	Depth (cm)	Load (kg)	I (m/min)	dw/dt (kg/min)	FH (cm)	FD (cm)	FI
1	48	1	27.2	9	0.021	0.018	81.27	0.005	2.54	0.050	0.453	0.020	7.55	4.04	0.50
2	66	1	27.2	25	0.053	0.053	81.27	0.005	2.54	0.050	0.353	0.017	4.96	3.50	0.40
3	7	1	21.1	40	0.077	0.102	81.27	0.006	2.54	0.065	0.375	0.022	14.06	3.84	0.50
4	153	1	27.2	80	0.157	0.142	81.27	0.005	2.54	0.050	0.298	0.012	5.29	2.14	0.30
5	98	1	27.2	90	0.202	0.202	81.27	0.005	2.54	0.050	0.169	0.008	1.50	1.50	0.30
6	133	1	27.2	90	0.202	0.251	81.27	0.005	2.54	0.050	0.237	0.011	3.29	2.29	0.50
7	41	2	29.4	11	0.023	0.024	81.27	0.005	10.16	0.201	0.935	0.172	45.69	9.61	1.00
8	52	2	30.0	11	0.023	0.027	81.27	0.005	10.16	0.201	0.965	0.156	45.69	10.58	1.00
9	58	2	27.2	25	0.053	0.058	81.27	0.005	10.16	0.201	0.867	0.154	47.27	10.55	1.00
10	171	2	27.2	65	0.117	0.095	81.27	0.005	10.16	0.201	0.699	0.130	54.24	10.07	1.00
11	154	2	27.2	80	0.157	0.147	81.27	0.005	10.16	0.201	0.618	0.123	33.57	8.29	1.00
12	103	2	27.2	90	0.202	0.211	81.27	0.005	10.16	0.201	0.564	0.112	21.00	7.63	0.90
13	132	2	27.2	90	0.202	0.268	81.27	0.005	10.16	0.201	0.560	0.092	20.86	8.96	1.00
14	39	3	31.7	11	0.024	0.028	81.27	0.010	1.27	0.050	0.338	0.018	5.72	4.95	0.70
15	60	3	27.2	25	0.053	0.053	81.27	0.010	1.27	0.050	0.372	0.017	8.73	5.79	0.90
16	175	3	27.2	65	0.117	0.109	81.27	0.010	1.27	0.050	0.000	0.000	0.00	0.00	-0.70
17	152	3	27.2	80	0.157	0.139	81.27	0.010	1.27	0.050	0.279	0.013	4.29	4.29	0.40
18	97	3	27.2	90	0.202	0.203	81.27	0.010	1.27	0.050	0.000	0.000	0.00	0.00	-0.90
19	49	4	27.2	9	0.021	0.019	81.27	0.010	2.54	0.101	0.681	0.063	19.91	7.49	1.00
20	38	4	31.7	11	0.024	0.026	81.27	0.010	2.54	0.101	0.660	0.060	26.54	6.38	1.00
21	67	4	27.2	25	0.053	0.055	81.27	0.010	2.54	0.101	0.508	0.046	31.84	4.88	0.95
22	8	4	21.1	40	0.077	0.101	81.27	0.013	2.54	0.130	0.499	0.059	15.33	5.35	0.90
23	146	4	27.2	80	0.157	0.128	81.27	0.010	2.54	0.101	0.477	0.044	20.43	4.86	0.90
24	95	4	27.2	90	0.202	0.209	81.27	0.010	2.54	0.101	0.380	0.035	10.40	4.20	0.70
25	124	4	27.2	90	0.202	0.299	81.27	0.010	2.54	0.101	0.208	0.019	6.50	2.50	0.30
26	37	5	31.7	11	0.024	0.025	81.27	0.010	5.08	0.201	0.790	0.141	45.94	13.02	1.00
27	50	5	29.4	11	0.023	0.025	81.27	0.010	5.08	0.201	0.824	0.137	47.35	9.77	1.00
28	40	5	29.4	11	0.023	0.027	81.27	0.010	5.08	0.201	0.802	0.130	46.45	8.63	1.00
29	65	5	27.2	25	0.053	0.056	81.27	0.010	5.08	0.201	0.554	0.099	34.92	7.29	1.00
30	59	5	27.2	25	0.053	0.059	81.27	0.010	5.08	0.201	0.634	0.111	38.90	8.46	1.00
31	166	5	29.4	25	0.052	0.061	81.27	0.010	5.08	0.201	0.677	0.128	33.88	9.50	1.00
32	6	5	21.1	40	0.077	0.101	81.27	0.013	5.08	0.260	0.683	0.162	38.94	9.30	1.00
33	145	5	27.2	80	0.157	0.131	81.27	0.010	5.08	0.201	0.542	0.089	31.50	7.25	1.00
34	96	5	27.2	90	0.202	0.200	81.27	0.010	5.08	0.201	0.416	0.076	29.83	7.67	0.95
35	131	5	30.0	90	0.199	0.285	81.27	0.010	5.08	0.201	0.409	0.088	20.40	7.40	1.00
36	126	5	27.2	90	0.202	0.315	81.27	0.010	5.08	0.201	0.437	0.079	23.40	8.20	1.00

Continued

Table 5.-- Continued.

File #	Burn #	Grp #	Temp C*	RH %	EMC (frac)	ME (frac)	Sigma (1/cm)	Beta	Depth (cm)	Load (kg)	I (m/min)	dw/dt (kg/min)	F1 (cm)	F2 (cm)	FI
37	36	6	31.7	11	0.024	0.023	81.27	0.010	10.16	0.402	0.938	0.346	85.78	18.23	1.0[illegible]
38	51	6	30.0	11	0.023	0.025	81.27	0.010	10.16	0.402	1.020	0.384	30.78	15.95	1.0[illegible]
39	63	6	27.2	25	0.053	0.056	81.27	0.010	10.16	0.402	0.911	0.340	80.36	20.14	1.0[illegible]
40	61	6	27.2	25	0.053	0.057	81.27	0.010	10.16	0.402	0.371	0.329	86.47	10.3[illegible]	1.[illegible]
41	173	6	27.2	65	0.117	0.098	81.27	0.010	10.16	0.402	0.777	0.30[illegible]	60.3[illegible]	13.1[illegible]	1.[illegible]
42	143	6	27.2	80	0.157	0.142	81.27	0.010	10.16	0.402	0.706	0.241	55.13	1[illegible]	1.[illegible]
43	102	6	27.2	90	0.202	0.219	81.27	0.010	10.16	0.402	0.569	0.210	43.11	1[illegible]	[illegible]
44	127	6	27.2	90	0.[illegible]	0.297	81.27	0.010	10.16	0.402	0.505	.1[illegible]	[illegible]3.[illegible]	[illegible]	[illegible]
45	45	7	27.2	9	0.021	0.014	81.27	0.010	20.32	0.804	1.270	[illegible]	154.[illegible]	[illegible]	1.[illegible]
46	[illegible]	7	27.2	25	0.053	0.058	81.27	0.010	20.32	.804	1.[illegible]	.[illegible]31	[illegible]	[illegible]	[illegible]
47	172	7	27.2	65	0.117	[illegible]	81.27	0.010	20.32	.804	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
48	147	7	27.2	[illegible]	0.157	[illegible]	81.27	0.010	20.32	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
49	[illegible]	7	27.2	[illegible]	0.157	[illegible]	81.27	0.010	20.32	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
50	[illegible]	7	27.2	[illegible]	[illegible]	0.236	81.27	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	163	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 5.-- Continued.

File #	Burn #	Grp #	Temp C*	RH %	EMC (frac)	ME (frac)	Sigma (J/cm)	Beta	Depth (cm)	Load (kg)	R (m/min)	dw/dt (kg/min)	FH (cm)	FD (cm)	FI
79	3	0	21.1	40	0.077	0.106	81.27	0.052	5.08	1.042	0.695	0.663	117.56	52.08	1.00
80	44	11	27.2	9	0.021	0.017	81.27	0.080	2.54	0.804	0.663	0.454	82.39	43.24	1.00
81	70	11	27.2	25	0.053	0.063	81.27	0.080	2.54	0.804	0.438	0.340	81.46	49.13	1.00
82	9	11	21.1	40	0.077	0.132	81.27	0.070	3.81	1.042	0.509	0.485	68.35	34.16	1.00
83	155	11	27.2	80	0.157	0.143	81.27	0.080	2.54	0.804	0.343	0.216	36.00	28.89	1.00
84	99	11	27.2	90	0.202	0.202	81.27	0.080	2.54	0.804	0.213	0.153	23.33	21.44	0.70
85	129	11	27.2	90	0.202	0.212	81.27	0.080	2.54	0.804	0.223	0.155	17.43	20.14	0.80
86	203	11	27.2	95	0.236	0.227	81.27	0.080	2.54	0.804	0.229	0.153	21.50	21.38	0.90
87	156	0	29.4	5	0.010	0.021	6.30	0.010	5.08	0.224	0.000	0.000	0.00	0.00	-0.60
88	54	12	32.0	12	0.023	0.026	6.30	0.010	20.32	0.895	0.159	0.137	19.10	14.89	1.00
89	81	12	27.2	25	0.053	0.058	6.30	0.010	20.32	0.895	0.093	0.076	21.33	10.17	0.80
90	180	12	27.2	65	0.117	0.112	6.43	0.010	20.32	0.895	0.000	0.000	0.00	0.00	-0.55
91	122	12	27.2	90	0.202	0.199	6.30	0.010	20.32	0.895	0.000	0.000	0.00	0.00	-0.90
92	204	13	31.7	15	0.034	0.010	6.30	0.020	5.08	0.448	0.046	0.017	3.00	4.63	0.40
93	31	13	29.4	15	0.035	0.026	6.30	0.020	5.08	0.448	0.042	0.018	5.83	4.42	0.50
94	74	13	27.2	25	0.053	0.057	6.30	0.020	5.08	0.448	0.000	0.000	0.00	0.00	-0.85
95	14	13	21.1	40	0.077	0.124	6.30	0.020	5.08	0.448	0.000	0.000	0.00	0.00	-0.80
96	26	14	29.4	10	0.023	0.026	6.30	0.020	10.16	0.895	0.098	0.081	21.64	10.57	0.70
97	80	14	27.2	25	0.053	0.059	6.30	0.020	10.16	0.895	0.065	0.050	17.33	7.50	0.70
98	18	14	21.1	40	0.077	0.114	6.30	0.020	10.16	0.895	0.043	0.035	6.50	5.69	0.50
99	195	14	27.2	85	0.177	0.179	6.30	0.020	10.16	0.895	0.000	0.000	0.00	0.00	-0.90
100	113	14	27.2	90	0.202	0.192	6.30	0.020	10.16	0.895	0.000	0.000	0.00	0.00	-0.80
101	159	15	27.2	5	0.013	0.025	6.30	0.020	20.32	1.790	0.329	0.510	69.00	29.13	1.00
102	169	15	29.4	25	0.052	0.068	6.30	0.020	20.32	1.790	0.179	0.292	40.67	19.39	1.00
103	179	15	27.2	65	0.117	0.113	6.43	0.020	20.32	1.790	0.116	0.203	27.36	13.17	1.00
104	200	15	27.2	85	0.177	0.176	6.30	0.020	20.32	1.790	0.065	0.104	18.88	11.50	1.00
105	117	15	27.2	90	0.202	0.217	6.30	0.020	20.32	1.790	0.065	0.130	27.25	10.25	0.50
106	142	15	27.2	90	0.202	0.238	6.30	0.020	20.32	1.790	0.070	0.115	10.00	10.13	0.70
107	210	15	27.2	95	0.236	0.283	6.30	0.020	20.32	1.790	0.000	0.000	0.00	0.00	-0.30
108	27	16	29.4	11	0.023	0.022	6.30	0.040	2.54	0.448	0.045	0.018	5.31	4.95	0.70
109	82	16	27.2	25	0.053	0.059	6.30	0.040	2.54	0.448	0.000	0.000	0.00	0.00	-0.80
110	17	16	21.1	40	0.077	0.119	6.30	0.040	2.54	0.448	0.000	0.000	0.00	0.00	-0.80
111	25	17	29.0	11	0.023	0.024	6.30	0.040	5.08	0.895	0.092	0.077	24.11	8.79	0.90
112	73	17	27.2	25	0.053	0.061	6.30	0.040	5.08	0.895	0.063	0.052	22.05	7.50	0.80
113	10	17	21.1	40	0.077	0.112	6.30	0.040	5.08	0.895	0.037	0.030	11.33	6.10	0.50
114	197	17	27.2	85	0.177	0.190	6.30	0.040	5.08	0.895	0.000	0.000	0.00	0.00	-0.95
115	115	17	27.2	90	0.202	0.193	6.30	0.040	5.08	0.895	0.000	0.000	0.00	0.00	-0.70

Continued

Table 5.-- Continued.

File #	Burn #	Grp #	Temp C*	RH %	EMC (frac)	Mf (frac)	Sigma (1/cm)	Beta	Depth (cm)	Load (kg)	R (m/min)	dw/dt (kg/min)	FH (cm)	FD (cm)	FI
116	158	18	27.2	5	0.013	0.020	6.30	0.040	10.16	1.790	0.250	0.409	56.88	20.88	1.00
117	77	18	27.2	25	0.053	0.058	6.30	0.040	10.16	1.790	0.232	0.380	88.00	19.86	1.00
118	16	18	21.1	40	0.077	0.122	6.30	0.040	10.16	1.790	0.116	0.193	39.82	14.47	1.00
119	199	18	27.2	85	0.177	0.175	6.30	0.040	10.16	1.790	0.060	0.110	16.13	8.63	1.00
120	114	18	27.2	90	0.202	0.200	6.30	0.040	10.16	1.790	0.059	0.091	21.00	10.38	0.90
121	144	18	27.2	90	0.202	0.243	6.30	0.040	10.16	1.790	0.053	0.083	9.88	3.75	0.80
122	211	18	27.2	95	0.236	0.276	6.29	0.040	10.16	1.790	0.000	0.000	0.00	0.00	-0.40
123	160	19	27.2	5	0.013	0.018	6.30	0.040	20.32	3.580	0.517	1.583	245.00	49.13	1.00
124	79	19	27.2	25	0.053	0.059	6.30	0.040	20.32	3.580	0.398	1.304	155.83	34.83	1.00
125	178	19	27.2	65	0.117	0.108	6.43	0.040	20.32	3.580	0.252	0.822	89.79	30.29	1.00
126	121	19	27.2	90	0.202	0.165	6.30	0.040	20.32	3.580	0.125	0.411	53.00	20.88	1.00
127	193	19	27.2	85	0.177	0.168	6.30	0.040	20.32	3.580	0.182	0.545	72.25	23.88	1.00
128	139	19	27.2	90	0.202	0.229	6.30	0.040	20.32	3.580	0.131	0.391	49.38	22.50	0.80
129	212	19	27.2	95	0.236	0.281	6.30	0.040	20.32	3.580	0.032	0.245	41.13	14.88	1.00
130	24	20	29.0	12	0.027	0.023	6.30	0.080	2.54	0.895	0.080	0.069	22.21	8.96	0.90
131	78	20	27.2	25	0.053	0.056	6.30	0.080	2.54	0.895	0.053	0.044	15.17	6.50	0.90
132	19	20	21.1	40	0.077	0.104	6.30	0.080	2.54	0.895	0.036	0.033	7.15	5.44	0.50
133	194	20	27.2	85	0.177	0.192	6.30	0.080	2.54	0.895	0.000	0.000	0.00	0.00	-0.95
134	116	20	27.2	90	0.202	0.209	6.30	0.080	2.54	0.895	0.000	0.000	0.00	0.00	-0.90
135	32	21	29.4	15	0.035	0.026	6.30	0.080	5.08	1.790	0.154	0.237	67.38	15.63	1.00
136	75	21	27.2	25	0.053	0.058	6.30	0.080	5.08	1.790	0.117	0.184	43.75	14.17	1.00
137	15	21	21.1	40	0.077	0.113	6.30	0.080	5.08	1.790	0.075	0.126	34.07	8.87	1.00
138	198	21	27.2	35	0.177	0.181	6.30	0.080	5.08	1.790	0.039	0.062	13.63	7.38	0.90
139	118	21	27.2	90	0.202	0.204	6.30	0.080	5.08	1.790	0.043	0.079	18.38	7.14	0.90
140	143	21	27.2	90	0.202	0.238	6.30	0.080	5.08	1.790	0.032	0.052	7.11	6.33	0.70
141	213	21	23.0	95	0.235	0.295	6.30	0.080	5.08	1.790	0.000	0.000	0.00	0.00	-0.90
142	157	22	27.2	5	0.013	0.016	6.30	0.160	2.54	1.790	0.084	0.140	30.13	11.50	1.00
143	168	22	29.4	25	0.052	0.065	6.30	0.160	2.54	1.790	0.056	0.090	25.53	7.35	1.00
144	176	22	27.2	65	0.117	0.109	6.43	0.160	2.54	1.790	0.038	0.063	20.46	5.16	0.90
145	119	22	27.2	90	0.202	0.163	6.30	0.160	2.54	1.790	0.022	0.037	7.89	4.39	0.50
146	196	22	27.2	85	0.177	0.206	6.30	0.160	2.54	1.790	0.023	0.035	8.86	4.86	0.70
147	140	22	27.2	90	0.202	0.237	6.30	0.160	2.54	1.790	0.000	0.000	0.00	0.00	-0.85
148	53	23	30.0	11	0.023	0.028	6.30	0.160	5.08	3.580	0.109	0.393	81.93	17.09	1.00
149	76	23	27.2	25	0.053	0.059	6.30	0.160	5.08	3.580	0.090	0.288	86.17	15.83	1.00
150	177	23	27.2	65	0.117	0.111	6.43	0.160	5.08	3.580	0.062	0.197	33.17	11.49	1.00
151	192	23	27.2	85	0.177	0.140	6.30	0.160	5.08	3.580	0.048	0.162	37.50	9.98	1.00
152	120	23	27.2	90	0.202	0.205	6.30	0.160	5.08	3.580	0.037	0.125	33.00	7.90	1.00
153	201	23	27.2	80	0.157	0.209	6.30	0.160	5.08	3.580	0.035	0.126	31.38	8.50	1.00
154	141	23	27.2	90	0.202	0.232	6.30	0.160	5.08	3.580	0.038	0.123	25.63	8.25	1.00
155	214	23	27.2	95	0.236	0.289	6.30	0.160	5.08	3.580	0.026	0.086	22.38	7.75	1.00

Continued

Table 5.-- Continued.

File #	Burn #	Grp #	Temp C*	RH %	EMC (frac)	Mf (frac)	Sigma (1/cm)	Beta	Depth (cm)	Load (kg)	R (m/min)	dw/dt (kg/min)	FH (cm)	FD (cm)	FI
156	164	0	29.4	9	0.020	0.019	3.15	0.010	10.16	0.448	0.000	0.000	0.00	0.00	-0.90
157	203	24	31.7	15	0.034	0.009	3.15	0.020	10.16	0.895	0.037	0.030	12.13	6.13	0.30
158	28	24	29.4	11	0.023	0.044	3.15	0.020	10.16	0.895	0.044	0.037	14.63	8.92	0.70
159	92	24	27.2	25	0.053	0.064	3.15	0.020	10.16	0.895	0.000	0.000	0.00	0.00	-0.70
160	30	25	29.4	15	0.035	0.025	3.15	0.040	10.16	1.790	0.083	0.138	25.73	16.82	0.90
161	85	25	27.2	25	0.053	0.061	3.15	0.040	10.16	1.790	0.038	0.059	11.38	10.83	0.80
162	11	25	21.1	40	0.077	0.059	3.15	0.040	10.16	1.790	0.000	0.000	0.00	0.00	-0.70
163	106	25	27.2	90	0.202	0.216	3.15	0.040	10.16	1.790	0.000	0.000	0.00	0.00	-0.90
164	56	26	29.5	11	0.023	0.025	3.15	0.040	20.32	3.580	0.389	1.331	189.30	101.58	1.00
165	90	26	27.2	25	0.053	0.066	3.15	0.040	20.32	3.580	0.215	0.705	69.50	46.63	1.00
166	21	26	21.1	40	0.077	0.136	3.15	0.040	20.32	3.580	0.104	0.350	45.43	34.64	1.00
167	185	26	27.2	75	0.053	0.160	3.15	0.040	20.32	3.580	0.042	0.148	10.83	15.25	0.80
168	105	26	27.2	90	0.202	0.203	3.15	0.040	20.32	3.580	0.033	0.107	9.13	15.75	0.25
169	137	26	27.2	90	0.202	0.261	3.15	0.040	20.32	3.580	0.000	0.000	0.00	0.00	-0.95
170	170	27	31.7	15	0.034	0.006	3.15	0.080	2.54	0.895	0.022	0.018	9.00	2.88	0.20
171	29	27	29.4	15	0.033	0.025	3.15	0.080	2.54	0.895	0.000	0.000	0.00	0.00	-0.70
172	87	27	27.2	25	0.053	0.061	3.15	0.080	2.54	0.895	0.000	0.000	0.00	0.00	-0.90
173	22	28	29.4	11	0.023	0.030	3.15	0.080	5.08	1.790	0.063	0.110	18.63	12.22	0.90
174	86	28	27.2	25	0.053	0.065	3.15	0.080	5.08	1.790	0.032	0.052	12.00	7.67	0.50
175	13	28	21.1	40	0.077	0.133	3.15	0.080	5.08	1.790	0.000	0.000	0.00	0.00	-0.80
176	104	28	27.2	90	0.202	0.221	3.15	0.080	5.08	1.790	0.000	0.000	0.00	0.00	-1.00
177	23	29	29.4	11	0.023	0.024	3.15	0.080	10.16	3.580	0.189	0.617	79.12	40.37	1.00
178	83	29	27.2	25	0.053	0.063	3.15	0.080	10.16	3.580	0.129	0.449	66.00	32.00	1.00
179	12	29	21.1	40	0.077	0.135	3.15	0.080	10.16	3.580	0.069	0.227	28.18	22.06	0.80
180	186	29	27.2	75	0.142	0.157	3.15	0.080	10.16	3.580	0.035	0.106	15.13	12.88	0.90
181	108	29	27.2	90	0.202	0.216	3.15	0.080	10.16	3.580	0.035	0.103	12.11	15.33	0.30
182	134	29	27.2	90	0.202	0.269	3.15	0.080	10.16	3.580	0.000	0.000	0.00	0.00	-0.90
183	34	30	29.4	10	0.023	0.023	3.15	0.080	20.32	7.161	0.420	2.750	326.74	97.86	1.00
184	89	30	27.2	25	0.053	0.058	3.15	0.080	20.32	7.161	0.308	2.017	208.66	61.40	1.00
185	93	30	27.2	25	0.053	0.061	3.15	0.080	20.32	7.161	0.295	1.932	240.98	62.00	1.00
186	181	30	27.2	65	0.117	0.117	3.11	0.080	20.32	7.161	0.168	0.963	100.82	48.72	1.00
187	188	30	27.2	75	0.142	0.154	3.15	0.080	20.32	7.161	0.141	0.837	146.37	36.25	1.00
188	135	30	27.2	90	0.202	0.204	3.15	0.080	20.32	7.161	0.063	0.394	35.13	26.38	1.00
189	109	30	27.2	90	0.202	0.210	3.15	0.080	20.32	7.161	0.112	0.673	62.38	30.13	1.00
190	207	30	27.2	95	0.236	0.245	3.15	0.080	20.32	7.161	0.072	0.394	55.50	32.75	1.00

Continued

Table 5.-- Continued.

File #	Burn #	Grp #	Temp C*	RH %	EMC (frac)	MF (frac)	Sigma (1/cm)	Beta	Depth (cm)	Load (kg)	R (m/min)	dw/dt (kg/min)	[illegible] (cm)	[illegible] (cm)	[illegible]
191	55	31	33.0	12	0.023	0.026	3.15	0.160	5.08	3.580	0.109	0.327	[illegible]	26.37	[illegible]
192	84	31	27.2	25	0.053	0.067	3.15	0.160	5.08	3.580	0.077	0.245	38.14	[illegible]	[illegible]
193	20	31	21.1	40	0.077	0.160	3.15	0.160	5.08	3.580	0.033	[illegible]	24.20	[illegible]	[illegible]
194	137	31	27.2	75	0.053	0.171	3.15	0.160	5.08	3.580	0.021	0.073	11.13	10.13	0.80
195	110	31	27.2	90	0.202	0.214	3.15	0.160	5.08	3.580	0.000	[illegible]	[illegible]	[illegible]	[illegible]
196	33	32	29.4	11	0.023	0.025	3.15	0.160	10.16	7.161	0.185	[illegible]	[illegible]	[illegible]	[illegible]
197	91	32	27.2	25	0.053	0.064	3.15	0.160	10.16	7.161	0.123	0.862	[illegible]	[illegible]	[illegible]
198	183	32	27.2	55	0.117	0.134	3.11	0.160	10.16	7.161	[illegible]	0.420	[illegible]	[illegible]	[illegible]
199	190	32	27.2	75	0.142	0.165	3.15	0.160	10.16	7.161	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
200	135	32	27.2	90	0.202	0.213	3.15	[illegible]	10.16	7.161	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
201	209	32	27.2	95	0.236	0.226	3.15	0.160	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
202	107	32	27.2	90	0.202	[illegible]	3.15	0.160	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
203	[illegible]	33	27.2	[illegible]	0.013	0.015	3.15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
204	[illegible]	[illegible]	27.2	25	0.053	0.058	3.15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
205	[illegible]	[illegible]	27.2	[illegible]	0.117	0.124	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
206	[illegible]	[illegible]	27.2	[illegible]	0.142	0.168	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
207	111	33	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
208	[illegible]	34	29.4	[illegible]	0.010	0.019	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
209	[illegible]	34	[illegible]	[illegible]	0.051	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
210	[illegible]	34	[illegible]	65	0.117	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
211	[illegible]	[illegible]	[illegible]	[illegible]	0.177	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
214	[illegible]	[illegible]	[illegible]	9	[illegible]	[illegible]	3.15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 6. -- Preliminary test fires.

File #	Burn #	Grp #	Temp C*	RH %	EMC (frac)	Mf (frac)	Sigma (1/cm)	Beta	Depth (cm)	Load (kg)	F (m/min)	dw/dt (kg/min)	FH (cm)	FD (cm)	FI
215	310	40	21.1	40	0.077	0.547	81.27	0.006	2.54	0.060	0.000	0.000	0.00	0.00	-0.90
216	307	40	21.1	40	0.077	0.423	81.27	0.006	7.62	0.181	0.253	0.042	16.90	5.70	0.90
217	307	40	21.1	40	0.077	0.524	81.27	0.006	7.62	0.181	0.000	0.000	0.00	0.00	-0.30
218	309	40	21.1	40	0.077	0.654	81.27	0.006	15.24	0.362	0.229	0.076	11.00	10.90	0.90
219	309	40	21.1	40	0.077	0.753	81.27	0.006	15.24	0.362	0.000	0.000	0.00	0.00	-0.80
220	305	40	21.1	40	0.077	0.329	81.27	0.020	2.54	0.201	0.223	0.041	15.00	10.16	0.90
221	305	40	21.1	40	0.077	0.520	81.27	0.021	2.54	0.211	0.000	0.000	0.00	0.00	-0.80
222	308	40	21.1	40	0.077	0.764	81.27	0.020	7.62	0.603	0.162	0.089	22.20	12.80	0.60
223	303	40	21.1	40	0.077	0.717	81.27	0.020	15.24	1.206	0.277	0.305	49.60	29.90	1.00
224	302	40	21.1	40	0.077	0.957	81.27	0.020	15.24	1.206	0.076	0.084	15.40	38.10	0.70
225	302	40	21.1	40	0.077	0.896	81.27	0.021	15.24	1.266	0.000	0.000	0.00	0.00	-0.70
226	311	40	21.1	40	0.077	0.560	81.27	0.040	2.54	0.402	0.000	0.000	0.00	0.00	-0.80
227	312	40	21.1	40	0.077	0.766	81.27	0.040	7.62	1.206	0.000	0.000	0.00	0.00	-0.70
228	313	40	21.1	40	0.077	1.190	81.27	0.040	15.24	2.412	0.000	0.000	0.00	0.00	-0.70
229	412	41	21.1	40	0.077	0.017	6.30	0.020	2.54	0.224	0.000	0.000	0.00	0.00	-0.75
230	413	41	21.1	40	0.077	0.118	6.30	0.020	7.68	0.677	0.000	0.000	0.00	0.00	-0.30
231	401	41	21.1	40	0.077	0.339	6.30	0.020	15.24	1.343	0.090	0.111	10.50	17.90	0.30
232	416	41	21.1	40	0.077	0.189	6.30	0.020	15.24	1.343	0.000	0.000	0.00	0.00	-0.65
233	407	41	21.1	40	0.077	0.059	6.30	0.040	2.54	0.448	0.022	0.009	6.00	4.30	0.50
234	404	41	21.1	40	0.077	0.241	6.30	0.040	2.54	0.448	0.000	0.000	0.00	0.00	-0.95
235	402	41	21.1	40	0.077	0.187	6.30	0.040	7.62	1.343	0.071	0.037	12.00	6.00	0.90
236	410	41	21.1	40	0.077	0.367	6.30	0.040	7.62	1.343	0.000	0.000	0.00	0.00	-0.95
237	409	41	21.1	40	0.077	0.463	6.30	0.040	15.24	2.685	0.053	0.130	23.90	7.80	0.90
238	405	41	21.1	40	0.077	0.211	6.30	0.080	2.54	0.895	0.000	0.000	0.00	0.00	-0.75
239	411	41	21.1	40	0.077	0.318	6.30	0.080	7.62	2.685	0.049	0.120	30.70	6.30	0.90
240	415	41	21.1	40	0.077	0.316	6.30	0.080	15.24	5.371	0.068	0.334	51.90	15.80	1.00
241	414	41	21.1	40	0.077	0.686	6.30	0.080	15.24	5.371	0.000	0.000	0.00	0.00	-0.95
242	419	42	21.1	40	0.077	0.037	3.15	0.040	7.62	1.343	0.041	0.050	9.60	11.00	0.20
243	419	42	21.1	40	0.077	0.037	3.10	0.040	7.62	1.343	0.000	0.000	0.00	0.00	-0.50
244	418	42	21.1	40	0.077	0.078	3.15	0.040	15.24	2.685	0.067	0.164	19.20	22.61	0.90
245	420	42	21.1	40	0.077	0.260	3.10	0.040	15.24	2.685	0.000	0.000	0.00	0.00	-0.50
246	426	42	21.1	40	0.077	0.113	3.10	0.080	2.54	0.895	0.000	0.000	0.00	0.00	-0.90
247	421	42	21.1	40	0.077	0.197	3.10	0.080	7.62	2.685	0.000	0.000	0.00	0.00	-0.70
248	424	42	21.1	40	0.077	0.313	3.15	0.080	15.24	5.371	0.030	0.147	24.30	16.70	0.90
249	424	42	21.1	40	0.077	0.400	3.10	0.080	15.26	5.378	0.000	0.000	0.00	0.00	-0.40
250	427	42	21.1	40	0.077	0.107	3.15	0.160	2.54	1.790	0.000	0.000	0.00	0.00	-0.30
251	428	42	21.1	40	0.077	0.107	3.15	0.160	3.81	2.685	0.026	0.064	12.50	8.40	0.70
252	422	42	21.1	40	0.077	0.241	3.15	0.160	7.62	5.371	0.025	0.125	13.80	9.60	0.95
253	423	42	21.1	40	0.077	0.299	3.15	0.160	7.62	5.371	0.017	0.083	13.10	9.10	0.60
254	423	42	21.1	40	0.077	0.363	3.15	0.160	7.62	5.371	0.000	0.000	0.00	0.00	-0.60
255	429	42	21.1	40	0.077	0.630	3.15	0.160	15.24	10.741	0.013	0.128	12.20	9.10	0.50
256	431	42	21.1	40	0.077	0.776	3.15	0.160	15.24	10.741	0.000	0.000	0.00	0.00	-0.70

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Wilson, Ralph A.
1982. A reexamination of fire spread in free-burning porous fuel beds.
USDA For. Serv. Res. Pap. INT-289, 28 p. Intermt. For. and Range
Exp. Stn., Ogden, Utah 84401

Experimental evidence from 250 test fires confirms the general formulation of Rothermel's 1972 mathematical model for predicting fire spread in wildland fuels. Numerical coefficients are reevaluated for the empirical relations governed by fuel bed geometry. Fuel moisture damping is functionally separated from extinction phenomena. Hypotheses are proposed that propagation flux is related to the optical density of the fuel bed; that the burning mass loss rate of different fuel size classes is proportional to fuel particle surface area; and that the marginal limit of self-sustained burning is dependent on the total fuel surface area in the bed as well as the fuel moisture content. Difficulties of measurement and physical interpretation of reaction intensities are discussed.

KEYWORDS: fire behavior, fire model, moisture damping, extinction, reaction intensity

The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

The Intermountain Station includes the States of Montana, Idaho, Utah, Nevada, and western Wyoming. About 231 million acres, or 85 percent, of the land area in the Station territory are classified as forest and rangeland. These lands include grasslands, deserts, shrublands, alpine areas, and well-stocked forests. They supply fiber for forest industries; minerals for energy and industrial development; and water for domestic and industrial consumption. They also provide recreation opportunities for millions of visitors each year.

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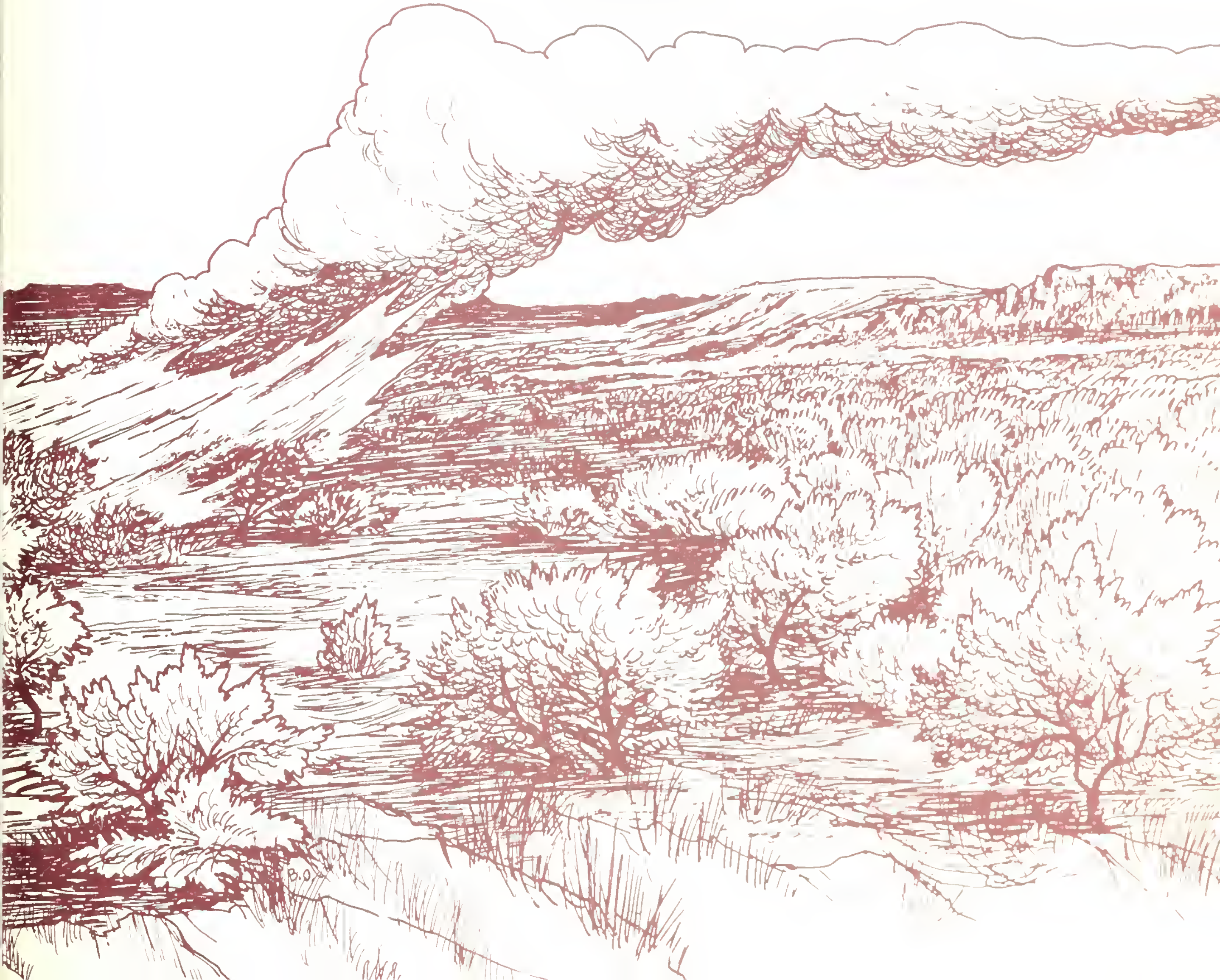
**Intermountain
Forest and Range
Experiment Station
Ogden, UT 84401**

Research Paper
INT-290

May 1982

Fuel and Fire Behavior Prediction in Big Sagebrush

James K. Brown



AUTHOR

JAMES K. BROWN received his bachelor's degree from the University of Minnesota in 1960, his master's from Yale University in 1961, and his Ph.D. from the University of Michigan in 1968, all in forestry. From 1961 to 1965 he did research on field measurement of fuel properties and fire-danger rating systems while with the Lake States Forest Experiment Station. In 1965 he transferred to the Northern Forest Fire Laboratory, Missoula, Mont., where he conducted research on the physical properties, inventory, and prediction of fuels. He currently is leader of a fire effects and use project in Missoula.

RESEARCH SUMMARY

Fuel properties of big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* and *Artemisia tridentata* ssp. *vaseyana*) were sampled in Montana and Idaho and used in mathematical modeling of fire behavior. Relationships between height of sagebrush and crown area, bulk density, size distribution of foliage and stemwood, and fraction dead stemwood are shown.

Sagebrush age related poorly to crown area, height, and bulk density. Surface area to volume ratios of foliage averaged 32 cm^{-1}. Predicted rate of spread and fireline intensity are shown for sagebrush ranging in height from 20 to 120 cm and in coverage from 10 to 40 percent. Grass and forbs ranged from 34 to 170 g/m^2. Sagebrush loading ranged from 0.5 to 10 t/ha and bulk density from 3 to 15 kg/m^3. Rate of spread and intensity for a cured phenological condition were two to three times greater than for uncured. The proportion of dead stemwood had little effect on predicted fire behavior. Verification on three prescribed fires showed reasonably good agreement between observed and predicted rates of spread, but poor agreement for flame length and intensity.

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Fuel and Fire Behavior Prediction in Big Sagebrush

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INTRODUCTION

Modeling rate of spread and fire intensity in sagebrush can aid fire management planning. Mathematical modeling of fire spread and intensity employing Rothermel's model (1972) has been applied successfully using stylized fuel models in the National Fire-Danger Rating System (Deeming and others 1977) and in nomographs (Albini 1976a).

Slash hazard can be appraised from predicted fuel loadings using a program called HAZARD (Puckett and others 1979). Dynamic modeling of fuels and fire behavior over time was demonstrated in chaparral (Rothermel and Philpot 1973) and in palmetto-gallberry fuel complexes where fire behavior depended on age of rough and height of understory (Hough and Albini 1978).

Except for stylized fuel models, applications of fire behavior modeling have involved relatively continuous and uniform fuels such as slash, chaparral, and southern rough. More difficult is modeling of fire spread and intensity in discontinuous and nonuniform fuels such as sagebrush and other xeric site shrub types found particularly in western United States. Inherent in Rothermel's (1972) model is the assumption that fuels are continuous and homogeneous. Properties such as particle size distribution, loading, and bulk density are considered uniform over a rating area. Arid land shrub types violate these assumptions, often to a considerable degree, because shrubs grow in a discontinuous, patchy pattern. Herbaceous fuels between the shrubs are often sparse or absent.

To increase knowledge of fuels and prediction of fire behavior in sagebrush, a study was undertaken to quantify fuel properties and model fire behavior for a variety of sagebrush conditions. This paper reports on this study by describing relationships between fuel properties and height of sagebrush, and by demonstrating how fire modeling might be applied to sagebrush. The fire behavior predictions show to what extent rate of spread and Byram's fireline intensity (Brown and Davis 1973) vary in sagebrush by height, percent cover, foliage moisture, and fraction dead stemwood. Results offer more potential help in planning fire control operations than in planning prescribed fire. However, in both activities, fire behavior predictions from current models might prove useful.

Characterization of fuels is described first, followed by discussion of fire behavior modeling. Metric units are used throughout the paper because [illegible] plant dimensions which are more appropriately measured and described in the metric system. The [illegible] measurement system is used to [illegible] for fire modeling values that might be [illegible] interest to managers.

FUEL CHARACTERIZATION

Fieldwork

Values of fuel properties required to operate Rothermel's (1972) fire spread model can vary substantially from one area to another. They include bulk density of individual plants, loading of live and dead components by particle size, and particle surface area-to-volume ratios. Loading is weight per unit area. Bulk density is weight of fuel per unit volume of fuel bed and is usually computed as the ratio of loading to fuel depth.

Relationships for predicting foliage and stem biomass developed by Harniss and Murray (1976) for mountain big sagebrush (*Artemisia* ssp. *vaseyana*), Rittenhouse and Sneva (1977) for Wyoming big sagebrush (*A. tridentata* ssp. *wyomingensis*), and Uresk and others (1977) for basin big sagebrush (*A. tridentata* ssp. *tridentata*) appeared adequate to estimate loadings for fire modeling. Frandsen[1] went a step further with the estimates of Uresk and others (1977) and Rittenhouse and Sneva (1977) by developing an analytical method that separated their biomass into size classes and expressed it as loadings dependent upon crown area and height. Information relating plant dimensions to bulk density, particle size distribution, and fraction of dead stemwood was limited or absent in the literature. Thus this study was designed to establish relationships between these fuel properties and height and cover of sagebrush.

Individual plants of subspecies *wyomingensis* and *vaseyana* (hereafter referred to as *A. wyomingensis* and *A. vaseyana*) were sampled because these subspecies occupy extensive areas and are known to be flammable. For each subspecies, 10 plants were measured in each of nine stands scattered from southwest Montana to southern Idaho. Heights and ages of sampled plants are shown in table 1.

---

[1] [illegible]

Table 1.—Height and age of sampled sagebrush plants

Height	Number plants		Age	Number plants	
	A. vaseyana	*A. wyomingensis*		*A. vaseyana*	*A. wyomingensis*
cm			*Years*		
0- 20	4	4	0-10	19	24
21- 40	23	25	11-20	31	27
41- 60	25	29	21-30	21	13
61- 80	30	27	31-40	13	12
81-100	8	5	41-50	3	7
			51-60	3	7

For selected plants, the following measurements were taken:

1. Height from the ground to the tallest point on the plant; sporadic or occasional seed stalks were disregarded.
2. Length of long axis of crown in plain view.
3. Length perpendicular to long axis at the widest point.
4. Height from ground to beginning of crown; crown is recognized by the existence of foliage or dense fine dead branchwood that once supported foliage.
5. Crown shape based on integration of plan shape and profile shape (Mawson and others 1976).
6. Diameters measured twice perpendicularly on main stems at ground level or on secondary stems arising within 15 cm of the ground.
7. Fraction of stemwood less than 0.6 cm in diameter that is dead, estimated for each secondary stem.
8. Age of plant by counting growth rings.
9. Percent cover of litter, grass-forbs, and soil occurring beneath the perimeter of each plant; estimated ocularly.
10. Loading of litter, grass, and forbs beneath sagebrush plants.

Material for weighing was collected from 10- by 10-cm and 20- by 20-cm plots placed beneath each plant where litter and herbaceous vegetation appeared average in amount. Dead-to-live ratios were determined for grass and forbs collected in late June after new growth occurred.

Fuel Property Relationships

Loading

Loading was determined from estimates of individual plant biomass divided by estimates of individual plant crown area. Equations were derived by Frandsen[1] using data from Rittenhouse and Sneva (1977) for *A.* [*tridentata*] *wyomingensis*:

$$m = 10^{-2.2522} \quad A^{0.5553} \quad H^{1.1780} \qquad (1)$$

$$m = 10^{-3.1639} \quad A^{0.7409} \quad H^{1.7351} \qquad (2)$$

where:

m = weight, grams
A = crown area, square centimeters
H = sagebrush height, centimeters.

For the fire behavior modeling exercise, individual plant biomass was estimated from equation (1) for foliage, and equation (2) for woody biomass. Except for these estimates of biomass, all other fuel relationships were determined from the field study described in this paper. To solve equations (1) and (2), crown area was predicted from height. Loading was computed by dividing individual plant weight by crown area.

Crown Area

The Pearson correlation coefficient for crown area related to age was 0.16 for *A. vaseyana* and 0.18 for *A. wyomingensis*. The weak correlations probably resulted from the characteristic of sagebrush to grow rapidly in height and crown area for several years followed by a long period of very slow growth. To model fuels dynamically, a relationship between age of plants and fuel characteristics is desirable. Unfortunately, the relationship between age of sagebrush and crown area was poo Because crown area is essential to estimating sagebrush loading, dynamic modeling based on age was impractical. The relationship between crown area and height, however, was considerably more precise than between crown area and age (table 2), and was picked for modeling fuel characteristics. Although a test of differences in slope and intercept between *A. wyomingensis* and *A. vaseyana* was highly significant, the equation for combined data was selected because the difference was small.

Bulk Density

Bulk density was computed using weights of foliage plus 0- to 0.6-cm live and dead stemwood, and foliage plus 0- to 2.5-cm live and dead stemwood. The latter was used for fire behavior modeling. Weight of stemwood greater than 2.5 cm was omitted from the calculation of bulk density because this size class is believed to contribute a relatively small amount of heat to the flame front, and it can distort the influence of bulk density on modeled fire behavior. Fuel bed volumes used to compute bulk densities were estimated as the crown volumes of each plant. The volume between the bottom of the crown and the ground, which often was negligible, was excluded from the volume estimate. Crown shapes approximated primarily elliptical ellipsoids and elliptical paraboloids.

Bulk density varied greatly; however, it was significantly related inversely to height (table 2). Differences in regression slopes between the subspecies were significant at the 0.05 level. However, because variation was substantial and the differences between species not large enough to be important in predicting fire behavior, the combined data equation was used in fire modeling. The correlation coefficient between bulk density and age was 0.26 for *A. vaseyana* and nonsignificant -0.02 for *A. wyomingensis*.

Table 2.—Regression equations for sagebrush

Regression equation	Subspecies	Number plants	R^2	Standard error	a	b
$\ln A = a + b(\ln H)$	Vas	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Wyo	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	All	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$\ln BD1 = a + b(\ln H)$	Vas	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Wyo	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	All	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$F = a + b(\ln H)$	Vas	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Wyo	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	All	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$P1 = a + b(1/H)$	All	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$P2 = a + b(H)$	All	[illegible]	[illegible]		[illegible]	[illegible]
$BD2 = b(BD1)$	All	176	[illegible]	[illegible]	[illegible]	[illegible]
$\ln D = a + b\ln(\text{age})$	Vas	59	[illegible]	[illegible]	[illegible]	[illegible]
	Wyo	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	All	176	[illegible]	[illegible]	[illegible]	[illegible]

[1] A = crown area, square meters.
H = plant height, centimeters.
BD1 = bulk density of foliage and 0- to 0.6-cm stemwood, grams per cubic centimeter.
BD2 = bulk density of foliage plus 0- to 2.5-cm stemwood, grams per cubic centimeter.
F = fraction of foliage.
P1 = fraction of foliage plus 0- to 0.6-cm stemwood.
P2 = fraction of foliage plus 0- to 2.5-cm stemwood and
D = fraction of 0- to 0.6-cm stemwood that is dead

Size Proportions

Fractions of foliage and stemwood were determined for each stem using weight and diameter relationships developed by Brown (1976). For plants having more than one stem, the fractions of foliage and stemwood for the entire plant were computed using the sum of all secondary stem weights.

The fraction of plant biomass in foliage had a slight inverse relationship with height (table 2). The difference in regression estimates between subspecies was significant at the 0.01 level, but the differences were very small and unimportant for fire modeling. Cumulative proportions of stemwood were related to height for the combined subspecies (table 2). The fractions of foliage and 0- to 0.6-cm and 0.6- to 2.5-cm stemwood determined by subtracting cumulative proportions remained reasonably constant with change in height (fig. 1). A comparison of the fractions of foliage and stemwood for threetip sagebrush (*A. tripartita*) from Murray[2] and for *A. vaseyana* and *A. wyomingensis* showed rather small differences. *A. tripartita* had a somewhat greater proportion of foliage and 0- to 0.6-cm stemwood.

Fractions Dead

The fraction of dead stemwood varied substantially with height. Attempts at regression analysis including transformations failed to uncover unreasonable fits throughout the range of height. Thus, the data were plotted and visually divided into the four height groups shown in table 3.

Fraction dead correlated more closely with age than with height (table 1). In four stands of *A. tridentata*, Murray (1975) observed dead-to-live ratios ranging from 0.04 at a stand age of 12 years to 0.27 at 45 years. Uresk and others (1977) found that dead stemwood of *A. tridentata* averaged 11 percent of the total plant biomass. Other data[3] for *A. tridentata* showed percent dead of the total plant to range from 43 percent at a height of 20 cm to 54 percent at 100 cm.

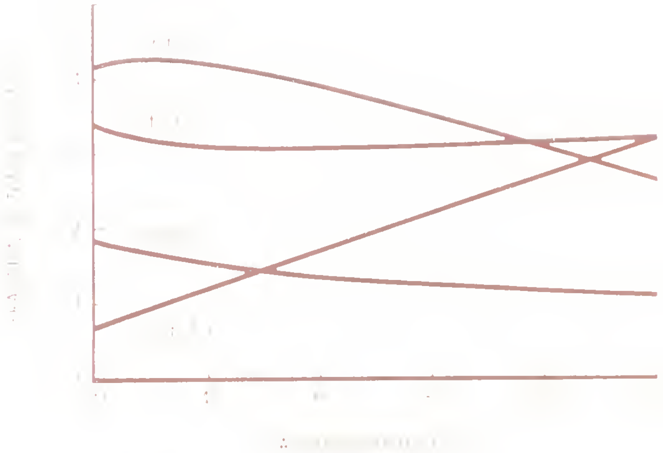

Figure 1.—Fractions of foliage, 0- to 0.6-cm, 0.6- to 2.5-cm, and 2.5- to 7.6-cm stemwood (live and dead together) for *A. vaseyana* and *A. wyomingensis* combined.

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[2] Murray, Robert B., and Quin Jacobson. An evaluation of dimension analysis for predicting shrub biomass. Manuscript in process. USDA Sci. Ed. Agric. Res., (submitted to J. Range Manage.)

[3] Data from Robert Martin, USDA For. Serv., Pac. Northwest For. and Range Exp. Stn., Bend, Oreg.

Table 3.—Fraction of 0- to 0.6-cm stemwood that is dead by height classes and age

Height interval	Average height	Number observed	Fraction dead	Average age
— — — — — cm	— — — — —			Years
10-24	19	17	0.071	9
25-34	30	24	.168	16
35-79	58	125	.349	24
80-104	87	12	.484	36

Ratios of dead-to-live grasses and forbs were plotted over sagebrush age and loading of live grass-forbs. This ordination failed to show any relationship between the dead-to-live ratio and kind of grass (bunchgrass or annual grass), degree of utilization, or live loading. Some ratios were infinitely small and others excessively large; thus, the median ratio rather than the average seemed more appropriate to use in fire modeling. The median dead-to-live ratio was 0.77, which is 43 percent of the total plant weight.

Litter and Grass Beneath Sagebrush

Coverage of litter averaged 52 percent. Loading of litter, including bare patches of soil beneath plants, averaged 78 g/m^2. Grass loadings ranged from 22 to 224 g/m^2 with a median value of 88. Forbs were sparser, having a median loading of 20 g/m^2.

Foliage Surface Area-to-Volume Ratio

Surface area-to-volume ratios describe the amount of surface area surrounding a unit volume of particle and relate to ease of ignition. For sagebrush foliage, they were determined by measuring thickness on a sample of leaves and computing as:

$\sigma = 2/t$ (Brown 1970) (3)

where:

σ = surface area-to-volume ratio, cm^{-1}
t = leaf thickness, cm.

Ten leaves from a mixture of the subspecies *A. wyomingensis* and *A. vaseyana* were chosen at random from each of three sites in Montana and Idaho. For the three sites, σ averaged 32 cm^{-1};

	Location		
	Dillon	Mackay	Challis
Average thickness, mm	0.716	0.677	0.553
Average σ, cm^{-1}	28.2	30.0	36.7
Stand. dev. σ, cm^{-1}	2.5	3.9	4.5

For stemwood, σ was determined using average diameters of the 0- to 0.6-cm and 0.6- to 2.5-cm size classes (Brown 1976) to solve the surface area-to-volume formula for cylinders:

$\sigma = 4/d$ (4)

where:

d = stem diameter, cm.

Height Estimation

Since loading and size proportions related reasonably well to height, height was used as the primary independent variable for modeling fuels. Height and age, however, were poorly correlated ($r = 0.24$, *A. vaseyana* and $r = 0.27$, *A. wyomingensis*). Thus, use of age for dynamic modeling of sagebrush fuel and fire behavior over time would yield inconclusive information.

An important practical question is: How should managers estimate height to properly determine loading This was investigated by first solving equation (2) for height given an average loading for each stand. Next, th average stand height from solution of the loading equation was compared to an average maximum height of each stand obtained by averaging the two largest height per stand. The ratio of average height-to-average maximum height was 0.802. In defining the top of a stan of sagebrush by scanning, a person tends to view the tops of the highest plants. Thus, a rule for determining proper height is to take 0.8 of the average large plant height or essentially 0.8 of an eyeball scan of the sagebrush.

FIRE BEHAVIOR MODELING

Fuel Inputs

Fire behavior was modeled for two phenological situations that reflect relatively lush vegetation of early summer and cured vegetation of fall:

Case A: All sagebrush foliage alive; 57 percent of grasses and forbs alive.

Case B: One-third of sagebrush foliage (the ephemeral leaves) considered dead; all grasses and forbs cured or dead.

For each phenological situation fuel loadings were varied to correspond with sagebrush ranging from 20 to 120 cm in height and 10 to 40 percent in cover. Loadings of grasses and forbs ranged from 34 to 168 g/m^2 (300 to 1,500 lb/acre). These conditions were chosen in order to show the extent to which rate of spread and fireline intensity vary in the sagebrush type.

Rate of spread and fireline intensity were predicted using the computer program FIREMOD (Albini 1976b). Preliminary modeling of fire behavior was undertaken to determine the importance of litter and herbaceous vegetation beneath sagebrush plants. Litter, grasses, and forbs existing within the crown circumference of sagebrush were considered part of the sagebrush for fire behavior modeling. Herbaceous vegetation existing among sagebrush plants was handled separately from sagebrush itself for predicting fire behavior.

Preliminary modeling showed that for large sagebrush plants, litter had little influence on rate of spread and fireline intensity. For small plants, however, presence of litter significantly influenced fire behavior. Because litter was an important fuel in small sagebrush, an average litter loading of 77.3 g/m^2 (690 lb/acre) was used as an input to all sagebrush modeling. Litter loading appeared unrelated to characteristics of sagebrush, thus it could not be predicted as a function of the sagebrush.

To evaluate the importance of modeling grass beneath sagebrush of varying heights, fire behavior was predicted at two diverse grass loadings distributed in three ways: (a) equally within and between sagebrush, (b) twice as much beneath as between sagebrush, and (c) three times as much beneath as between sagebrush. Results showed that, for given grass loadings, varying the ratio of grass beneath and between sagebrush had little influence on predicted fire behavior. Thus, for further modeling of fire behavior, herbaceous vegetation was assumed to be evenly distributed beneath and between sagebrush.

Fire behavior predictions were based on sagebrush fuel loadings and bulk densities shown in tables 4 and 5. The loadings in table 5 can be expanded to include stemwood greater than 2.5 cm by multiplying them times the expansion factor. The following percent fuel moisture contents were assumed:

	Dead	Alive
Shrub foliage	5	65
Shrub stems	7	65
Herbaceous vegetation	5	80
Litter	5	–

The moisture content for living herbaceous vegetation was derived from air-dry moisture contents of wheatgrass (*Agropyron* sp.) and fescue (*Festuca* sp.) at the time of seed ripening (USDA Forest Service Region 4 range manual). The living sagebrush moisture content represents moisture levels from August into autumn according to Britton[4] and Olson (1978).

Table 4.—Fuel loading and bulk density of individual sagebrush plants used in fire behavior modeling

Sagebrush height	Foliage loading	Stemwood loading 0 to 0.6 cm	Stemwood loading 0.6 to 2.5 cm	Bulk density
cm	— — — — — *g/m²*	— — — — —	— — — — —	*kg/m³*
20	108	199	244	15.0
40	175	353	478	9.25
60	237	535	675	5.82
80	295	737	827	4.54
100	350	956	928	3.75
120	401	1190	970	3.20

The fraction of dead stemwood in sagebrush was:

Sagebrush height	Diameter class 0 to 0.6 cm	Diameter class 0.6 to 2.5 cm
cm		
< 25	0.07	0.11
25-34	.17	.11
35-79	.35	.11
80 +	.48	.11

[illegible] were:

Sagebrush foliage	[illegible]
0 to 0.6 cm stemwood	[illegible]
0.6 to 2.5 cm stemwood	[illegible]
Litter	[illegible]
Herbaceous vegetation	[illegible]

Other fuel variables required for the model [illegible] such as heat content, particle density, and mineral contents, were held constant [illegible] FIREMOD program.

Predicted Fire Behavior

Rate of Spread

Rate of spread was computed as an average of spread rates for grass and sagebrush each weighted by their respective percent cover. The approach of weighting spread rates by percent cover of component fuel types appears to furnish more realistic predictions than does the alternative of averaging fuels before predicting spread rates. This is especially true when distinctly different kinds of fuel exist within a single vegetation type (Brown 1981).

Rates of spread at 13 km/h (8 mi/h) midflame height windspeed are shown in figure 2 for case A and figure 3 for case B. Rate of spread varies considerably because of changes in grass loading rather than sagebrush loading. Rate of spread is very sensitive to the amount of finely divided dead fuel. To illustrate, in case B, where all grass and one-third of the sagebrush foliage is assumed dead, rates of spread are approximately two to three times higher than in case A. Caution is advised in interpreting figures 2 and 3 because some combinations of grass loading and sagebrush cover may be unrealistic. For example, a vegetative community composed of 40 percent sagebrush cover and 170 g/m² (1,500 lb/acre) of grass probably does not exist.

For the low coverage of sagebrush, rate of spread is almost totally dependent on the rate of spread of grass. Even large sagebrush plants contribute little to rate of spread because 80 to 90 percent of the spread rate is determined by grass. However, as coverage of sagebrush increases to 30 or 40 percent, rate of spread is noticeably increased, especially for the taller plants. The effect of an increased sagebrush coverage on rate of spread is illustrated in figures 2 and 3 by the crossover of curves for 10 and 40 percent cover. Rates of spread for grass and sagebrush are equal at the crossover point.

Table 5.—Fuel loading of sagebrush foliage and 0- to 2.5-cm diameter stemwood at varying heights and percent cover

Sagebrush height	Percent cover 10		20		30		40		Expansion factor
cm	— — — — —	— — —	*t/ha (tons/acre)*	— — —	— — —				
20	0.55	(0.26)	1.1	(0.49)	1.7	(0.74)	2.2	(0.98)	[illegible]
40	1.0	(.45)	2.0	(.90)	3.0	(1.3)	4.0	[illegible]	[illegible]
60	1.4	(.64)	2.9	(1.3)	4.3	(1.9)	5.8	(2.6)	[illegible]
80	1.9	(.83)	3.7	(1.7)	5.6	(2.5)	7.4	[illegible]	[illegible]
100	2.2	(1.0)	4.5	(2.0)	6.7	(3.0)	8.9	[illegible]	[illegible]
120	2.6	(1.1)	5.1	(2.3)	7.7	(3.4)	10.2	[illegible]	[illegible]

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[4] Data from Carlton Britton, Texas Tech University

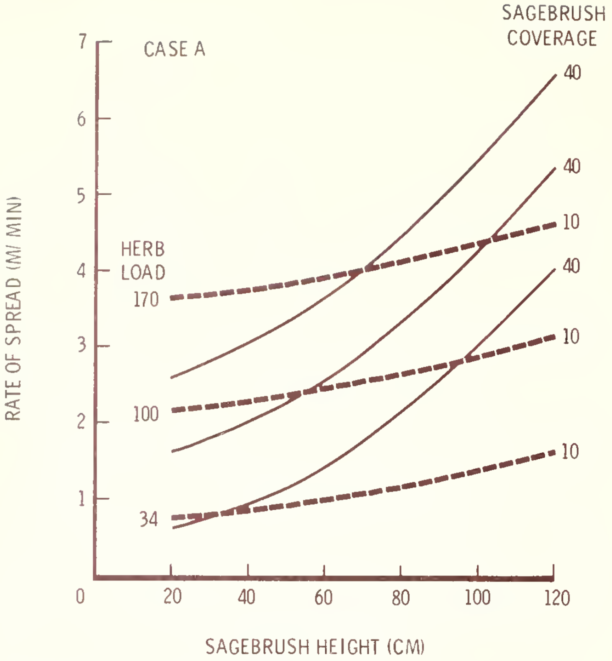

Figure 2.—Rate of spread at 13-km/h (8-mi/h) midflame-height wind-speed and grass and forb loadings of 170 g/m^2 (1,500 lb/acre), 100 g/m^2 (900 lb/acre), and 34 g/m^2 (300 lb/acre). Grass and forbs are 57 percent alive and sagebrush foliage entirely alive.

The sagebrush community is typically discontinuous patches of grass, shrubs, and bare soil. Because current fire modeling cannot deal adequately with discontinuities, predicted fire behavior at low fuel loadings and windspeeds can be misleading. Although fire will not spread at sparse loadings and low windspeeds, mathematical predictions based on the uniform fuel assumption show that fires do spread. Thus, the validity of predicted fire behavior must be evaluated using other knowledge about conditions that limit fire spread.

Reports on prescribed burning in sagebrush (Britton and Ralphs 1979) and pinyon-juniper (Klebenow and Bruner 1976), and discussion with several people who have burned sagebrush, suggest some minimum conditions required for fire to spread:

1. For grass at 35 to 60 g/m^2 (300 to 500 lb/acre), at least 6 to 8 km/h (4 to 5 mi/h) of wind is needed to spread fire, depending on fuel distribution. Bunchgrasses will require more windspeed or loading than other grasses to satisfy minimal conditions for spread of fire.

2. For grass at 35 g/m^2 (300 lb/acre) and less, and sagebrush at less than 20 percent coverage, a wind of 16 km/h (10 mi/h) or more may be required to spread fire.

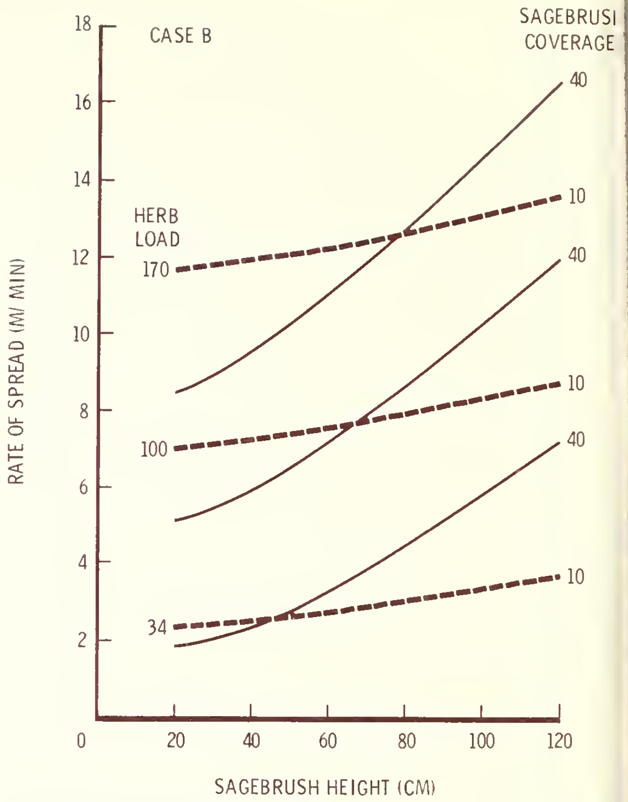

Figure 3.—Rate of spread at 13-km/h (8-mi/h) midflame-height wind-speed and grass and forb loadings of 170 g/m^2 (1,500 lb/acre), 100 g/m^2 (900 lb/acre), and 34 g/m^2 (300 lb/acre). Grass and forbs are entirely dead and sagebrush foliage is one-third dead.

Fireline Intensity

Fireline intensities for case A are shown in figure 4 and for case B in figure 5. Average intensities determine from intensities of sagebrush and grass weighted by their respective coverage are presented for 10 and 40 percent cover of sagebrush. Intensity is also graphed fo sagebrush alone, or in other words, for 100 percent sagebrush. The weighted average intensities are probably of little practical value because they fail to reflect either th intensity of grass alone or of sagebrush. Intensity of sagebrush alone should provide a more realistic and useful estimate of fireline intensity, particularly for fires where the time between ignition of adjacent sagebrush plants is less than the burnout time of individual plants. Predicted fireline intensities of grass are also of less importance because they range from 10 to 100 times les than for sagebrush alone (fig. 6).

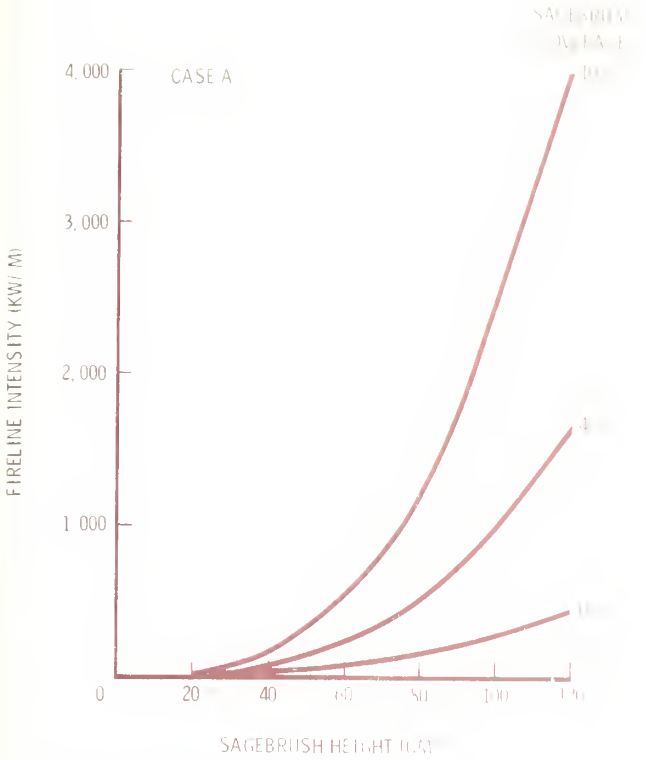

Figure 4.—Fireline intensity at 13-km/h (8-mi/h) midflame-height windspeed and 100 g/m² (900 lb/acre) of grass and forbs. Grass and forbs are 57 percent alive and sagebrush entirely alive.

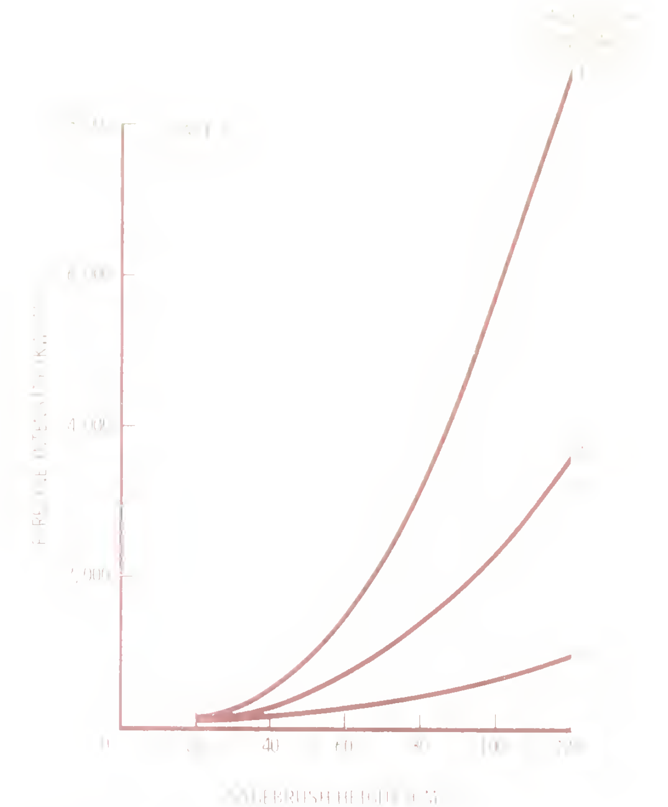

Figure 5.—Fireline intensity at 13-km/h (8-mi/h) midflame-height windspeed and 100 g/m² (900 lbs/acre) of grass and forbs. Grass and forbs are entirely dead and sagebrush foliage is one-third dead.

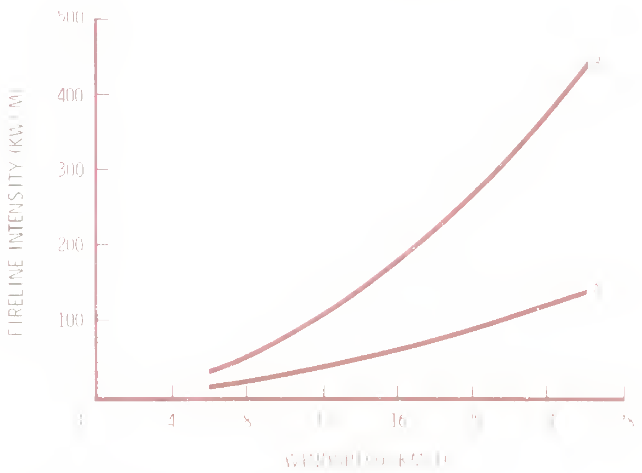

Figure 6.—Fireline intensity of grass and forbs for cases A and B at 100 g/m² (900 lb/acre) and varying midflame-height windspeeds.

Fuel moisture content greatly influences fireline intensity, as is shown in comparing cases A and B (figs. 4 and 5). Intensities for the completely cured condition average about 2.5 times greater than for the higher fuel moisture condition of early summer.

Conceptually, fireline intensity is the amount of energy released from a cross section of unit width through the propagating portion of a fire front over a specified unit of time. To help interpret Byram's fireline intensities in terms of working near fire and controlling it, the following tabulation taken from Puckett and others (1979) is presented:

Intensity	**Flame length**	**Fire situation**
kW/m (Btu/ft/s)	*m (ft)*	
70 to 170 (20 to 50)	0.6 to 0.9 (2 to 3)	Easily attacked and controlled. People can work right up to the edge of the fire without extra protection.
345 (100)	1.2 (4)	This is about the limit beyond which people are unable to work at the fire edge. Direct attack with hand crews may be difficult.
1 700 to 2 400 (500 to 700)	2.4 to 2.7 (8 to 9)	Spotting begins to be a problem, and the limit of direct attack is probably reached in this range of intensities.

As an example in using this information with figures 4 and 5, excessive fireline intensities taken as 2 000 kW/m exist for sagebrush greater than about 60 cm for case B and 90 cm for case A. Different windspeeds will alter fireline intensities and, of course, fire management implications.

Effects of Wind and Slope

Estimates of fire behavior in figures 2 through 5 can be adjusted for certain windspeeds using figure 7. The adjustment factors are ratios of rates of spread at 26- to 13-km/h (16- to 8-mi/h) windspeed and at 13- to 6-km/h (8- to 4-mi/h) windspeed. The adjustment factors for intensity were determined similarly. Figure 7 was developed for case A. For case B, add 0.1 to the case A adjustment factor for intensity and 0.3 for rate of spread. The wind adjustment factors vary with sagebrush height and other variables. However, the adjustment factors are approximately 3 for rate of spread and 2.5 for intensity. Doubling windspeed from 13 to 26 km/h (8 to 16 mi/h) increases rate of spread approximately 3 times and intensity 2.5 times. Cutting windspeed in half from 13 to 6 km/h (8 to 4 mi/h) reduces rate of spread by a factor of 3 and intensity by a factor of 2.5. Fire behavior could be interpolated between 6 and 26 km/h (4 and 16 mi/h); however, predictions below 6 km/h (4 mi/h) are not recommended because of inadequacies in the modeling.

Figures 2 through 5 are based on horizontal terrain. For a 30 percent slope, rate of spread and intensity can be expected to increase 2 to 3 times over the zero slope estimates, and 4 to 7 times for a 50 percent slope. The effects of wind and slope on rate of spread and intensity are analytically complex. Graphical determination of rate of spread and intensity as functions of fuel moisture content, windspeed, and slope require use of nomographs such as presented by Albini (1976a).

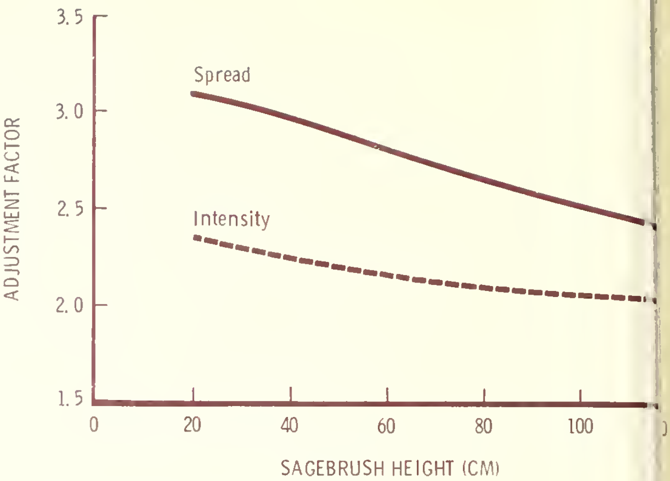

Figure 7.—Adjustment factors for estimating rate of spread and fireline intensity from a windspeed of 13 to 6 km/h (8 to 4 mi/h) and 13 to 26 km/h (8 to 16 mi/h) for case A. For case B, add 0.3 to the adjustment factor for rate of spread and add 0.1 for intensity.

Effects of Dead Stemwood

The proportion of dead stemwood in sagebrush was increased to evaluate the relative influence of shrub decadence. The fractions of dead stemwood used in modeling decadent conditions were:

Sagebrush height, cm	**Fractions of stemwood considered dead**	
	0 to 0.6 cm	**0.6 to 2.5 cm**
< 25	0.07	0.45
25 to 34	.35	.45
35 to 79	.45	.45
80 +	.55	.45

The change in fire behavior from original to decadent conditions was an increase of approximately 5 percent for rate of spread and 10 percent for intensity. The small increase in predicted fire behavior due to decadence is probably because most of the stemwood is represented by fairly small surface area-to-volume ratios. The original conditions are averages from data gathered during summer 1978. The decadent conditions are hypothetical. The fractions of dead could be higher; although if they were higher, predicted fire behavior probably would not increase greatly.

Verification

To test the accuracy of predicted fire behavior in the sagebrush vegetation type, appropriate data were located for prescribed burns in three different areas:

1. Oregon—In two experimental burns, reported by Britton and others (1977), rate of spread and flame length were measured and fireline intensity estimated.
2. Montana—A single prescribed burn with several observation periods was conducted near Dillon. Flame length was estimated and data supplied by Ed Mathews,

Montana Department of Natural Resources, Division of Forestry.

3. Idaho—On a prescribed fire near Challis, rate of spread and flame length were measured and data supplied by Steve Bunting, University of Idaho.

Estimates of windspeed, slope, fine fuel moisture, grass and forb loading, and height and coverage of sagebrush were obtained for the burns and used in FIREMOD to predict rate of spread, flame length, and fireline intensity. However, because data were not collected to test the fire models specifically, single observed and predicted values were not determined. Rather, a range of predicted and observed values were compared.

Agreement between observed and predicted rates of spread was considered good. At the worst, one burning period was underpredicted by about 50 percent. Agreement between observed and predicted flame lengths, however, was poor. Flame lengths were consistently predicted at about one-half of the observed values. Fireline intensity was estimated from fuel consumption on the Oregon fires; for the other sites it was estimated using flame lengths in Byram's equation and solving for intensity:

$$L = 0.45\ I^{0.46} \qquad (5)$$

where:

L = flame length, feet
I = fireline intensity, Btu/ft/s.

Predicted fireline intensities were 3 to 6 times less than the observed values. Predicted flame lengths and fireline intensities were computed using fuel characteristics of sagebrush alone. The poor agreement between observed and predicted intensity values demonstrates the need to interpret figures 3 and 4 with caution. The limited verification reported here indicates that the figures show intensities that are low by at least a factor of 2.

There may be two reasons for the poor verification of flame lengths and intensities. First, the field observations of flame length may not agree well with the definition of flame length embodied in the mathematical predictions. Second, the combustion of sagebrush in the flame front may proceed at a greater rate than predicted. [illegible]

IMPLICATIONS AND CONCLUSIONS

This study demonstrates the [illegible] knowledge concerning fuels and fire behavior in sagebrush communities. The most [illegible] is probably in identifying control difficulties and [illegible] leading to erratic and dangerous fire behavior. Fire behavior predictions are particularly [illegible] illustrating the relative differences in fire behavior between various fuel and weather conditions, such as between grazed and ungrazed vegetation, varying heights and coverages of sagebrush, differing quantities of grasses and forbs, and varying windspeeds and slopes.

Perhaps the weakest aspect of current fire behavior modeling is the inability to predict minimum fuel, weather, and topographic conditions required for fire to spread in a sustained manner. Particularly needed for planning prescribed fire is information on combinations of fuel loading, fuel moisture content, and windspeed that permit fire to spread. Properly designed field experiments to verify mathematical models of rate of spread and intensity in sagebrush are also needed to assure reliable information for a variety of other fire management applications.

[illegible]

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Relationships between height of big sagebrush and crown area, fuel loading, bulk density, size distribution of foliage and stemwood, and fraction dead stemwood are presented. Based upon these relationships, modeled rate-of-fire spread and fireline intensity are shown for sagebrush ranging in height from 20 to 120 cm and in coverage from 10 to 40 percent. Verification of predicted fire behavior and applications are discussed.

KEYWORDS: sagebrush, fire behavior modeling, fuel modeling, range fuels

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Indexing Western Spruce Budworm Activity Through Radial Increment Analysis

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RESEARCH SUMMARY

Past western spruce budworm (WSBW) activity in western Montana Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests was assessed through radial incr ment analyses of cores extracted at diameter breast height. A growth function, defined as the cumulative sur of squared mean annual radial increment, was graphically compared between WSBW host (Douglas-fir) and nonhost (ponderosa pine [*Pinus ponderosa* Laws.]) trees. Negative inflections of host radial growth curves relative to nonhost indicated WSBW activity; these inflections were quantified and transformed to a severity index that represents the intensity of the WSBW activity. A hazard index that may reflect effects of WSBW on establishment of natural regeneration is proposed and may be suitable for analyses relating WSBW activity to regeneration probability. Acceleration of nonhost ponderosa pin radial growth during WSBW activity in mixed Douglas-fir stands was observed.

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INTRODUCTION

Research concerning influences of western spruce budworm (WSBW), *Choristoneura occidentalis* Freeman, on conifer regeneration establishment and growth is dependent upon valid estimates of the periodicity and intensity of past budworm activity. Because aerial survey records of WSBW infestations maintained by the Forest Service lack the resolution needed at the stand level, and because direct estimates of defoliation apply only to the most recent 3 or 4 years, past WSBW activity may be best assessed by examining the radial incremental growth of surviving trees. This approach was used by Blais (1954, 1958, 1962, 1964) and by Mott and others (1957) in balsam fir (*Abies balsamea* [L.] Mill.) forests in the eastern United States, and by Williams (1967) in grand fir (*A. grandis* [Dougl.] Forbes)-Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests in the West; however, procedural details varied between investigators.

Although all of the preceding studies demonstrated that past spruce budworm activity could be dated by incremental analysis, no methods of inferring intensity were given. Research concerning the influence of WSBW on establishment and growth of conifer regeneration following harvest cuts depends on an estimate not only of when WSBW activity occurred, but also a measure of the intensity and potential hazard to the regeneration process. Our hypothesis is that Douglas-fir (host) and ponderosa pine (*Pinus ponderosa* Laws.) (nonhost) within an uncut stand have similar radial growth patterns in the absence of WSBW defoliation. Because past WSBW activity would cause different radial growth patterns, the period of activity can be detected and measured. This paper describes a method to estimate the occurrence, intensity, and potential hazard of past WSBW infestations in Douglas-fir forests of western Montana. The terms outbreak, infestation, or activity mean that WSBW feeding was intensive enough to have caused an observable effect on radial growth of host trees within a stand.

METHODS

Collection and Measurement of Cores

Increment cores were collected from trees at 50 locations in western Montana during 1979 (fig. 1). Of these locations, 46 were coincident with a random selection of various harvest cuts in the Douglas-fir climax series; habitat types (Pfister and others 1977) were determined for each stand. History of WSBW was not known in these areas. The other four locations were purposely selected as baseline to test our hypothesis that radial growth pattern of Douglas-fir known to have been previously infested by WSBW is different from that of ponderosa pine at the same location. Two of these stands (156 and 158) had been heavily defoliated since 1960 and two (157 and 159) had no previous record of WSBW activity.[1] Habitat type of these four baseline stands was *Pseudotsuga menziesii/Physocarpus malvaceus*; among them slope, aspect, and elevation were similar, mean annual precipitation and other site variables were assumed to be similar.

Trees sampled for cores were selected from the uncut stands adjacent to harvested stands and were always at least 66 ft (20 m) from the stand boundary to minimize growth response to cutting. Three to four WSBW host/nonhost tree pairs were selected at each site; to minimize stand density effects, they were required to be dominant or codominant, live, and similar in diameter. If WSBW were present in the stand at the time of sample tree selection, then the most obviously defoliated host trees were chosen. It was assumed that these trees would be the best records of past WSBW activity. Diameter breast height (d.b.h., inches), height (feet),

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[1] [illegible] USDA [illegible] Missoula, [illegible] 158. [illegible] USDA Forest Service [illegible] 157 and 159.

Figure 1.—Locations where increment core collections were made.

crown class, and percent live crown were measured on each sample tree (USDA Forest Service 1978).

Two 0.197-inch (5-mm) diameter increment cores were extracted at d.b.h. from opposite sides of each sample tree parallel to the topographic contour. Cores were inserted in labeled plastic straws that were thermically sealed to prevent moisture loss, returned to our laboratory, and kept frozen until measured.

Using a Bannister Incremental Measuring Machine annual increment was cross dated (Fritts 1976) and measured in millimeters (0.01 mm accuracy) on each core for the period 1956-78. Current increment was not measured because cores were collected throughout the 1979 growing season.

Data Analysis of Baseline Locations

Radial Growth and Precipitation

In the absence of WSBW, radial growth of Douglas-fir should be similar to that of ponderosa pine at the same location, and both should vary directly with precipitation. To test this supposition, mean incremental growth of Douglas-fir and ponderosa pine within each of the four baseline stands was plotted against time and compared to seasonal precipitation[2] as recorded at the Lubrecht site (Steele 1979). Julian and Fritts (1968) showed that a single weather station can relate to ring widths of trees 20 or more miles (32 or more km) distant. Because these four stands were within 30 miles (48 km) of the Lubrecht Experimental Forest, Lubrecht weather data were assumed to represent these sites.

Statistically, radial growth of Douglas-fir not affected by WSBW should be predictable by ponderosa pine radial growth. To test this concept, Douglas-fir radial growth was regressed year-by-year against radial increment of ponderosa pine separately for the locations with and without WSBW history. Regressions were compared within and between the locations.

Cumulative Growth Function

To enhance graphical comparison of Douglas-fir radial growth with that of ponderosa pine, mean radial incremental growth was computed by species within location and a cumulative growth function (CGF) was developed.

let $g_{56}, g_{57}, \ldots, g_{78}$ = mean incremental growth of a species for 1956, 1957, . . . , 1978. Cumulative growth for 1960 was defined as $G_{cum\,60} = g_{56}^2 + g_{57}^2 + g_{58}^2 + g_{59}^2 + g_{60}^2$.

This was done for each year of increment between 1956 and 1978 inclusive, and the resultant numbers were graphed against time. The base year was always 1956. Host and nonhost data for each location then were plotted separately on the same graph.

Severity Index

To estimate the relative intensity of past WSBW activity, the assumed "normal" slope of the host curve was subjectively extended past the WSBW-induced inflection, and the ratio of actual/potential (A/P) CGF near the time of the outbreak was estimated. An index of outbreak intensity is 1-A/P in that it refers to how much more the host trees should have grown in the absence of WSBW; this value is the "severity index" and is bounded by 0 and 1, with 1 indicating [illegible].

Data Analysis of Random Locations

Cumulative growth functions were computed and interpreted and severity indices were calculated for WSBW activity in each of the 46 random locations. [illegible] a standard [illegible] that past WSBW activity occurred when the Douglas-fir CGF curve diverged negatively (downward) from that of ponderosa pine consecutively for a period of [illegible] or more years.

Hazard Index

A WSBW outbreak does not necessarily represent high hazard to the probability of securing natural host conifer regeneration following a harvest cut unless the outbreak overlaps the 10-year period immediately following the cut. During this time site conditions are optimal for regeneration establishment. Since all of the 46 random locations (but not the baseline locations) were coincident with stands harvested between 1955 and 1975, a theoretical index was developed to express the potential influence of WSBW activity on establishment of natural regeneration in the cutover stands. This index is named "hazard index" and is defined as the product of the severity index of an outbreak and a weighting factor. Weighting factors are arbitrary multipliers that presumably represent the relative importance of the time of outbreak occurrence to the likelihood of securing natural host regeneration. If severity index is a reasonable estimate of the intensity of a WSBW outbreak, and if outbreaks of different intensity cause differential effects of the same order on regeneration, then the product of the severity index and the weighting factor of that outbreak is an index of the influence of that outbreak on the probability of securing natural host regeneration. The weighting factors for various periods of WSBW activity are:

Period of WSBW activity	Weighting factor
Entirely before cut	1
Includes 0-4 years following cut	4
Begins 5-10 years following cut	2
Begins 11 years or more following cut	1

These factors are arbitrary and are based on the following rationale. All outbreaks likely would have an adverse effect on establishment of host regeneration either because WSBW feeding weakens trees and causes long term reduction of cone and seed crops or because direct larval feeding destroys current cones and seeds. Thus, the minimum weighting factor was set at 1 and represents activity that occurred either entirely before the cut or 11 or more years following harvest. Highest likelihood of an adverse effect would occur when an outbreak includes the period 0-4 years following the cut, during which time seeds and cones would be directly damaged by WSBW feeding and seedbed conditions for natural

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[2] Seasonal precipitation is that which falls between October 1 and June 30 and is likely most influential [illegible] growing season.

host regeneration establishment would be best; this value was set at 4. Budworm feeding 5-10 years following harvest probably would have an intermediate effect, so this factor was defined as 2.

RESULTS AND DISCUSSION

Baseline Locations

Radial Growth and Precipitation

The hypothesis that WSBW host and nonhost trees respond similarly to local climatic variation in the absence of WSBW is supported by our data. Douglas-fir mean annual radial increment was very similar to that of ponderosa pine at stand 157 (Schwartz Creek), which had no history of WSBW, and both appear to be correlated with precipitation; growth peaks and troughs coincide with seasonal precipitation peaks and troughs (fig. 2). In the Lubrecht WSBW-infested stand 158, mean annual radial increment of ponderosa pine follows the precipitation pattern (fig. 3); however, growth of the WSBW-affected Douglas-fir diverges negatively from the pine and does not vary with precipitation. Corresponding trends (not shown) were noted for the other two stands with known WSBW history. Mean annual radial increme data for the four baseline locations are shown in table

Regression of mean annual radial increment of Douglas-fir against corresponding mean annual radial increment of ponderosa pine within each of the four stands provides further support that radial increment analysis can be used to identify past WSBW activity (table 1). The coefficients of determination (r^2) between Douglas-fir and ponderosa pine at Miller Creek and Schwartz Creek were 0.40 and 0.71, respectively. Similarly, regression slopes were 1.18 and 1.09. These values are much higher than corresponding r^2 of 0.20 and 0.15 and slopes of 0.50 and -0.31 obtained at Lubrecht and Valley Creek, where past WSBW activity is known to hav been high. The very low r^2 and low slope calculated for the WSBW-infested stands suggests that WSBW altered Douglas-fir radial growth. In the absence of WSBW, the near-unity slopes and higher r^2 show that Douglas-fir an ponderosa pine of similar dominance and size are also similar in radial growth pattern. This is interpreted as a normal response to precipitation and intrinsic site variables. Blais (1954) and Mott and others (1957) reache conclusions similar to ours.

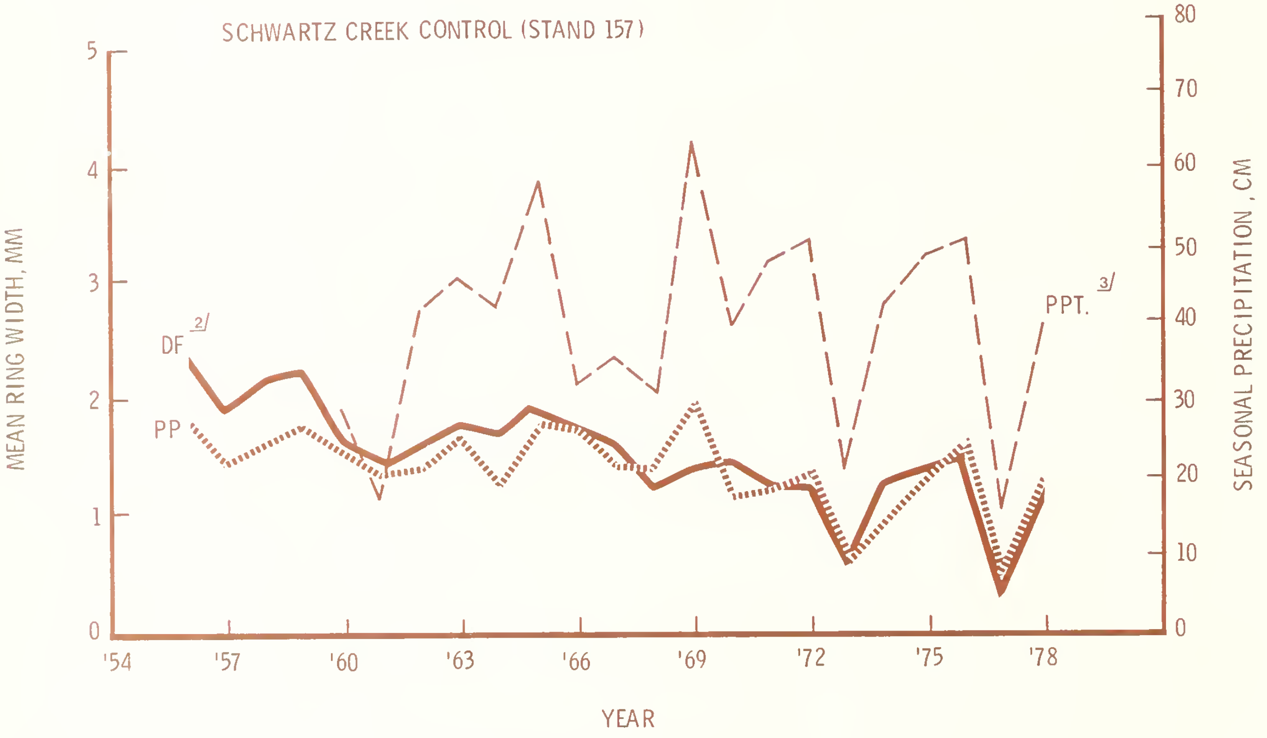

Figure 2.—Seasonal precipitation and mean annual radial increment of ponderosa pine and Douglas-fir in a stand with no history of western spruce budworm.[1]

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[1] 1979 data, mean increment based on two cores from each of five trees of each species.

[2] DF = Douglas-fir, PP = ponderosa pine.

[3] PPT = seasonal precipitation that is the total precipitation between October 1 of a base year and June 30 of the following year. Data for 1956-59 were not available.

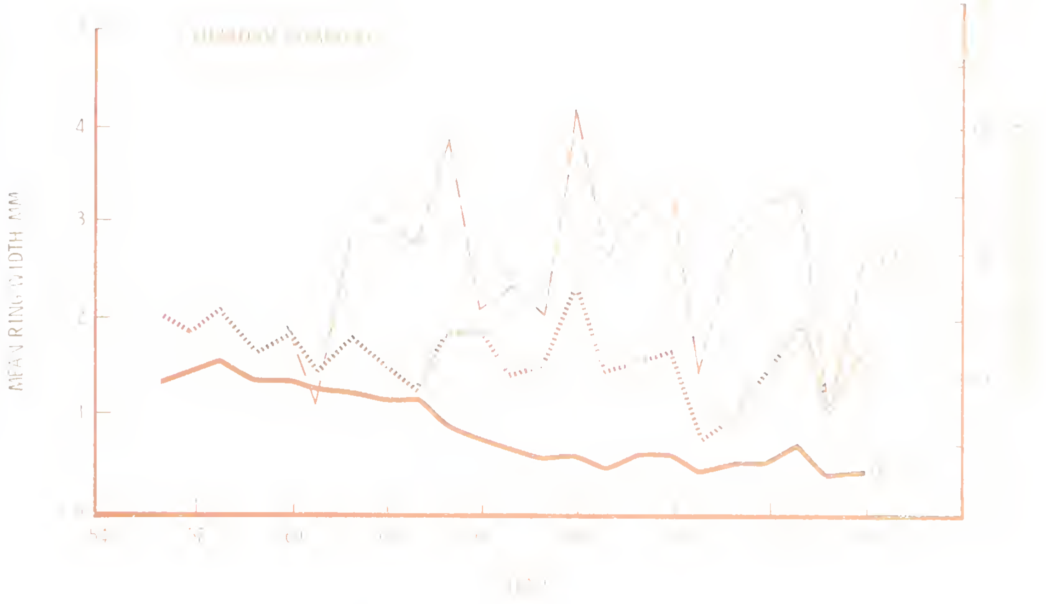

Figure 3.—Seasonal precipitation and mean annual radial increment of ponderosa pine and Douglas fir in a stand continuously infested with western spruce budworm during 1958-79

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[1] 1979 data mean increment based on two [illegible] trees of each species

[2] DF = Douglas-fir PP = ponderosa pine

[3] PPT = seasonal precipitation that is the total [illegible] between October 1 of a base year and June 30 of the following year. Data for 1956-59 were not available

Table 1.—[illegible]

		Mean annual [illegible] increment							
		WSBW absent				WSBW present			
		Stand [illegible] Miller Creek		Stand 157 Schwartz Creek		Stand [illegible] [illegible]		Stand [illegible] [illegible]	
Year	PPT	DF	PP	DF	PP	DF	PP	DF	PP
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		Miller Creek		Schwartz Creek		[illegible]		[illegible]	

Cumulative Growth Function

No important differences were observed between CGF graphs of Douglas-fir and ponderosa pine from the WSBW-free stands in Schwartz and Miller Creeks (figs. 4 and 5). However, obvious negative departures of the Douglas-fir curve relative to ponderosa pine occurred in the WSBW-infested stands at Lubrecht and Valley Creek (figs. 6 and 7). Inflections of the host curve correspond closely with the known occurrences of WSBW outbreaks in the two areas, and presumably represent the growth-retarding influence of WSBW at that time.

Severity Index

The CGF curves for stand 156 at Valley Creek indicated that two separate WSBW infestations occurred between 1956 and 1978, and that the second was the most intense (fig. 7). The severity index for the first infestation, which occurred between 1960 and 1963, inclusive, was 0.41 (table 2); the second infestation, lasting from 1969 through 1978, had a calculated severity index of 0.74. Stand 158 (Lubrecht) had one infestation active from 1960 to 1978 (fig. 6) with a severity index of 0.65 (table 2). The infestations at these two stands are known to have been acute during the last 10 years; the severity indices appear to be a sensitive measure in that they reflect that observed intensity

Random Locations

Interpretation of CGF graphs showed that 38 of the 4 randomly selected stands had evidence of past WSBW activity (table 2); examples are shown in figures 8 and 9. It was assumed that WSBW was the only biotic factor responsible for abnormal inflections of the host growth curves, to the exclusion of needle cast fungi, root diseases, and other insects; we believe this is a valid assumption.

The cumulative growth function may be expected to differ between trees of different ages and species. We did not age our sample trees; however, this was not a problem because of the way in which CGF curves were compared within stand; we considered abrupt slope changes of host curves to be indicative of WSBW activit providing that the curve change was not observed on the nonhost graph. Also, the data showed that curves of Douglas-fir and ponderosa pine (fig. 3) were similar in stands without a WSBW history. Both species are long lived and on similar sites probably do have similar growt characteristics. The squared growth function tends to emphasize deviation from normal growth, especially in the case of prolonged growth depression. This makes th subjective interpretation of deviation from normal growt much easier; also, the squared growth function tends to be a linear transformation of a normal cumulative growt function.

Development of a regression of CGF against time may have better represented expected growth of the host rather than visual extension of the host curve; however, in many cases data were insufficient at the lower end of each curve to do that. Therefore, the visual method was judged to be the best alternative.

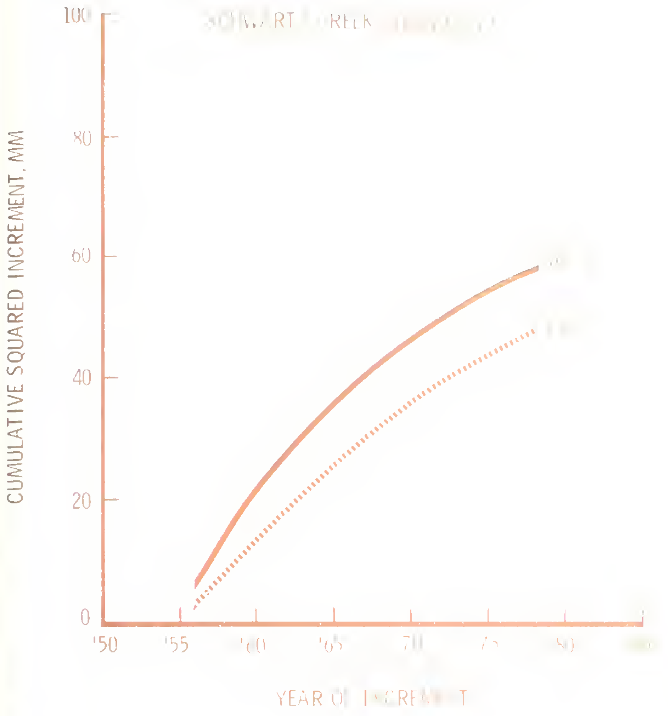

Figure 4.—Cumulative growth function for ponderosa pine and Douglas-fir at a site with no history of western spruce budworm.

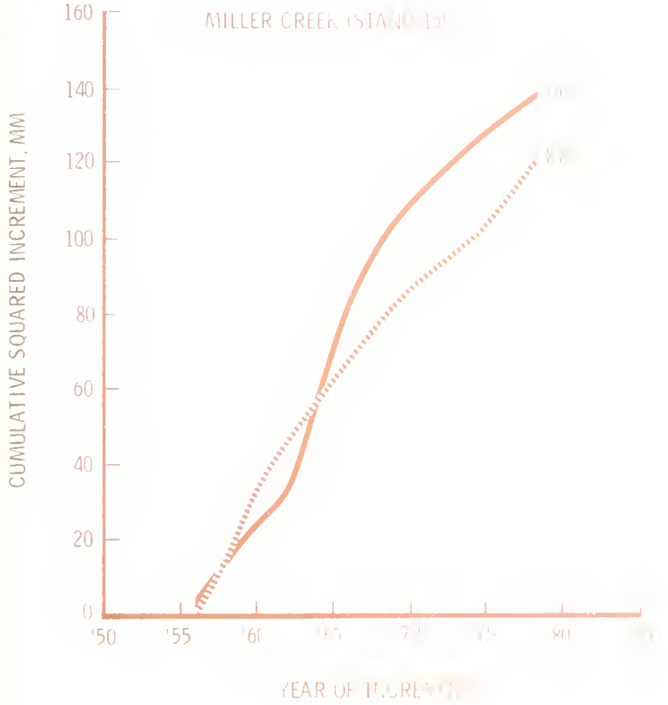

Figure 5.—Cumulative growth function for ponderosa pine and Douglas-fir at a site with no history of western spruce budworm.

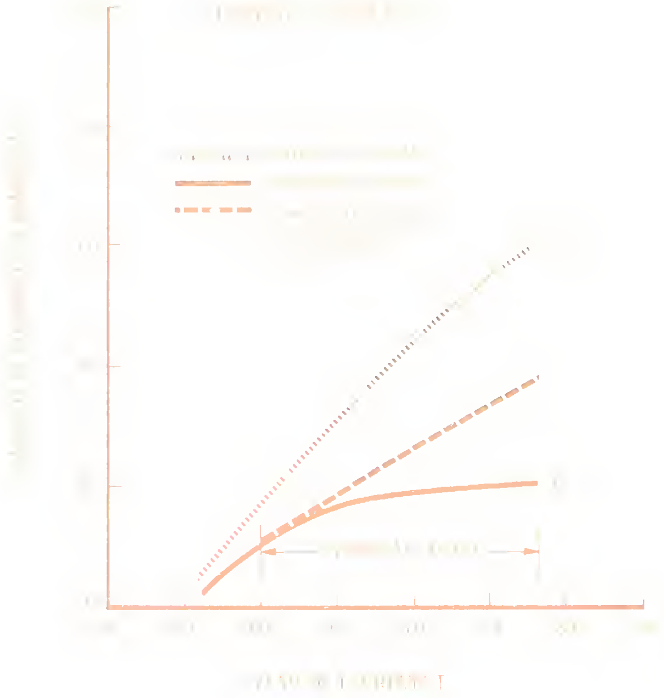

Figure 6.—Cumulative growth function for ponderosa pine and Douglas-fir at a site where western spruce budworm has been active between 1960 and 1979.

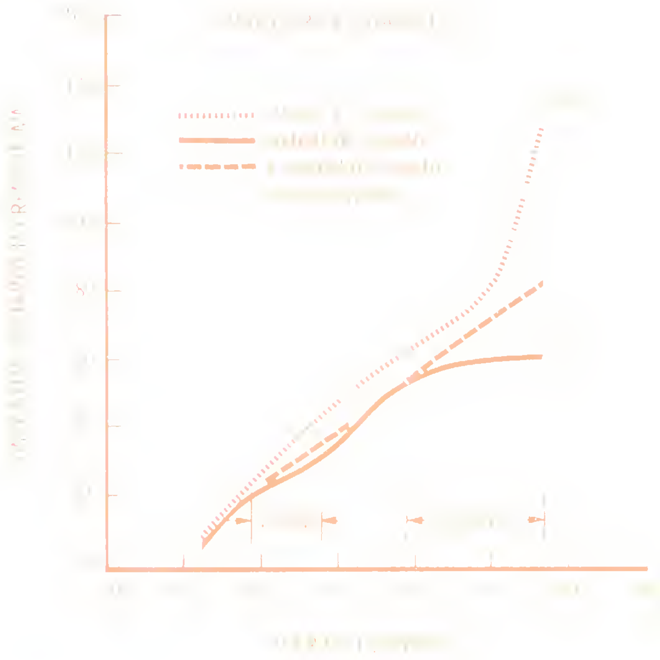

Figure 7.—Cumulative growth function for ponderosa pine and Douglas-fir at a site with two known periods of western spruce budworm activity: 1958-64 and 1969-73.

Table 2—Western spruce budworm (WSBW) history, severity indices, and hazard indices interpreted from CGF graphs of Douglas-fir radial increment.

Stand number	Infestation number	Infestation start: Year	Infestation start: Actual growth (G)[1]	Infestation end: Year	Infestation end: Actual growth (T)[2]	Infestation end: Projected growth (P)[3]	Severity index[4]	Weighting factor[5]	Hazard index[6]
[7]157	0						0		0
[7]159	0						0		0
[7]156	1	1960	22.47	1963	28.06	32	0.41	—	—
[7]156	2	1969	52.87	1978	60.62	83	.74	—	—
[7]158	1	1960	10.28	1978	20.45	39	.65	—	—
005	0						0		0
021	0						0		0
023	0						0		0
130	0						0		0
132	0						0		0
134	0						0		0
144	0						0		0
146	0						0		0
002	1	1964	17.98	1977	25.78	39	[8] .37	4	1.48
019	1	1968	5.94	1975	10.44	14	[8] .44	4	1.76
020	1	1960	7.86	1974	13.73	28	.71	4	2.84
025	1	1958	4.71	1967	15.11	19	.27	1	.27
026	1	1972	40.48	1978	44.36	54	.71	2	1.42
031	1	1966	4.58	1974	8.91	12	.42	4	1.68
035	1	1958	3.62	1974	15.00	23	[8] .41	4	1.64
054	1	1966	2.22	1970	2.70	3	.38	1	.38
054	2	1971	2.79	1974	2.94	3	.29	4	1.16
066	1	1971	63.09	1978	68.86	87	[8] .76	2	1.52
069	1	1964	22.82	1974	26.30	40	[8] .80	4	3.20
070	1	1964	6.51	1975	10.99	13	.31	4	1.24
073	1	1958	31.05	1962	56.00	71	.38	1	.38
074	1	1958	6.25	1974	30.41	55	.50	4	2.00
100	1	1958	30.41	1963	52.35	62	.31	1	.31
102	1	1971	11.42	1978	13.49	14	.20	4	.80
124	1	1967	17.66	1974	21.89	29	[8] .63*	4	2.52
127	1	1956	2.43	1978	37.94	52	[8] .28	4	1.12
126	1	1959	33.45	1978	96.22	144	.43	4	1.72
128	1	1971	31.56	1978	33.48	45	[8] .86	4	3.44
129	1	1958	3.81	1977	11.66	24	.61	4	2.44
131	1	1958	1.82	1978	7.41	15	.58	4	2.32
133	1	1958	2.18	1978	11.42	17	.38	4	1.52
135	1	1967	4.87	1978	6.14	8	.59	4	2.36
136	1	1958	1.28	1964	2.32	4	.62	4	2.48
137	1	1965	50.21	1975	71.76	96	.53	4	2.12
138	1	1965	16.66	1974	21.35	30	.65	4	2.60
139	1	1966	22.88	1974	29.60	36	[8] .49	4	1.96
140	1	1962	4.90	1973	6.99	8	.33	4	1.32
141	1	1958	4.15	1968	9.77	21	[8] .67	1	0.67
142	1	1970	138.18	1978	150.44	188	.75	4	3.00
145	1	1958	1.99	1963	3.03	5	[8] .65	1	.65
148	1	1972	25.38	1978	27.55	32	[8] .67	4	2.68
149	1	1971	60.34	1978	64.41	74	[8] .70	2	1.40
150	1	1970	53.28	1978	61.21	71	[8] .55	4	2.20
151	1	1959	7.51	1964	17.34	24	.40	1	.40
151	2	1967	23.62	1978	32.12	44	[8] .58	4	2.32
152	1	1958	9.40	1964	20.41	24	.25	1	.25
152	2	1972	36.90	1978	41.87	46	[8] .45	2	.90
153	1	1958	3.57	1977	16.02	33	[8] .58	4	2.32
154	1	1967	62.89	1975	76.37	92	.54	1	.54
						$\overline{X}$	.51		1.67

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[1] G = cumulative squared mean annual radial growth, mm, at start of infestation, computed from data.

[2] T = cumulative squared mean annual radial growth, mm, at end of infestation, computed from data.

[3] P = projected cumulative squared mean annual radial growth, mm, without WSBW, at end of infestation.

[4] Severity index $= 1 - \frac{T-G}{P-G}$

[5] Weight factor.

1 = Period of WSBW activity is entirely before date stand was harvested or begins 11 years or more following cut.
2 = Period of WSBW activity begins 5-10 years following date stand was harvested.
4 = Period of WSBW activity begins 0-4 years following harvest date of stand.

[6] Hazard index = severity index X weight factor

[7] Baseline stand with known WSBW history. Because these areas were not associated with previous harvest cuts, weighting factors were not assigned.

[8] Radial growth of ponderosa pine accelerated in these stands during the interpreted WSBW infestation on Douglas-fir.

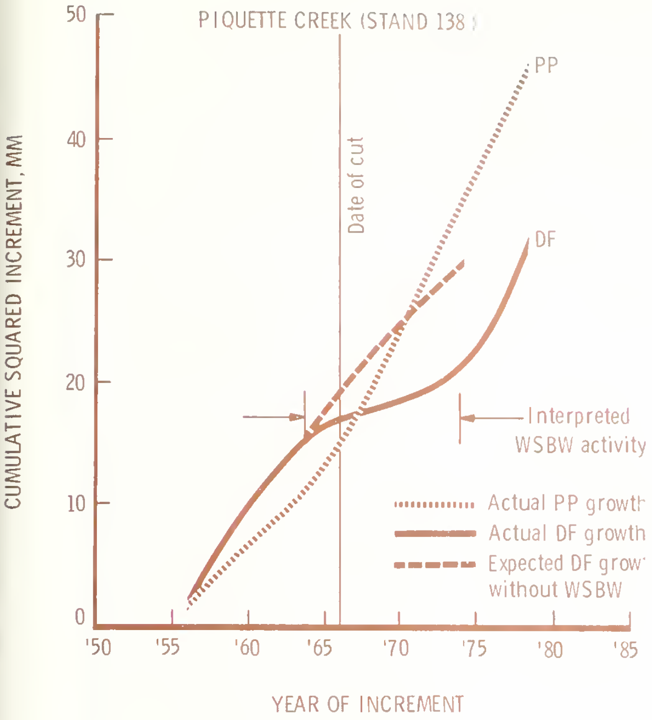

Figure 8.—Cumulative growth function for ponderosa pine and Douglas-fir and interpreted western spruce budworm activity at a site where western spruce budworm history was not known.

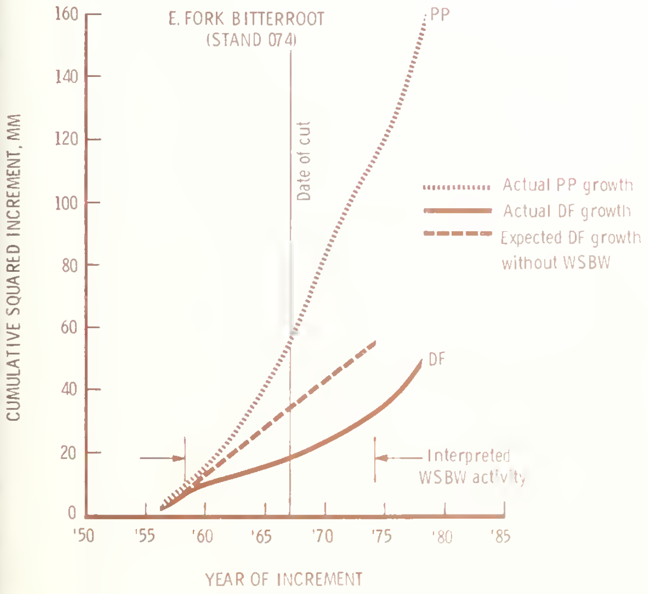

Figure 9.—Cumulative growth function for ponderosa pine and Douglas-fir and interpreted western spruce budworm activity at a site where western spruce budworm history was not known.

Severity Index

Intensity of inferred WSBW activity within the randomly sampled stands was represented by the severity index. Severity indices over the 38 stands with inferred WSBW activity ranged from 0.20 to 0.86; the mean was 0.51 (table 2). Only eight stands had no evidence of past WSBW activity, and two periods of WSBW activity were noted in three of the stands (54, 151, 152) during 1956-78.

Severity index may be useful in regression analyses of growth relationships. For example, nonhost radial growth acceleration could be quantified similar to the way it is done for host radial growth depression, and then regressed against severity index. Severity index also may be useful in multiple regression analyses of the influence of WSBW on stand structure, growth, and development over long time periods. We currently are developing working hypotheses on these concepts.

Inspection of the CGF graphs revealed that in 17 of the 38 stands with inferred WSBW history, the nonhost showed growth acceleration, presumably at the expense of the host (fig. 10). Table 2 shows that, of these 17 stands, 10 had severity indices equal to or above the mean value of 0.51. None of the pine in WSBW-free stands showed radial growth acceleration. Acceleration of nonhost radial growth in WSBW-affected stands may compensate for growth loss on host trees provided that the nonhost represents a large enough fraction of the stand.

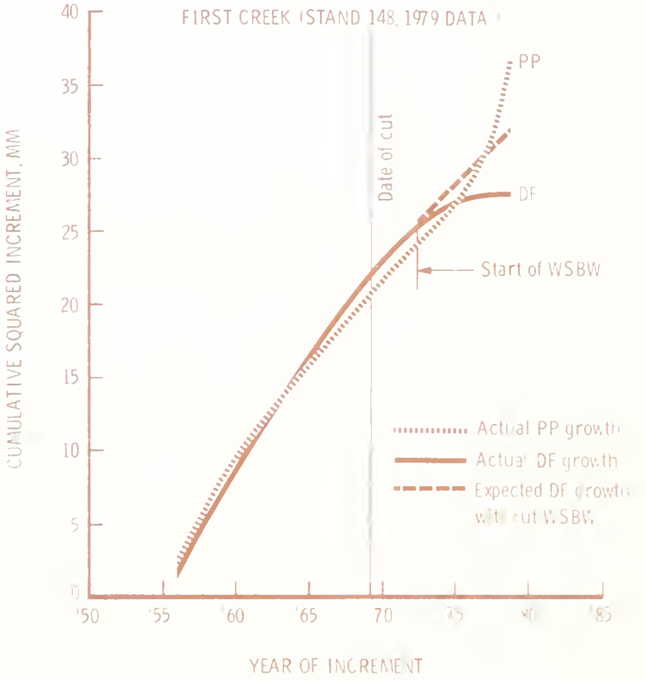

Figure 10.—Accelerated ponderosa pine radial growth during an interpreted western spruce budworm infestation.

Hazard Index

The influence of past WSBW activity on the process of regeneration establishment may be reflected in the stand WSBW hazard index. Hazard index over the 40 stands with evidence of past WSBW activity ranged from 0.25 to 3.44, with a mean of 1.67 (table 2). We currently are testing this index against probability of stocking and density of host regeneration as well as other relevant stand and site variables. Results will be reported in a future paper.

The severity and hazard indices developed from cumulative growth functions provide reasonable estimates of the occurrence and intensity of past WSBW activity. Our techniques are unique; Blais (1954, 1958, 1962, 1964) used graphic representation of actual yearly d.b.h. increment over time, and Mott and others (1957) and Williams (1966, 1967) used techniques modified from Duff and Nolan (1953) that assessed vertical, oblique, and horizontal diameter increment. Regardless of methods, all concluded that past spruce budworm outbreaks can be interpreted by tree ring analysis.

We believe that d.b.h. cores or discs are a reasonable means of collecting data to date past budworm outbreaks. However, incremental analysis of cores extracted at d.b.h. may not be the most sensitive test of past budworm activity. Mott and others (1957) and Williams (1967) presented data showing that budworm effect on diameter increment is most obvious at midcrown. Thomson and VanSickle (1980) developed a model to estimate volume losses caused by WSBW feeding. This model required data based on whole tree dissection, and they, too, found the most serious impact in the upper portions of affected trees. Nevertheless, Blais (1962) and Fritts (1976) expressed our concerns that in studies requiring rather large sample size, whole-tree dissection simply is not practical and d.b.h. cores can be used to detect previous budworm activity.

SUMMARY

This research shows that past western spruce budworm feeding activity in Douglas-fir habitat types can be detected by analysis of increment cores taken at d.b.h. A cumulative growth function, which for a given year is the sum of squared mean annual increment from a baseline year to the given year, is computed and plotted separately for WSBW host and nonhost species. Negative inflections of host curves relative to curves of nonhost likely reflect WSBW feeding. The magnitude of deflection is a measure of the severity of WSBW feeding; this is called the severity index. The severity index can be weighted to account for effects of WSBW feeding on the process of regeneration establishment following harvest of mature timber. The weighting is based on the temporal relationship of the infestation to the harvest; the weighted severity index is named hazard index.

We are just beginning to explore the use of these indices. Regression of severity index against site and stand variables may provide insight on silvicultural practices that will minimize the impact of WSBW feeding through the rotation period. Also, this technique may be useful in historical studies to document periodicity of WSBW outbreaks.

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Past western spruce budworm (WSBW) activity in western Montana Douglas-fir (*Pseudotsuga menziesii*) forests was assessed through radial increment analyses of cores extracted at diameter breast height. A growth function, defined as the cumulative sum of squared mean annual radial increment, was graphically compared between WSBW host (Douglas-fir) and nonhost (ponderosa pine [*Pinus ponderosa*]) trees Negative inflections of host radial growth curves relative to nonhost indicated WSBW activity; these inflections were quantified and transformed to a severity index which represents the intensity of the WSBW activity. A hazard index that may reflect effects of WSBW on establishment of natural regeneration is proposed and may be suitable for analyses relating WSBW activity to regeneration probability. Acceleration of nonhost ponderosa pine radial growth during WSBW activity in mixed Douglas-fir stands was observed.

KEYWORDS: *Choristoneura occidentalis*, western spruce budworm, radial increment, western spruce budworm severity and hazard

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