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ACKNOWLEDGMENTS

The study reported here represents one part of a statewide cooperative investigation by the Northern Region and Intermountain Forest and Range Experiment Station, USDA Forest Service; Montana Department of Fish, Wildlife and Parks; School of Forestry, University of Montana; and Missoula District Bureau of Land Management.

I am indebted to more than 90 employees and volunteers from these agencies who participated in the study. In particular, I appreciate the long hours and hard miles walked by Reuel Jansen, John Firebaugh, Larry Mitchell, and Steve Gilbert.

RESEARCH SUMMARY

Distributions of elk pellet groups on an area of 215 km^2 (80 mi^2) were examined for a period of 8 years. Recorded changes in annual distribution describe both elk movement in response to disturbances in the forest environment and elk habitat selection in response to weather conditions.

Over the period of study, the single most important influence on elk distribution was weather. Severity of winter weather determined the location and extent of winter range. Snowfall during the hunting season resulted in elk concentrating in the least accessible areas available. Hot, dry summer weather forced selection of habitat areas providing cool, moist conditions.

The second determinant of elk distribution was logging. Elk consistently moved away from areas in which active logging was in progress. The distance moved and the time required for return varied depending on the location and duration of logging activity. Recommendations intended to reduce the time during which habitat is unavailable to elk are presented.

CONTENTS

INTRODUCTION

The Burdette Creek drainage in western Montana is a major wintering area for Rocky Mountain elk (*Cervus elaphus nelsoni*). In summer, these elk disperse over a large area of forested land including the several drainages adjacent to Burdette Creek. One of the drainages, Deer Creek, was the location of a USDA Forest Service timber sale from 1971 through 1974. The study reported here was initiated in 1970, with the objective of describing the annual distribution of elk in the area surrounding Burdette Creek during the period of the Deer Creek timber sale. Several smaller timber sales were also conducted on or near the study area during the 8 years of investigation.

STUDY AREA

The Burdette Creek-Deer Creek study area (fig. 1) includes about 215 km^2 (80 mi^2) of forested land 40 km (25 mi) due west of Missoula, Montana. About two-thirds of the area is Lolo National Forest. The remainder is a mixed ownership of U.S. Champion International, Burlington Northern, the State of Montana, and small private ranches.

For evaluation of elk distribution, the study area was divided into 12 subunits (table 1) representing drainages or areas in which habitats for elk were considered comparable. Subunits range in size from 745 to 2 722 ha (1,840 to 6,720 acres).

The west boundary of the area is Fish Creek, which flows north and off the study area at an elevation of 975 m (3,200 ft). Three major drainages, Deer Creek, Burdette Creek, and Lupine Creek, and four smaller drainages flow west and southwest to Fish Creek from the watershed divide at 1 890 m (6,200 ft). East of this divide, Eds, Gus, and Johns Creeks, and the South Fork of Petty Creek flow east to Petty Creek. The eastern study area boundary, through 1972, was the 1 524-m (5,000-ft) contour level. In 1973, this boundary was extended to the 1 219-m (4,000-ft) contour level between the South Fork and Johns Creek.

When the study began in 1970, vehicle access was limited to county roads along Fish Creek and Petty Creek, the Wagon Mountain Road on the southern ridgelines of the South Fork and Lupine Creek, and a low standard fire-control access road on the ridge north of Eds Creek and south along the watershed divide to the ridge between Johns Creek and the South Fork. In addition, short spur roads ran 1 to 5 km (1 to 3 mi) in the bottoms of several drainages.

Throughout the study area, but especially on southerly aspects, open talus slopes and rock outcrops are common. The area is rough, steep, and deeply incised. Most slopes are in excess of 50 percent. Streams are considered intermittent above 1 500 m (4,921 ft) but most contain flowing water year round except during very dry years.

Vegetation on the area consists of subalpine fir (*Abies lasiocarpa*) and lodgepole pine (*Pinus contorta*) types above 1 500 m and Douglas-fir (*Pseudotsuga menziesii*) types below that elevation. Forests on south and west aspects contain a high proportion of ponderosa pine (*Pinus ponderosa*) and a few moist, northerly aspects support western redcedar (*Thuja plicata*). Conifer cover on most of the study area exceeds 50 percent, but drier aspects have grassy openings, and fire-created shrub fields are common on southerly aspects. The largest nonforested opening on the area is the 800- to 1 200-ha (2,000- to 3,000-acre) shrubfield in Burdette Creek. This area burned in 1917 and is currently dominated by mixtures of snowbrush ceanothus (*Ceanothus velutinus*), mallow ninebark (*Physocarpus malvaceous*), mountain maple (*Acer glabrum*), Scouler willow (*Salix scouleriana*), and serviceberry (*Amelanchier alnifolia*).

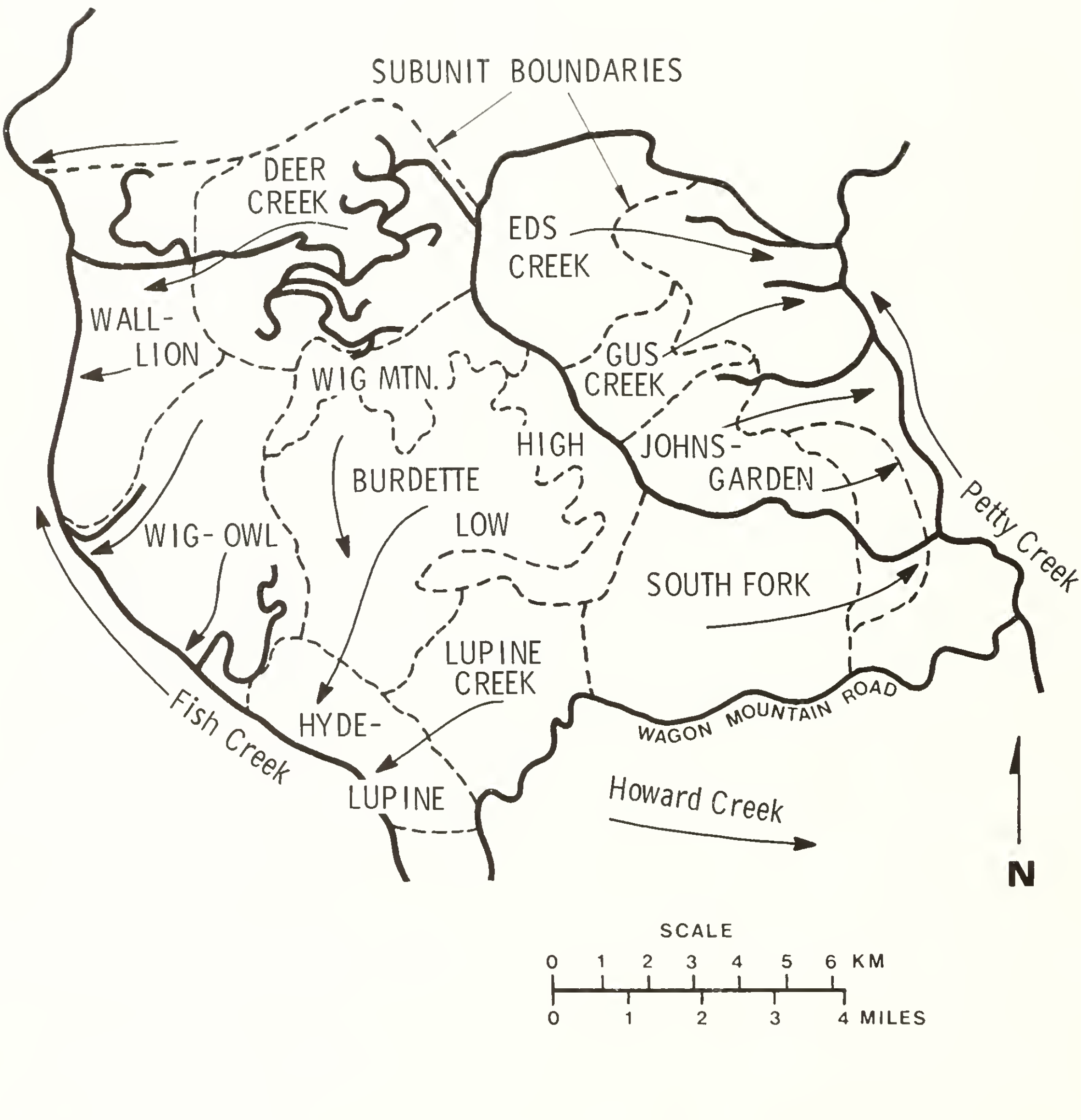

Figure 1.--Road system and diagrammatic representation of drainages and subunits, Burdette Creek-Deer Creek study area.

Table 1.--*Subunits of the Burdette Creek-Deer Creek study area*

Subunit name	Areas		Description
	Hectares	*Acres*	
Wall-Lion	2 428	6,000	Wall Canyon to Lion Creek including lower Deer Creek. Mostly open timber stands on south- and west-facing steep slopes.
Deer Creek	2 720	6,720	Upper two-thirds of drainage. Mostly closed canopy, undisturbed forest until 1 017 ha (2,512 acres) were logged, 1971-74.
Eds Creek	2 639	6,520	Drainage above 1 524 m (5,000 ft). Mostly closed canopy, undisturbed forest.
Wig-Owl	2 363	5,840	Two small drainages. Both are extensively roaded and logged. South- and west-facing slopes.
Wig Mountain	745	1,840	Burdette Creek drainage above 1 524 m (5,000 ft) adjacent to the ridge of Deer Creek. About half forested and half open shrubfields.
Burdette High	987	2,440	Drainage above 1 524 m (5,000 ft) adjacent to the watershed divide and Lupine Creek. Mostly closed canopy forest.
Burdette Low	2 639	6,520	Drainage below 1 524 m (5,000 ft). Major winter range in open shrubfields on south aspects. Closed canopy on north aspects.
Gus Creek	1 117	2,760	Drainage above 1 524 m (5,000 ft). Closed canopy, undisturbed forest.
Johns-Garden	1 489	3,680	Two drainages above 1 524 m (5,000 ft). After 1972, transects were installed in Garden Creek to 1 219 m (4,000 ft). Closed canopy until the 1975-77 timber sale.
South Fork	2 169	5,360	Drainage above 1 524 m (5,000 ft); to 1 219 m (4,000 ft) after 1972. Closed canopy, undisturbed forest with some shrubfield openings.
Lupine Creek	1 441	3,560	Upper 4.8 km (3 mi) of drainage. Open shrubfields on south and west aspects, closed canopy forest on north aspect.
Hyde-Lupine	777	1,920	Lower 1.6 km (1 mi) of Hyde Creek, Burdette Creek, and Lupine Creek. Selectively logged, pastureland, and several homesites.
Study area	21 513	53,160	Total Burdette Creek-Deer Creek study area.

METHODS

Within the area described, pellet groups were counted in continuous belt transects 1.2-m (4-ft) wide. Transects were located along the contour at 152 m (500 ft) vertical intervals from 1 067 to 1 981 m (3,500 to 6,500 ft) elevation. Counts were conducted during late August and early September from 1970 to 1977. Locations of pellet groups were recorded and each group was categorized as fresh, new, old, or very old on the basis of softness, color, and degree of weathering. Approximately 547 km (340 mi) of transect were surveyed and 7 to 10 thousand pellet groups were recorded each year.

In analysis, very old pellet groups were deleted on the assumption that such pellets were deposited in previous years. Some loss of information concerning winter distribution may be inherent in this assumption. All other pellet groups and transect areas were summarized to obtain the average pellet group density for each subunit and for the study area (table 2).

Table 2.--*Pellet groups per hectare by subunit, Burdette Creek-Deer Creek study area, 1970 to 1977 (pellet groups per acre = 0.405 times pellet groups per hectare)*

Subunit	Pellet groups per hectare by year							
	1970	1971	1972	1973	1974	1975	1976	1977
Wall-Lion	113	102	68	42	41	98	66	59
Deer Creek	122	71	40	28	27	33	32	58
Eds Creek	163	125	79	92	77	56	68	50
Wig-Owl	140	113	55	38	62	121	128	71
Wig Mountain	167	122	55	97	55	30	54	137
Burdette-High	92	122	30	65	45	86	85	40
Burdette-Low	203	108	111	87	123	115	218	174
Gus Creek	156	97	54	83	81	79	78	50
Johns-Garden	118	65	59	75	40	78	62	29
South Fork	155	100	74	77	86	90	65	43
Lupine Creek	155	114	96	70	106	169	95	49
Hyde-Lupine	105	65	72	24	45	96	82	56
Study area, average	147	101	68	63	68	88	89	76

CULTURAL DISTURBANCES AND WEATHER

During the 8 years of study, a variety of human activities with potential influence on elk distribution occurred within and adjacent to the study area. The timber sale on Deer Creek was the activity of major interest. Table 3 presents a brief summary of other timber sales, vehicle traffic, and hunting seasons. In addition, the severity of winter weather and other unusual weather conditions are indicated.

Table 3.--[illegible]

Events	Occurrence in the year preceding August and September pellet count							
	1970	1971	1972	1973	1974	1975	1976	1977
Deer Creek timber sale								
Roads constructed, 85 km (53 mi)		X	X			Roads closed - -		
Active logging, 26,372 MBF on 1 017 ha (2 512 acres)		X	X	X	X			
Slash disposal, planting						X	X	[illegible]
Other timber sales (subunit):								
Howard Creek (off area)			X		X			
Lupine Creek (Hyde-Lupine)				X	X			
Garden Creek (Johns-Garden)					[illegible]			
South Fork						X		
Lion Creek (Wall-Lion)							X	
Wagon Mountain Road (off area)								
Johns Creek (ridge with Gus Creek)						X		
Eds Creek						X		X
Elk trap in Wig Creek				X	X	Road washed out		
Fire patrol, recreation traffic	X	X	X	X	X		X	X
Hunting season, days (year preceding count)	56	43	48	[illegible]	[illegible]	54	57	56
Snow during hunt	X				X		X	
Winter weather severity[4]	2	[illegible]	1	[illegible]	[illegible]	3	[illegible]	1
Hot, dry summer				[illegible]				X

[1]A planting crew was in the drainage briefly during the spring of 1977.
[2]Road construction preceding active logging.
[3]In these years, a 5-day bull season in September preceded the general October-November hunting season.
[4]On a scale of 5, 3 is average, 1 is very mild, and 5 is severe. These judgments are based on both weather records and Montana Department of Fish, Wildlife and Parks evaluations for western Montana.

ELK DISTRIBUTION

Variance analysis of pellet density data (table 2) revealed that significantly high ($P < 0.05$) elk use occured on the winter range in Burdette Creek and that the study area elk population declined significantly during the first 2 years of study. This decline was not considered a treatment effect. A similar trend was indicated by Montana Department of Fish, Wildlife and Parks checking station records for Game Management Unit 203, which includes the study area.

Evaluation of annual changes in elk distribution was based on the hypothesis that the proportion of elk use in each subunit should remain constant from year to year if elk are uninfluenced by disturbances or weather. For this test, pellet density data were adjusted to an annual population base of 100, distributed to reflect the percentage of elk use in each subunit. Within subunits, elk use was further subdivided by aspect and altitude and tested with variance analysis for differences among years. Annual percentages of elk use by subunit, 1970 to 1977, and significant changes in elk distribution ($P < 0.10$) are presented in figure 2.

Comparison of figure 2 and table 3 revealed that most of the significant changes in elk distribtuion could be explained as responses to identified cultural disturbances or weather. Many smaller changes that were not statistically significant were also explained; however, there were few instances in which elk response was a simple negative or positive reaction to a single event. Several distributional changes represent cumulative shifts in elk use over a period of years and, in a few cases, significant change occurred because of sequential similar responses to completely unrelated events. Negative response to active timber sales occurred several times and, in every year of the study, the influence of weather on elk distribution was apparent. The following discussion identifies the causes and examines the importance of weather and human activities in determining the way elk use the available habitat.

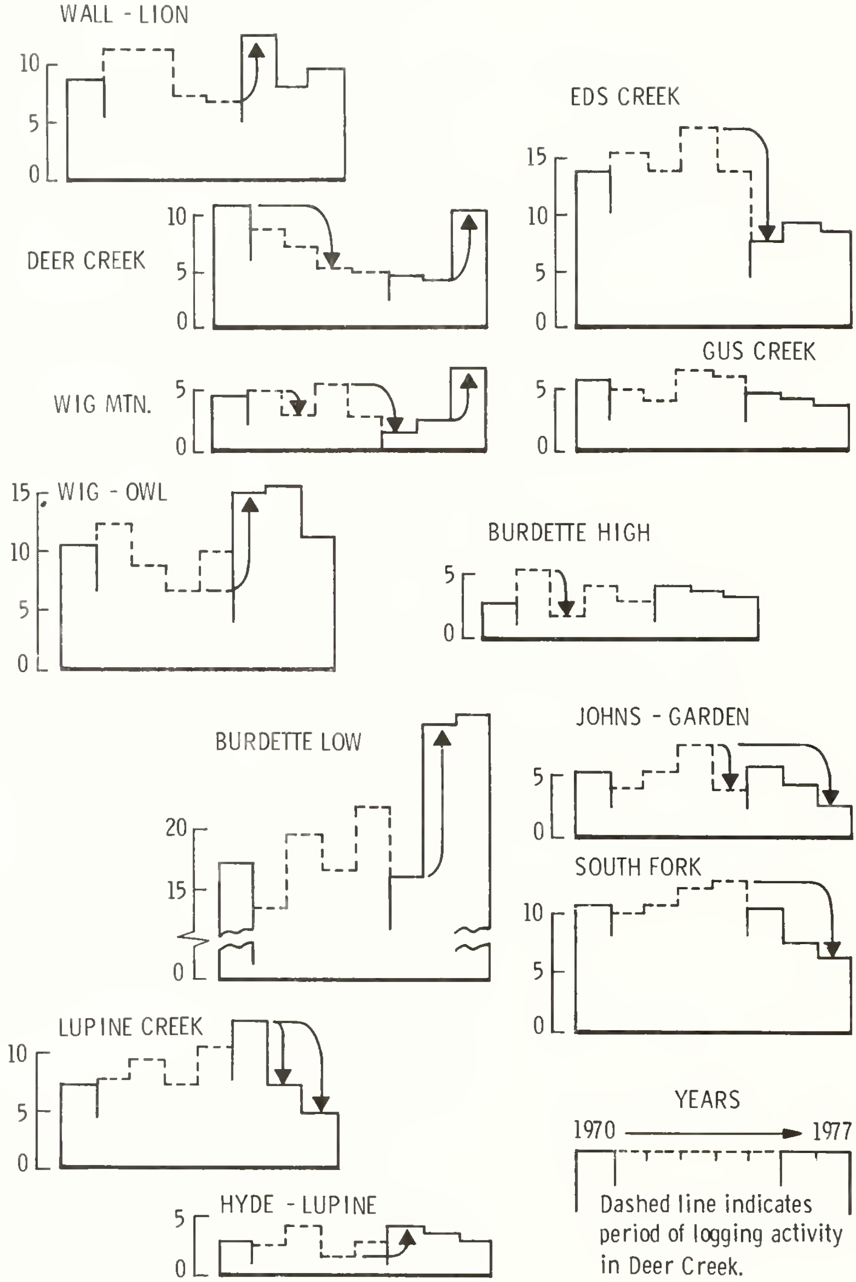

Figure 2.--Annual percentages of elk use by subunit, 1970-1977. Arrows indicate significant ($P < 0.10$) changes.

1970 Count

In the year preceding the first (1970) pellet count, human activities on the study area included the hunting season, fire patrols, recreation traffic, and some timber-marking work in Deer Creek. Final timber sale preparation activities in Deer Creek may have caused a slight depression in elk use; but with the exception of the Burdette Creek winter range (Burdette Low), all subunits of the study area were used by elk about as expected on the basis of proportionate area. The Burdette winter range received more use than might have been expected during a relatively mild winter. Snow fell during the 1969 hunting season, and I suspect that elk movement into the relatively inaccessible Burdette Creek drainage was precipitated by hunting pressure rather than winter weather.

1971 Count

Beginning in September 1970, activity in Deer Creek increased from occasional foot travel to substantial road construction, daily logging traffic, and major modifications of forest cover. All of the main roads and about half the timber harvest were completed during this period, but most of the logging took place on the north side of the drainage. The proportion of elk use declined in Deer Creek and increased in the immediately adjacent subunits. While none of these changes in elk use of subunits were individually significant, the probability of simultaneous random increases in all five subunits adjacent to Deer Creek is only one in 32 ($P = 0.03$).

The winter of 1970-71 was more severe than the preceding winter, but there was little early snowfall and elk were not forced onto the traditional winter range in Burdette Creek. As a result, the Wall-Lion and Wig-Owl subunits had increased winter use. The influence of late-season, deeper snow is also evident in the decline of elk use in subunits east of the watershed divide. Elk wintering in Gus Creek, Johns-Garden, and the South Fork subunits remained below 1 524 m (5,000 ft) for a longer than usual period of time. As a result, fewer pellet groups were detected on transects located above that elevation.

1972 Count

In the year preceding this count, logging and road construction continued in Deer Creek. The focus of activity, however, shifted to the south side of the drainage. There a spur road was built to the ridge at the Wig Mountain subunit between Deer Creek and Burdette Creek. The proportion of elk use in Deer Creek continued to decline, and declines were recorded in the subunits immediately adjacent to the ridgeline disturbance (Wig Mountain, Wig-Owl, and Burdette High). Two of these declines were statistically significant. The pattern was consistent with a hypothesis that elk move away from areas that have direct, line-of-sight contact to a source of disturbance.

Identification of the subunits into which elk moved is conjectural. Statistically significant increases were not recorded for any subunit, and all apparent increases could reasonably have been caused by factors other than the Deer Creek timber sale. Increased elk use of the Burdette Low, Lupine Creek, and Hyde-Lupine subunits, for example, was highest around 1 372 m (4,500 ft) as was expected following the severe winter weather of 1971-72. Increased elk use of the Johns-Garden and South Fork subunits appeared to be a result of elk movement away from an active timber sale just outside the study area in Howard Creek. Nevertheless, use of subunits to which elk might have been expected to retreat does suggest that animals moved as much as 8 km (5 mi) from the ridgeline disturbance in Deer Creek.

1973 Count

Timber harvest in Deer Creek was virtually completed and, by August 1973, most of the heavy equipment had been removed. The decline in elk use continued and finally reached a statistically significant level. Elsewhere on the study area, other distributional changes of less than statistical magnitude appeared to correlate with weather conditions and man-caused activities.

During the mild winter of 1972-73, there was little reason for elk to concentrate on the traditional winter range, and a decline in the use of Burdette Low was recorded. Elk response to hot and dry summer weather is persuasively demonstrated by declines in the use of all south- and west-facing subunits and concurrent increased use of all east-facing subunits and subunits above 1 524 m (5,000 ft). At the same time, the Howard Creek timber sale may have amplified the increased use of the South Fork and Johns-Garden subunits. The depressed use of Wig-Owl and Lupine Creek also reflects response to an elk trap in Wig Creek and some selective logging at the mouth of Lupine Creek.

1974 Count

Final logging operations and hauling of logs from Deer Creek were completed in the spring and summer of 1974. The disturbance was not continuous, but roads remained open and elk use remained low. Minor declines in elk use of the Wig Mountain and Burdette High subunits and an increase in Wig-Owl usage might have been associated with logging traffic, but these changes probably represent a general return to normal from the increases associated with hot summer weather in 1973.

Snowfall during the 1973 hunting season, and a winter of average severity, are reflected in increased elk use of Burdette Low and Lupine Creek and declines in elk use of Eds Creek and Gus Creek above 1 524 m (5,000 ft). New transects below 1 524 m in the South Fork also confirm increased elk use during the winter; but road construction in Garden Creek resulted in significant elk movement out of the Johns-Garden subunit.

1975 Count

Following an early bull season, but before the general elk hunting season in October 1974, the road to Deer Creek was closed with a gate. Only slash-burning crews and USDA Forest Service vehicles entered the drainage. Thus, the 1975 pellet count represents the first year of road closure after logging. Despite reductions in disturbance, elk use continued to decline. Elk use was also significantly depressed in the Wig Mountain subunit adjacent to some of the Deer Creek slash treatment areas.

Significant increases in elk use of the Wall-Lion and Wig-Owl subunits were not considered a response to the closure of Deer Creek. Similar increases in elk use occurred in all west- and south-facing drainages except Burdette Creek. And, in every case, the increase was recorded on transects at 1 372 m (4,500 ft)--which is considered indicative of winter use. Apparently, the initially mild winter weather of 1974-75 allowed elk to remain in areas outside Burdette Creek and, despite extremely cold weather during February, the expected movement to traditional winter range never occurred.

Road construction activity in the South Fork was reflected in a minor depression of elk use; and road construction on the ridge between Gus Creek and Johns Creek caused a minor depression in elk use of Gus Creek. Concurrently, a significant decline in elk pellet densities occurred in Eds Creek. During 1975, road construction and logging were initiated on a private holding on the north side of Eds Creek at about 1 521 m (5,000 ft). The area involved was relatively small, but the location, on a ridge overlooking much of the drainage, was very disturbing to elk.

1976 Count

In 1976, a combination of events resulted in a significant increase in elk use of the Burdette Creek drainage: the 1975 hunting season began in mid-October; and snowfall in October was the highest recorded during this study. As a result, elk moved into Burdette Creek earlier than in any previous year. The winter of 1975-76 was relatively mild, but low temperatures persisted through March; so elk movement off the winter range was delayed. Also, active timber sales in Lion Creek to the west and in all subunits east of Burdette Creek further inhibited normal spring and summer dispersal.

Inaccessibility of the Wig-Owl subunit during the hunting season (table 3) contributed to continued heavy use; but Lupine Creek, which hunters can reach on foot from the Wagon Mountain Road, received significantly less elk use than in previous years. In Deer Creek, the roads remained closed, but some slash burning and tree planting occurred and no increase in elk use was recorded.

1977 Count

Following 6 consecutive years of declining elk use, including 3 years of post-logging road closure, elk pellet densities in Deer Creek nearly doubled between 1976 and 1977. Proportionately, elk use in 1977 was almost the same as that recorded in the year before logging started. Elsewhere on the study area, declining elk use was recorded in all subunits in which logging was in progress; and in two of these subunits, Johns-Garden and the South Fork, the declines were statistically significant. In Lion Creek, logging was completed and even though the roads remained open, a minor increase in elk use occurred in the Wall-Lion subunit.

Independent of the response to timber sale activities, elk distribution in 1977 again demonstrated the strong influence of weather conditions. The winter of 1976-77 was extremely mild and, in the absence of snow pack, elk were able to remain at all elevations throughout the study area. Elk use of the Burdette winter range should have declined from the high recorded in 1976. However, the mild winter was followed by a hot, dry summer and elk response was limited by a number of conditions that did not exist in the hot, dry summer of 1973. Use of the south- and west-facing subunits (Wall-Lion, Wig-Owl, Lupine Creek, and Hyde-Lupine) was depressed, as in 1973, but movement to the cooler, moist subunits on the east side of the study area was inhibited by active timber sales. Use of the Wig Mountain subunit, which is above 1 524 m (5,000 ft) increased significantly, but a similar increase in the use of Burdette High was inhibited by logging activity in adjacent drainages.

For a substantial period of time in 1977, Deer Creek and Burdette Creek were the only areas of suitable habitat actually available to elk. In both subunits, a large drainage without active disturbance included a considerable area of north aspect on which small streams provided either flowing water or moist vegetation. Thus, while it is significant that Deer Creek became acceptable to elk following the timber sale, it may be even more significant that reoccupation of the drainage was not an elective choice. Instead, it appears that elk reentry to the drainage was forced by circumstances of weather and active timber sales.

DISCUSSION AND CONCLUSIONS

While the foregoing narrative description provides a persuasive summary of elk distributional changes and causal relationships, several assumptions were necessary to the continuity of the narrative. Implicit in all interpretations is the assumption that established patterns will ordinarily be repeated. Thus, any major modification of elk distribution requires repeated reinforcement to overcome behavioral patterns based on reenactment of previous experience. Elk response to weather occurs relatively quickly because the reinforcement is virtually continuous until the animal locates acceptable habitat. Response to timber sale activities, on the other hand, may require several years because the disturbance involves sporadic seasonal shutdown and substantial changes in logging activity patterns.

Changes in the annual distribution of pellet groups on the Burdette Creek-Deer Creek study area describe both elk movement in response to disturbances in the forest environment and elk habitat selection in response to weather conditions. In any year and for a variety of reasons, areas of otherwise acceptable elk habitat are caused to be unavailable for a period of time. The net result must be utilization of less desirable habitat or crowding of animals into habitat that remains acceptable. Management recommendations to reduce the time period of habitat unavailability and recommendations to improve the habitat where crowding does occur should benefit elk.

Over a period of years, the single most important influence on elk distribution in the Burdette Creek-Deer Creek area was weather. And, whereas the manager has no control over weather, there were at least three responses by elk that can be used by managers. There was fairly strong evidence that acceptable winter range may include more area than is usually considered in habitat improvement planning. In 4 of the 8 years of study, elk were able to spend a substantial part of the winter period above 1 524 m (5,000 ft) on areas normally considered summer range. Increased forage production at this elevation is not as critical for elk as increases below 1 372 m (4,500 ft) might be, but the benefits could be greater than is usually assumed.

Another important response by elk was the early movement to less accessible areas when snow fell during the hunting season. Normally, snow aids the hunter in tracking elk and thereby increases the annual harvest. If adequate refuge areas do not exist, overharvest is a distinct possibility.

Finally, the behavorial response of elk to hot, dry summer weather in 2 different years can be taken as further evidence of the importance of cool, moist habitat types to the overall integrity of elk summer ranges (Lyon 1975)[1]. Maintenance of body temperature at some relatively constant level may be comparable to feeding as a daily preoccupation for elk.

The second determinant of elk distribution--and one over which the manager has considerable control--was logging. Elk consistently moved away from areas where active logging was in progress; however, the distances traveled varied considerably. The greatest movement and the strongest negative response were recorded following logging operations on ridgelines where men and heavy equipment were visible over large areas (Deer Creek, 1972; Eds Creek, 1975; South Fork, 1975-77). A somewhat less negative response and shorter movement occurred when logging was conducted below ridgelines (Deer Creek, 1971; Lion Creek, 1976); at the ends of ridges (Garden Creek, 1974-77; Johns Creek, 1975-77); and at the mouths of drainages (Lupine Creek, 1973-74; Eds Creek, 1976-77).

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[1]Lyon, L. Jack. 1975. Coordinating forestry and elk management in Montana: Initial recommendations. Trans. North Am. Wildl. and Nat. Resour. Conf. 40:193-201.

Despite the [illegible] ive logging did follow rela- tively consisten[illegible] esult in complete abandon- ment of a subunit [illegible] ted, a return movement to the logged area w[illegible] eared to continue only as long as men and m[illegible] ed appeared to be only as far as necessary [illegible] l forest and even long spans across undi[illegible] fective as topography in reducing the dist[illegible]

Return moveme[illegible] siderably harder to evalu- ate on the basis o[illegible] a typical situation, removal of heavy e[illegible] did not compensate for the continuing sporadic disturban[illegible] the presence of slash burning and planting crews. In addition, the learned behavior imposed by 5 consecutive years of logging activity may have further contributed to a delayed return. In several other sale areas, where logging activity was not prolonged, minor recoveries from depressed elk use were recorded as an immediate response to removal of men and equipment (Hyde-Lupine, 1975; Johns-Garden, 1975; Eds Creek, 1976; Lion Creek, 1977).

In accordance with these results, several management actions can be suggested for reducing the distances moved by elk and reducing the time during which the habitat is unacceptable. As suggested in 1975 by the initial recommendations of the Montana Cooperative Elk-Logging Study (Lyon 1975, *see* footnote 1):

> Planning for timber sales in elk summer range should provide for a security area immediately adjacent to the disturbed area during active logging and road construction.

We are still unable to specifically define a security area other than to point out that the area selected "...should provide a line-of-sight topographic barrier and be inaccessible to motorized traffic." The area probably should be at least as large as the area disturbed, and any ridgeline between the timber sale and the security area should be protected from disturbance.

In addition to providing a nearby area to which elk can retreat, several further options can reduce the total effect of disturbance. Logging completed on summer range during the winter months, for example, may result in little distributional change. Where winter logging is not possible, there may be opportunities to reduce the time elapsed between first entry and completion. Smaller sales, completed in 1 or 2 years, are less disturbing and the areas involved are more likely to be reoccupied immediately. Road closures, like the closure imposed on the Deer Creek drainage of this study, would probably be more effective if vehicle traffic was severely limited and all disturbance, including slash disposal and planting, was completed in a short time.

Finally, it is suggested that the number of concurrent active timber sales in any one management unit on elk summer range should be limited. In this study, the original objective involved evaluation of the influence of a single large timber sale on elk distribution. As the study progressed, the number of active sales on the study area increased each year until only one of the study area subunits remained undisturbed. Concurrently, the proportion of elk use in that undisturbed subunit increased from 17 percent to over 30 percent of all use on the study area. The ridgeline road running south from Deer Peak was closed in 1978 to help alleviate this problem; at the same time, the difficulties of access for fire control and hunting have been substantially increased.

Land managers constantly encounter situations in which the solution of one problem becomes the cause of another. In the context of multiple-use management there is probably no logic capable of eliminating all conflicts between resource values. However, the degree of conflict can be considerably reduced and, in the management of elk habitat, very substantial positive results can be achieved through appropriate planning.

Lyon, L. Jack
1979. Influence of logging and weather on elk distribution in western Montana. USDA Forest Serv. Res. Pap. INT-236, 11 p. Intermt. For. and Range Exp. Stn. Ogden, Utah 84401.

Reports and evaluates the significance of weather conditions and logging activities on elk distribution. Recommendations for reducing the effects of disturbance on elk are presented.

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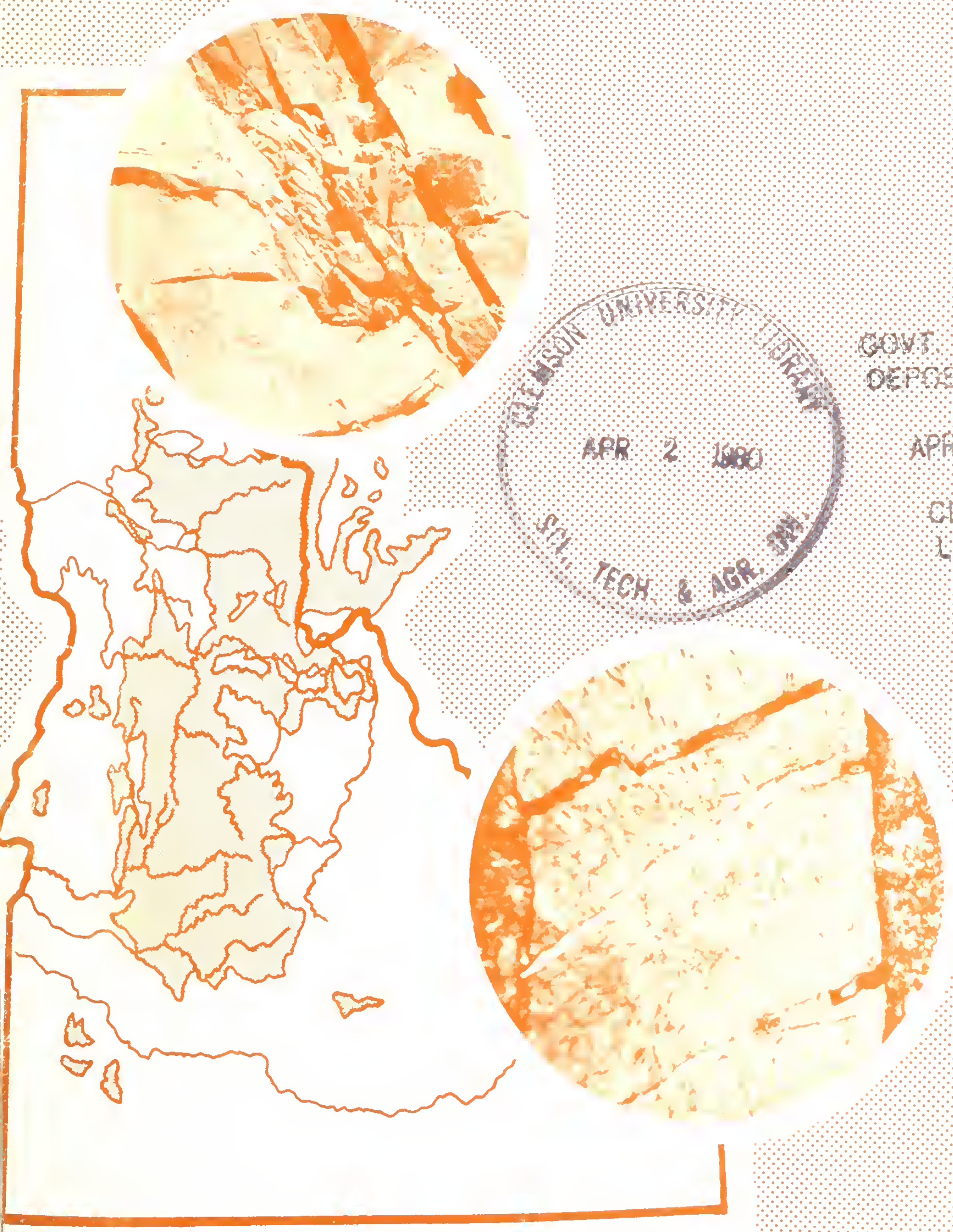

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RESEARCH SUMMARY

The mechanical properties of granitic rock and the derived weathered materials are intimately related to slope stability in the Idaho batholith. Processes and products of physical weathering, chemical weathering, and hydrothermal alteration of batholithic rocks can be ranked in terms of degree of weathering and used to predict slope stability.

Bulk density, hardness, unconfined compressive strength, and velocity of sonic wave transmission of weathered rock samples are all strongly correlated with weathering properties. Following subtle, initial hydrolysis of biotites, physical weathering processes are dominant in the breakdown of rock to grus at and near the soil surface. Grus is often formed with little alteration of biotites and feldspars to secondary minerals or amorphous oxides of silicon, aluminum, and iron.

Bedrock buried at depths below the rooting zone is subject to intense chemical weathering and mineral alteration. The degree to which chemical weathering processes can proceed is related to the inherent slope stability of the site. On gentle slopes with low erosion rates, chemical weathering can advance to a point where the weathered product consists of quartz grains embedded in a matrix of clays and crystalline and amorphous oxides of silicon, aluminum, and iron.

X-ray diffraction patterns of powdered bedrock samples show decreases in peak intensity, diffuseness of d-spacings, and complete absence of some reflections with increasing weathering. Intermediate stages of chemical weathering of individual minerals can result in clay minerals that are not in equilibrium with current pedogenic conditions favoring formation of kaolinite, halloysite, and illite. We have found iron-rich smectite-iddingsite alteration after biotite and interstratified clays of undetermined origin.

Low temperature hydrothermal alteration is common in the Idaho batholith, although it is frequently difficult to determine on the basis of mineralogy alone. The frequency of occurrence of hydrothermal alteration is associated with major and minor structural lineaments mapped by satellite imagery. Alteration products are often located in clay seams bounded by shear zones. Mineralogies may be dominated by smectites and zeolites (clinoptilolite), but often the clays may be kaolinite, halloysite, and minor mixed-layer illite-montmorillonite. Altered zones with this latter more normal group of clay minerals may reflect a combination of surface weathering and hydrothermal alteration.

The morphology of Idaho batholith soils is not particularly suited for predictions of subsurface weathering characteristics. The strong topographic influence on slope stability, coupled with youthful soils resulting from high erosion rates, masks or obliterates the soil morphology-bedrock weathering relationship. The relationship between the pH of the B and C horizons and the degree of bedrock weathering is fairly well defined: the pH decreases from 6.3 to 4.9 as the parent rock becomes increasingly weathered. Other parameters, such as clay, free silica, and sesquioxide content, and soil color were not strongly correlated with weathering.

CONTENTS

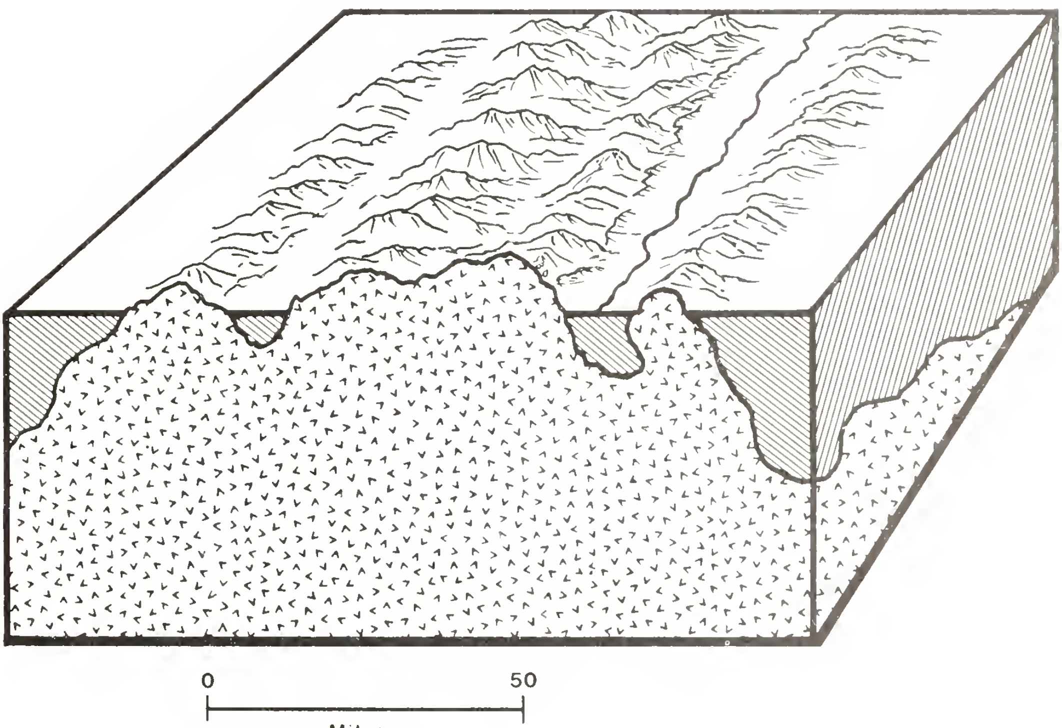
NOTE: A Weathering Guide for field use containing information from the section BEDROCK WEATHERING is appended inside the back cover.

INTRODUCTION

Batholiths are composite masses of granitic rocks that have areas ranging from ens to thousands of square kilometers. Batholiths generally cut sharply across their vall rocks and are surrounded by contact metamorphic aureoles clearly demonstrating formation by intrusion of magma from greater depths than the surrounding rock. Contacts between plutons and the adjoining country rocks are vertical or steeply dipping over listances measured in thousands of meters. The contacts are commonly gradational due o mutual exchange of material between intruded granite and country rock. In places, he granite at the boundaries passes into a zone of migmatite, consisting of metamorphosed ountry rock veined and streaked with intruded granite or pegmatite (Turner and 'erhoogen 1960). The main characteristics of batholiths are enormous size, method of mplacement, discordant relationship to the country rock, and lack of a visible floor.

The Idaho batholith is a typical batholith (fig. 1). It outcrops across Idaho nore or less continuously for about 250 miles (400 km) north-south and 80 miles (130 m) east-west (fig. 2). Larsen and others (1954) have dated the intrusion at 90 to 00 million years BP[1], indicating emplacement during the early and middle Cretaceous. he batholith was later uplifted by faulting and exposed by erosion, forming the resent group of mountain ranges in central Idaho.

IDAHO BATHOLITH



igure 1.--Typical bedrock relationship showing the discordant relationship between the Idaho Batholith and the country rock. Uplift subsequent to emplacement was followed by the removal of thousands of feet of overburden. (Vertical scale is exaggerated.)

[1]Years before present, used to express age of geologic or soil deposits.

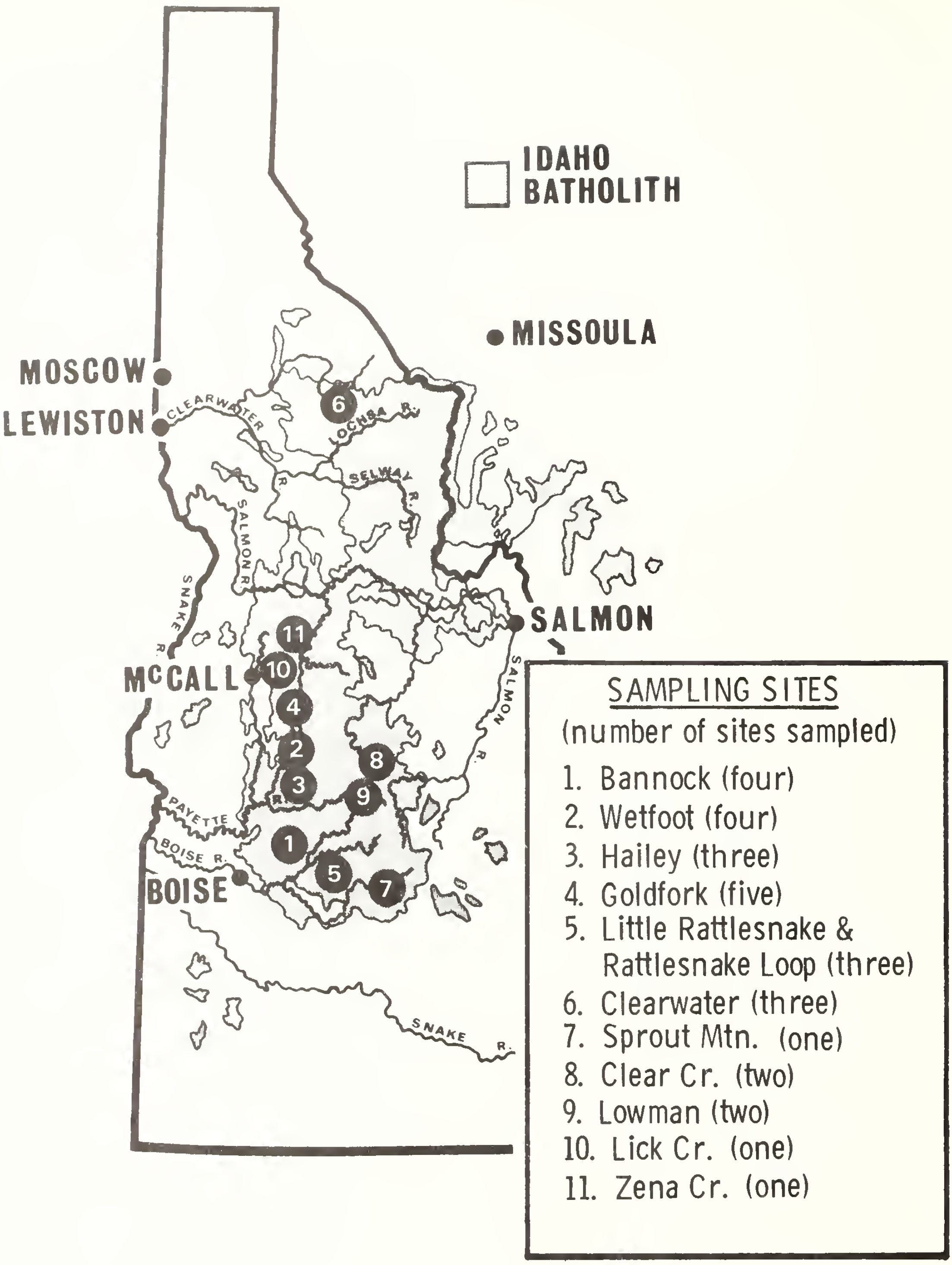


Figure 2.--Map of Idaho showing the location of the Idaho batholith and sampling sites within the batholith.

Much of the batholith is overlain by forest land administered by the Forest Service. Timber, water, forage, wildlife, and recreation are resources that support a substantial portion of the economic and social welfare of Idaho and its surrounding States. At present, the optimum utilization of these resources cannot be realized because of man's damaging activities, principally those related to logging and road construction. When imposed on the unstable landscapes of the batholith these activities have the potential of causing tremendous increases in erosion and sedimentation (Megahan and Kidd 1972a, 1972b; Rice and others 1972).

Streams of the Idaho batholith contain a sizeable resident game fish population and provide spawning and rearing grounds for anadromous fish; however, anadromous fish populations generally have been on the decline since about 1957 as a result of dam construction along the Columbia and Snake Rivers and increased sediment loads in rivers draining the Idaho batholith (Ortman 1967; Platts 1972; Mallet 1974).

Slope instability and resulting sedimentation have been matters of increasing concern to Forest Service land managers in the Northern and Intermountain Regions over the last two decades. Today, these problems are of paramount importance in decisions affecting multiple use of National Forest lands.

The relations between rock and soil properties and erosion in the batholith have been recognized as important, but largely unknown quantities in land management. In 1970, the Intermountain Forest and Range Experiment Station funded a 3-year cooperative venture between Howard University and the Station's research laboratory in Boise, Idaho. The purpose of the study was to investigate the engineering, mineralogical, chemical, and hydrological properties of soil and bedrock in the Idaho batholith. This paper deals primarily with the chemical and mineralogical properties of rocks, weathering products, and soil, and sheds light on rock weathering processes and soil genesis. Relationships between weathering products, and engineering and hydrologic properties of soil and bedrock are discussed in less detail. Some conclusions about the relationships between weathering and hydrothermal alteration processes and slope stability are also discussed.

BACKGROUND

Description of the Idaho Batholith — Geologic Setting

The Idaho batholith lies mainly in central Idaho, but extends in a northeasterly direction into Montana. Its surface outcroppings cover an area of about 16,000 mi^2 (41 000 km^2). The batholith is a member of a chain of large intrusive bodies extending along the western border of North America.

Much of the Idaho batholith belongs to an inner facies of rather uniform, light-colored granitic rock, mainly of granodiorite composition (Ross 1963). An outer mass or border zone of more calcic rock may have originally constituted an envelope that enclosed much of the main facies (Ross 1963). The Idaho batholith is zoned spatially and chemically; older, more mafic rocks are found at the western edge, becoming progressively more felsic and younger in a easterly direction (Bennett 1974)[2].

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[2]Bennett, Earl H., II. 1974. The general geology of that part of the Northern Rocky Mountain province containing the Idaho batholith. Unpubl. Rep. USDA For. Serv., Intermt. Reg., 228 p. Ogden, Utah.

Schmidt (1964) defined the zoning sequence from west to east on a transect near Cascade, Idaho. He distinguished a migmatite border zone, a quartz diorite gneiss zone, a leucocratic quartz diorite zone, a granodiorite zone, and, finally, a quartz monzonite zone, some 40 miles (65 km) east of the migmatite border. The batholith intrudes sedimentary and volcanic rocks ranging in age from Precambrian to Triassic.

A modal analysis of rock types in the batholith presented by Ross (1963) indicates that samples from the main inner facies are mainly granodiorite, although many are quartz monzonite. These analyses indicate that the main mass of the batholith may be somewhat more calcic than was thought previously (for example, see Larsen and Schmidt 1958).

Elevations in the batholith range from about 2,000 ft (730 m) where the Salmon River leaves the batholith to more than 10,000 ft (3 650 m) in the south-central part of the batholith. Because of the wide range in elevation, numerous climates are encountered in the batholith. Geomorphic features reflect both the tectonic setting and climatic diversity of the area.

The tectonic history of the Idaho batholith and adjoining areas has been important in controlling the gross landforms of the area. The Snake River downwarp and parallel trend of compensatory uplift north of the river plain control the major drainage systems within the entire State. Large-scale faulting associated with these tectonic events, and stream piracy virtually reversed the direction of flow of the Salmon River and turned its waters from the Missouri system to the Snake and Columbia Rivers (Anderson 1947). North-south striking faults along the western Idaho border tend to control valley development and drainage patterns in the western batholith. The northwes trending faults and structural control in general in eastern Idaho have controlled the orientation of drainages and of several mountain ranges, including the Bitterroot Range in the northeastern batholith.

Alpine glaciation played a major role in shaping the landscape during Quaternary times. Landforms in the Sawtooth Mountains, Stanley Basin area, the Salmon River Range east of McCall, Idaho, and the Bitterroot Mountains have all been modified to varying degrees by alpine glaciation.

In contrast, areas of lower elevation have landforms showing the influence of fluvial slope-forming processes. Deeply incised canyons and steep valley side slopes epitomize the landscapes. The area along the Middle Fork of the Salmon River in the central batholith provides a good example of such landscapes. Here, the combined effects of a major stream carrying a considerable sediment load and a changing base level associated with mountain uplift and the Snake River downwarp have produced the deeply incised canyons of the Salmon River Breaks area.

Eolian deposits are common in many areas of the northern Idaho batholith, and traces have been reported in the interior of the batholith as far south as the headwaters of the Deadwood River, east of Cascade, Idaho. The source of much of the loess in the northern batholith is glaciofluviatile material from the Columbia River Basin that was reworked by winds during the late Quaternary. Some loess is also of volcanic origin. Tephra falls from both Glacier Peak (12,000y BP) and Mazama (6,600y BP) have been reported in the northern Idaho batholith (Wilcox 1965), and tephra deposits are present in the south-central batholith east of Cascade, Idaho (Clayton and Wendt 1975), but their origin and age remain obscure.

Climatic Setting

Two basic precipitation sources operate within the region of the Idaho batholith. Most winter precipitation originates from cyclonic storms that develop over the Pacific Ocean. These storms travel on an easterly course over Washington and Oregon, losing much of their water content over the mountain barriers of the Cascade Range. Thus a distinct rainshadow effect reduces the precipitation delivered to the Idaho batholith region. Both the frequency and the intensity of winter cyclonic storms increase from south to north (Dean 1974)[3], and the rainshadow effect is less pronounced north of the Clearwater River.

Summer high-altitude convective storms developed from moist air moving north from the Gulf of Mexico are common in the region. These storms are of short duration, but precipitation intensities usually exceed those developed from cyclonic storms. Storm intensities of 3 inches/hour (7.6 cm/hour) have a probable return period (p = 0.5) of 4 years in the central Idaho batholith (Kidd 1964). The frequency of summer convective storms decreases from south to north (see footnote 3 on this page).

Mean annual precipitation in the batholith ranges from below 15 inches (38 cm) to over 70 inches (180 cm). The driest portions are the southern fringe of the batholith, the South Fork of the Boise River, and the main Salmon River Canyon in the central batholith. Mean annual precipitation in excess of 50 inches (127 cm) is rare in the southern half of the batholith, the only extensive area located in the Sawtooth Mountains. Mean annual precipitation in extensive areas of the batholith north of the Clearwater River exceeds 50 inches (127 cm) (see footnote 3).

Air temperatures within the Idaho batholith are most strongly influenced by topographic variations. Average annual temperatures decrease approximately 4.1° F (2.3° C) per 1,000-ft (365-m) gain in elevation over the range 3,600 ft (1 000 m) to 9,850 ft (3 000 m) above sea level. Mean monthly temperatures at all stations are highest in July and lowest in January. Average monthly maximum temperatures range from a high of 92° F (33° C) in July at several stations in the southern batholith below 4,000 ft (1 460 m) in elevation to a low of 26° F (-3° C) in January at Cobalt, elevation of 6,810 ft (2 480 m). The lowest average monthly minimum temperatures range from 0° F (-18° C) in January at Chilly Barton Flat, elevation 6,175 ft (2 250 m), to 33° F (1° C) in July at Warren, elevation 5,907 ft (2 154 m).

METHOD

Sample Sites and Field Procedures

Sampling sites for this study were selected to insure geographical, elevational, and climatic variability. Preliminary observations suggested that various landforms have distinctive bedrock weathering characteristics. For example, landscapes glaciated in late Pleistocene or Neoglacial time tend to be underlain by relatively hard, unweathered bedrock. In contrast, more highly weathered bedrock is commonly associated with landscapes that have undergone fluvial dissection and associated slope processes less erosive than glaciation. Sites were selected to provide a representative array of weathering and fracture density classes as described by Clayton and Arnold (1972).

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[3]Dean, E. Nelson. 1974. Some climatic and hydrologic characteristics data for physiographic sections of that portion of the Northern Rocky Mountain Province containing the Idaho batholith. Unpubl. Rep. USDA For. Serv. Intermt. Reg., 141 p. Ogden, Utah.

Fifteen sites were selected for sampling and testing in 1970 and 14 in 1971. The sites were located in four National Forests: Boise, Clearwater, Payette, and Sawtooth. Location of the sampling areas and the number of sites sampled at each area are shown in figure 2.

We initially tried to sample bedrock by core drilling, but abandoned this procedure because of poor recovery of highly weathered and (or) fractured bedrock. The only acceptable alternative to core drilling was to select and sample sites on fresh road-cut faces. A fresh roadcut was defined as one not exposed more than 2 months prior to sampling.

Rocks were hand-sampled at a variety of depths below the original surface and measured vertically from the top of the cut face. During 1970 sampling, several rock samples were taken systematically at predetermined depths from each face. Because of difficulty in assigning a single value of weathering (Clayton and Arnold 1972) at the sites selected in 1970, site selection and sampling methods were changed in 1971. Roadcut faces were then chosen for uniformity of weathering and fracturing along the entire exposed face, and a random sample of several rocks representative of the exposed face were collected and treated compositely as a single sample representative of the site.

At each site, a soil pit was dug above the roadcut and generally 15 to 60 feet (5 to 20 m) from the face. This soil is presumed to be formed from the parent material exposed in the roadcut. A description of the soil in the walls of each pit included the following: horizons, depth, color, structure, presence of clay films, percent by volume of stones and rocks, roots, pores, and horizon boundaries. Textures and pH were determined in the laboratory.

Site variables described included location, field classification of parent rock (lithology, weathering, and fracture density classes), surface stone and rock outcrop percent, landform, slope, aspect, elevation, and a description of the type and amount of erosion. We described the trees, shrubs, forbs, and grasses present and estimated relative amounts of vegetation (percent by number of stems for trees and shrubs) for the site as a whole. We assigned the vegetation to habitat types using the classification system proposed by Steele and others (1975).

Duplicate core samples were taken from each soil horizon by driving a brass cylinder (136.4 cc volume) horizontally into the side of the exposed soil pit. Horizons that contained too many stones damaged the sampling apparatus and therefore were not sampled for bulk density. In addition, grab samples were collected from all major horizons for laboratory analyses.

Laboratory Procedures — Soil

All soil samples were air-dried, then sieved through a 2 mm diameter sieve. Most analyses were performed on the <2 mm fraction of the soil. Water retention at 15 bars was determined with a pressure membrane apparatus. Retentions at 1/3 and 0.1 bar tension were determined with a porous plate pressure chamber device. Percent sand, silt, and clay are expressed as percentages by weight of the <2 mm fraction. They were determined by the hydrometer method in a sedimentation cylinder. The 136.4 cc soil core samples were ovendried and weighed to the nearest 0.01 of a gram in order to determine bulk density. Soil pH values were determined on the <2 mm fraction on a 1:1 soil paste. Values reported are averages of duplicate samples. Cation exchange capacities were determined in duplicate on <2 mm soil samples. This analysis employed saturation of the exchange complex with sodium followed by removal of the sodium by means of ammonium acetate. Sodium was determined by flame emission spectroscopy. Free iron (Fe_2O_3) was determined on soil samples (<2 mm) after removal of organic matter with 30 percent H_2O_2. A citrate-dithionite extraction was employed and iron determined colorimetrically with o-phenanthroline. Free silica (SiO_2) was determined on the clay fraction (<2 μm) of soils. Organic matter was removed by digestion in 30 percent H_2O_2. Clay samples were then deferrated using a citrate-dithionite extraction after buffering to pH 7.2 with $NaHCO_3$. Samples of deferrated clays were dried and free SiO_2 was removed by boiling for 5 minutes in a 2 percent Na_2CO_3 solution. Silica was determined by the molybdate blue method. Free alumina (Al_2O_3) was determined on the same extract for a few samples. Aluminum was determined by atomic absorption spectroscopy utilizing a N_2O oxidant.

Organic matter determinations were run on paired samples in a carbon combustion furnace (900° C) using continous oxygen flow.

Clays (<2 μm) were separated from the <2-mm fraction by sedimentation, then sucked onto ceramic plates for mounting in the diffractometer. This method produces samples with basal cleavage orientation. Copper Kα radiation was used to produce the x-ray diffractograms. A variety of heat treatments and ethylene glycol solvation were used to confirm presence of the various clay minerals. Peaks on the diffractograms were marked and, for each mineral assemblage, the relative intensities were semiquantitatively indicated. Minerals were considered present either in trace amounts, minor amounts, abundant amounts, or dominant amounts.

The sand and silt fraction left after decanting the clay for x-ray analysis was sieved. The heavy minerals were then separated from the fine sand fraction (0.25 to 0.10 mm) with bromoform and mounted on microscope slides. These slides were examined for etching of the mineral grains and mineral alteration.

Laboratory Procedures — Rock

Bulk density determinations were taken on each rock sample prior to subsampling by weighing, coating with paraffin, and measuring the volume by water displacement.

Rock samples that had been pulverized in a ball mill for 5 minutes were analyzed for free Fe_2O_3. The powdered rock was analyzed the same way that soil samples were, except that predigestion in H_2O_2 was omitted.

Descriptions of each sample included: (1) presence of iron oxide staining and source mineral, (2) color of biotites and appearance of biotite grain boundaries, (3) degree of opacity of feldspars, (4) frequency of intergranular fractures, and (5) extent of argillation by color, and degree of staining of mineral faces with a 1 percent solution of p-aminophenol (method after Dodd 1955).

Thin sections were prepared from rocks from all sites. Two hundred point counts were made to provide a petrologic description for each sample. Sections were examined for individual mineral weathering products and degree of weathering, but no point counts were made to quantify the amount of weathering. Instead, a visual estimate of percent weathering of primary mineral types was made. We also described mineral pleochroism, twinning (relict in secondary minerals), grain structure and orientation, and undulose extinction if present (principally in quartz).

Rock samples were pulverized in a ball mill, sieved to pass a 60-mesh (d = 0.25 mm) screen and sprinkled on vaseline-coated slides. These slides were x-rayed using copper $K\alpha$ radiation scanning the range 3° 2Θ through 32° 2Θ. Although this method was of little value in identifying weathering products, it did provide information about degree of weathering of primary feldspars.

Data from all field descriptions and laboratory procedures are reported by Hampton and others (1974a). X-ray diffraction studies on the soils are described by Clayton (1974). Selected soil and rock properties related to engineering research, results of seismic studies and hydraulic conductivity testing of fractured bedrock are presented by Hampton and others (1974b).

BEDROCK WEATHERING

The transition from fresh bedrock to weathered bedrock involves numerous chemical and physical processes. These processes manifest themselves in the physical and mineralogical (chemical) properties of the rock itself.

Granitic rock such as that found in the Idaho batholith is formed under tremendous pressures (1000 to 1500 bars) and high temperatures (600 to 800 °C). Rock formed under these conditions is in a state of disequilibrium when brought to the surface.

The overriding driving force for weathering processes is a continued readjustment the rock must make toward a thermodynamic equilibrium dictated by the changing environment the bedrock is subjected to when brought to the earth's surface. As Ollier (1969) points out, it is not necessary to assume that cooled magma at depth ever achieved a true thermodynamic equilibrium; only that this rock, when brought to the earth's surface, is less in equilibrium with surface conditions than its potential weathering products.

The physical properties and mineralogical changes reflecting various stages or degrees of weathering are numerous. To satisfy one intent of this study, to relate bedrock weathering to slope stability, we spent considerable effort in relating degree of rock weathering to mechanical strength and other engineering properties (Hampton and others 1974a; Hampton and others 1978).

We classified the samples in the field on the basis of semiquantitative degree of weathering (weathering class) and have used this as the dependent variable when field and laboratory measurments are compared. The seven weathering classes of Clayton and Arnold (1972) were used because they give reasonble field estimates of rock strength and secondary mineral formation. Many of the secondary mineral assemblages occur as a result of hydrothermal alteration or a combination of hydrothermal alteration and weathering. These processes will be distinguished whenever possible. The seven classes are described as follows:

Class 1. Unweathered Rock.--Unweathered rock will ring from a hammer blow; cannot be dug by the point of a rock hammer; joint sets are the only visible fractures no iron stains emanate from biotites; joint sets are distinct and angular; biotites are black and compact; feldspars appear to be clear and fresh.

Class 2. Very Weakly Weathered Rock.--Very weakly weathered rock is similar to Class 1, except for visible iron stains that emanate from biotite; biotites may also appear to be "expanded" when viewed through a hand lens; feldspars may show some opacity; joint sets are distinct and angular.

Class 3. Weakly Weathered Rock.--Weakly weathered rock gives a dull ring from a hammer blow; can be broken with moderate difficulty into hand-sized rocks by a hammer; feldspars are opaque and milky; no root penetration; joint sets are sub-angular.

Class 4. Moderately Weathered Rock.--Moderately weathered rock may be weakly spalling. Except for the spall rind, if present, rock cannot be broken by hand; no ring or dull ring from hammer blow; feldspars are opaque and milky; biotites usually have a golden yellow sheen; joint sets are indistinct and rounded to sub-angular.

Class 5. Moderately Well Weathered Rock.--Moderately well weathered rock will break into small fragments or sheets under moderate pressure from bare hands; usually spalling; root penetration is limited to fractures, unlike class 6 rock where roots penetrate the rock matrix; joint sets are weakly visible and rounded; feldspars are powdery; biotites have a light-golden sheen.

Class 6. Well-weathered Rock.--Well-weathered rock can be broken by hand into sand-sized particles (grus); usually, it is so weathered that it is difficult to determine whether or not the rock is spalling; roots can penetrate between grains; only major joints are preserved and filled with grus; feldspars are powdery; biotites may appear as thin silver or white flakes.

Class 7. Very Well Weathered Rock.--Very well weathered rock has feldspars that have weathered to clay minerals; rock is plastic when wet; no resistance to roots.

The initial process of unloading overburden material during uplift and erosion is xtremely important to all subsequent weathering processes. Small stress fractures and oints extant in the cooled magma at depth are expanded during overburden removal Ollier 1965). These fractures provide the necessary pathways for water, the key ngredient in both physical and chemical weathering, both of which are generally near-urface processes.

The distinctions between physical and chemical weathering in the Idaho batholith re sometimes obscure. They are contemporaneous processes and complement each other ynergistically. A typical example of this is provided by biotite weathering.

Initial weathering of individual biotite grains involves hydrolysis of nonframe-ork potassium, and hydrolysis and oxidation of iron and magnesium. Removal of iron nd magnesium oxides ensues (Walker 1949); the biotite grain forms fringed edges, xpands and allows increased water entry. The increased water entry results in greater train on the mineral because of hydration of weathering products and freeze-thaw echanisms. This strain allows entry of water, weak organic acid solutions, and helating agents that result in framework destruction and subsequent secondary mineral ormation. Expanded biotite grains can exert enough pressure on the surrounding rock o fracture it, or at least to weaken bonds between adjacent minerals, and thus start he transition from rock to grus. Framework destruction and subsequent expansion s the principal process in the conversion from weathering class 1 to class 4, and will e described in more detail later in this section.

Physical Weathering

The documentation of physical weathering as a singular process, distinct from chemical weathering, requires recognition of (a) physical breakdown of the rock (loss of strength) and (b) a lack of secondary mineral formation. These two conditions were never met in our rock weathering research. Microbrecciated rocks from shear zones frequently appear in hand specimen to be physically, but not chemically, weathered rocks. Such shear zones are common throughout the Idaho batholith and can easily be recognized by their abrupt contact with boundary rock of greater competence. In thin section, however, rock from shear zones is readily recognized by the degree of microbrecciation, marked undular extinction of quartz grains (strain deformation) and, often, presence of alteration products, such as epidote and garnets.

Physical weathering probably is the major cause of physical weakening in rocks from weathering class 2 to class 4 or 5. The processes that cause this loss of strength are all surface or near-surface phenomena, with freeze-thaw cycles and hydration-dehydration being the most important processes. However, freeze-thaw cycles probably are inconsequential below a soil depth of 12 inches (30 mm) and intergranular stresses resulting from hydration and dehydration probably are restricted to the top 6 to 10 feet (2 or 3 m) of bedrock, except along the faces of joint systems.

Chemical weathering requires that water be present, but there is no requirement for periodic drying. Chemical weathering is therefore favored in subsurface zones that are periodically wetted by deep seepage, but are not subject to evapotranspirational water loss.

Chemical weathering does aid in the physical weathering of some rocks. This has been observed by engineers and those concerned with road maintenance, who contend that granite bedrock weathers, decomposes, or "air slakes" within a year or two after construction. Hence, rock that required blasting for road construction becomes a sediment source and maintenance problem. Such rock has weathered chemically by hydrolysis and, possibly, by oxidation (Henin and Pedro 1965) of biotites and initial hydrolysis of feldspars, but it has not undergone physical weathering until it is exposed in a roadcut.

The chemical weathering at depth, which may only be visible as mild iron oxide staining and slight opacity of feldspars, has resulted in a network of fine intergranular fracturing. Thus, the rock is primed for water entry and will lose its strength rapidly upon surface exposure. Rock samples obtained from the Army Corps of Engineers show iron oxide stains in cores from a depth of 820 feet (270 m). Apparently, fracture systems are extensive and very deep weathering occurs, at least in some parts of the batholith.

Several clues can be observed in the field to determine whether hard, unrippable rock is likely to lose strength rapidly and spall within a year or two. If the feldspars are clear, particularly at their boundry with adjacent mineral grains, rapid deterioration of the rock is unlikely. We found that staining rock with a 1 percent solution of p-aminophenol (Dodd 1955) was useful for indicating slight chemical weathering that might be undetected in a macroscopic field examination of rock (Hampton and others 1974a). In contrast, presence of iron oxide stains around biotite grains is of little value in predicting strength after exposure.

Increase in size and frequency of intergranular fractures is the single best expression of increasing physical weathering. For this reason, we would expect rock bulk density to be a good descriptor of degree of physical weathering (fig. 3). Unweathered rock, class 1, shows bulk densities in excess of 2.6 g/cc, essentially equal to the solid phase density of the individual minerals. Weathering to class 2 is a chemical process involving initial hydrolysis of relatively easy-to-weather minerals, mainly biotite and plagioclase feldspars. These processes involve some expansion of mineral grains (Helley 1966; Clark 1967; Wahrhaftig 1965), which results in a lowering of bulk density to about 2.5 g/cc. Physical weathering processes exploit the small fractures resulting from the initial weathering, expand the fractures, and lower the bulk density to a range of 2.2 to 2.3 g/cc (weathering classes 3 and 4). At the same time, the rate of chemical weathering can increase due to the greater frequency of fractures. After this, the rocks disintegrate, forming grus. Little change occurs in bulk density until chemical weathering is quite advanced and secondary minerals make up a good proportion of the rock. Bulk densities of from 1.8 to 2.1 g/cc are common at this advanced stage of weathering (classes 6 and 7).

With increased physical weathering, we expected decreasing trends in rock hardness and strength along with the expected decrease in bulk density. These relationships were examined by plotting unconfined compressive strength of intact core samples and the hardness values developed by scleroscope against weathering classes. In addition, sonic wave velocities were measured on several core samples and related to weathering classes. These plotted relationships are presented in figures 4, 5, and 6. A more detailed study in Hampton and others (1978) essentially substantiates the results presented here.

The debates over insolation as an active process in physical weathering continue (Blackwelder 1933; Griggs 1936; Ollier 1969); however, both proponents and opponents of the insolation hypothesis agree that diurnal heating and cooling is most stressful to coarse-grained rocks, such as those in the Idaho batholith.

Exposed roadcuts are prime candidates for accelerated physical weathering resulting from diurnal fluctuations in temperature. This contention is supported by the observation that roadcuts produce substantial sediment during periods of no freezing or precipitation.

Nighttime relative humidities generally reach 100 percent, even during summer dry periods (data on file, Intermountain Station's research laboratory, Boise), and we might expect diurnal fluctuations in hydration of secondary minerals. These fluctuations may be a more important agent in producing sediment (grus) by granular disintegration than insolation.

Fire has also been proposed as a physical weathering phenomenon (Blackwelder 1927). This hypothesis has received recent support (Birkeland 1974).

We have observed flaking and granular disintegration of exposed boulders following wildfires and controlled burns in the Idaho batholith. These boulders may have been primed for such fire-induced weathering by previous chemical and physical weathering. Whether fresh (weathering class 1) rock would flake and disintegrate upon heating by fire is not known, although class 1 rock will readily flake upon heating with a Bunsen burner.

Chemical Weathering

The readjustment of bedrock to a surface environment involves chemical reactions brought about by the state of disequilibrium the rock is in when brought to the earth's surface by uplift and overburden removal. A few principal differences in surface environment dictate or define this state of disequilibrium: (1) lower pressure and temperature, (2) presence of copious amounts of water, (3) dissolved gases (principally O_2 and CO_2) in the water, and (4) presence of organic compounds, notably organic acids and chelating agents.

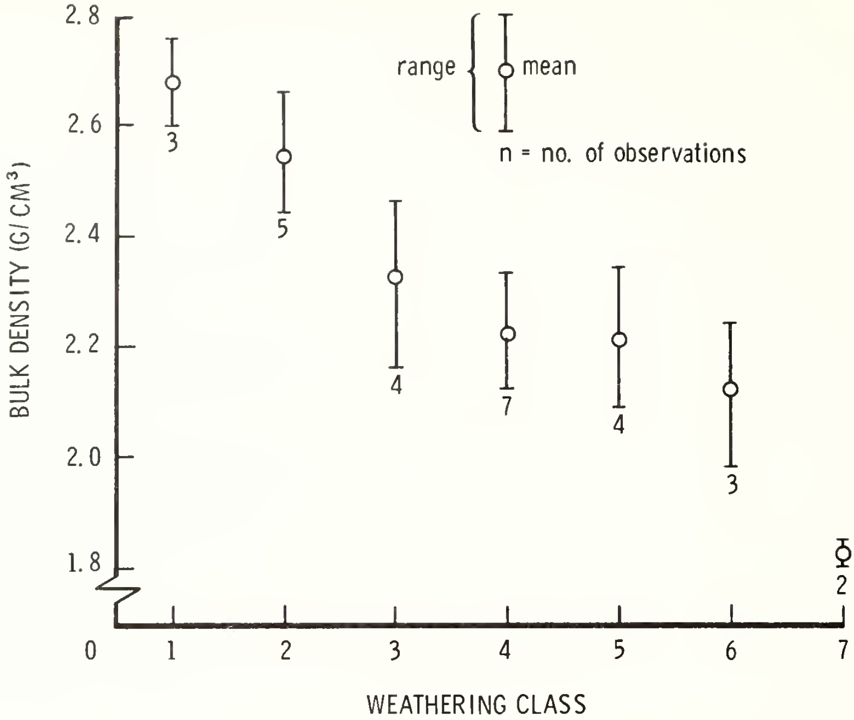

Figure 3.--Relationship between dry bulk density of bedrock (g/cc) and rock weathering class.

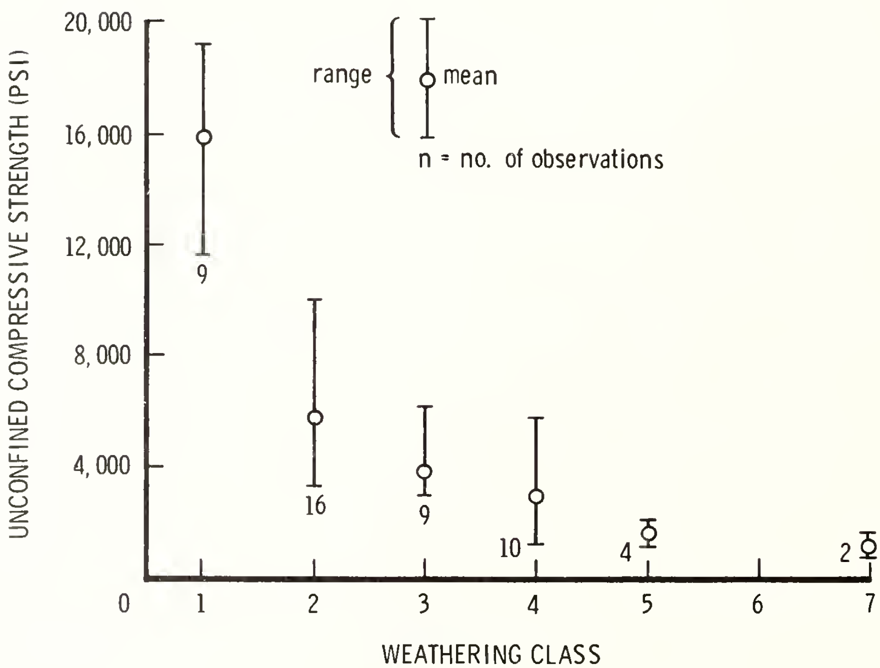

Figure 4.--Relationship between the unconfined compressive strength of rock cores measured in pounds per square inch (psi) and rock weathering class.

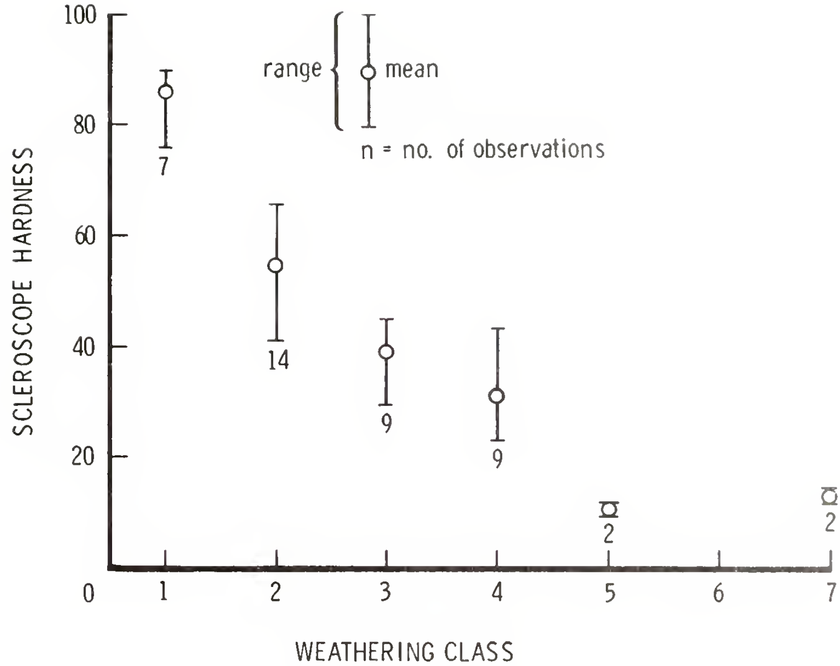

Figure 5.--Relationship between rock hardness measured with a scleroscope and rock weathering class.

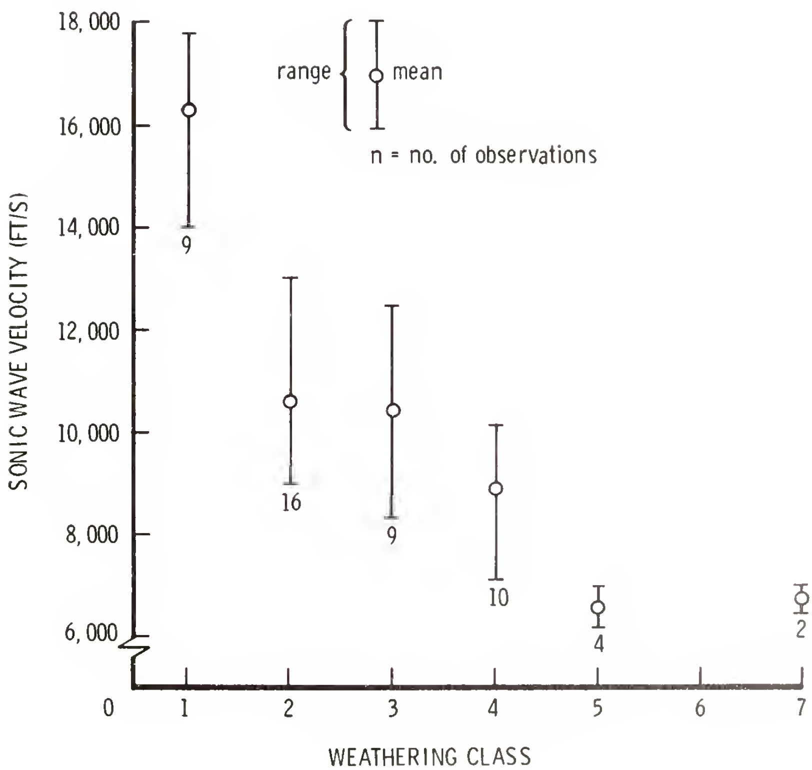

Figure 6.--Relationship between sonic wave velocity at an axial loading stress of 587 pounds per square inch and rock weathering class.

From theoretical considerations, the equilibrium byproducts of chemical weathering would be aluminosilicate clays, crystalline and amorphous oxides of silicon, aluminum, and base metals, especially calicium, sodium, iron, and potassium (Jackson 1965b). Studies of secondary minerals in soils in the Idaho batholith indicate the common solid by-products are kaolinite and halloysite, illite, allophane, and iron oxides. Primary quartz remains relatively unweathered.

The processes or reactions that produce those products may be thought of as desilication and alumination of primary minerals, since the reactions result in a net loss of silica relative to alumina (Jackson 1965a). Jackson (p. 16) identified three stages of desilication: "(a) mild desilication and alumination into phyllosilicate intergrades and allophane, (b) intermediate desilication (kaolinization), and (c) intensive desilication (laterization)." The products of mild and intermediate desilication in Idaho batholith soils are reflected in the clay mineralogy of batholith soils (Clayton 1974). The results of these soil processes will be discussed in a later section of this paper.

Weathering reactions and weathering products were studied below the soil in bedrock. This soil-bedrock boundary is easy to recognize in most instances, but is diffuse and poorly defined in weathering class 7 rock. The criterion for calling such material bedrock is the generally well-preserved fabric of interlocking mineral grains that give the appearance of granitic rock. This mineral grain accordance is not observed in soil peds in overlying C horizons, probably because of biotic and climatic (freeze-thaw) disturbances. Class 7 rock may also occur in gouge zones where less weathered adjacent rock is clearly below the lowest soil horizon. In other weathering classes, the soil-bedrock interface may be diffuse, but is readily recognized by the difference in structure, fabric, mechanical strength, and degree of oxidation.

A variety of techniques, including macroscopic (hand specimen) descriptions, thin section descriptions, chemical analysis, and x-ray analysis of pulverized rock samples were used to document chemical weathering. The important mineralogical differences between the weathering classes follow.

BIOTITE

Progressing from weathering class 1 to 6, biotite progresses from compact black grains to brown and golden grains having fringed edges. Biotites are absent in class 7 rock. No visible iron oxide stains emanate from biotites in class 1 rock. Iron oxide staining reaches a maximum in class 4 rock. In thin section, fresh biotites range in color from various browns to green and are pleochroic (fig. 7). They are strongly birefringent. Upon weathering, biotite grains have fringed edges, and iron oxide stains adjacent minerals (fig. 8). Upon further weathering, we have observed complete replacement of biotite by sericite (fig. 9) or possibly an iron-rich smectite-iddingsite (fig. 10).

This is in contrast to a study of ademellite weathering in the White Mountains, Calif., in which Marchand (1974) found little chemical weathering of biotite prior to grus formation. He attributes this to a drier climate, little evidence of chemical weathering, and a more pronounced physical weathering environment (Marchard, personal communication, 1976). In the Idaho batholith, we have never found grus formation without obvious chemical alteration.

Biotites in rock weathering classes 5 and 6 dye a violet to pink color when samples are treated with p-aminophenol. The purple-blue colors are characteristic of montmorillonoids and various shades of pink are characteristic of kaolin minerals, according to Dodd (1955). According to our interpretation, the presence of either color indicates argillation of the primary biotite without specifying the mineral because of the notable absence of smectites in batholith soils (Clayton 1974). However, this does not preclude the presence of smectites on weathered biotite grains.

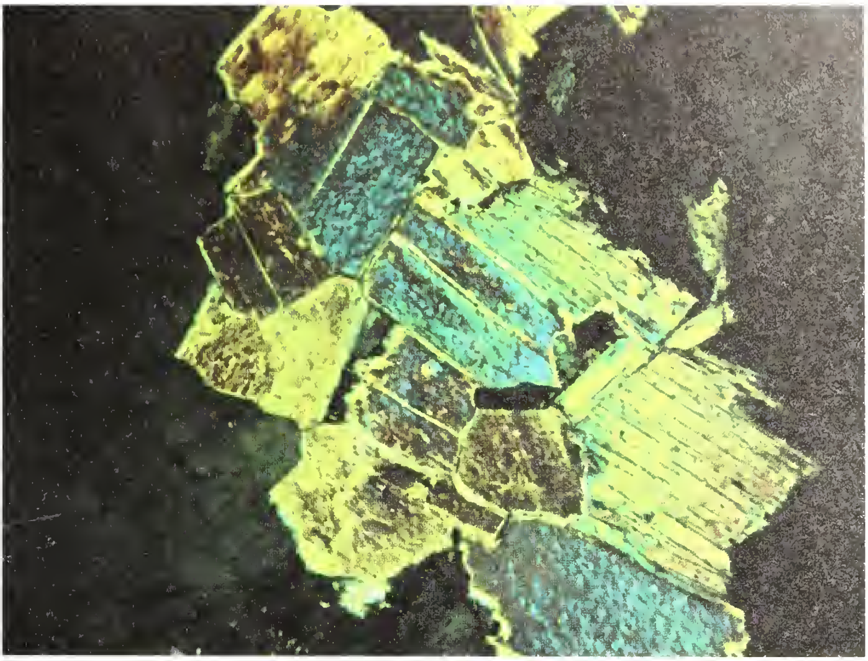

Figure 7.--Relatively fresh biotite grains exhibiting some weathering along grain boundaries (fringed edges). There is no apparent iron oxide staining of adjacent mineral grains. Magnification = 40X; nicols crossed. Transitional from weathering class 1 to 2.

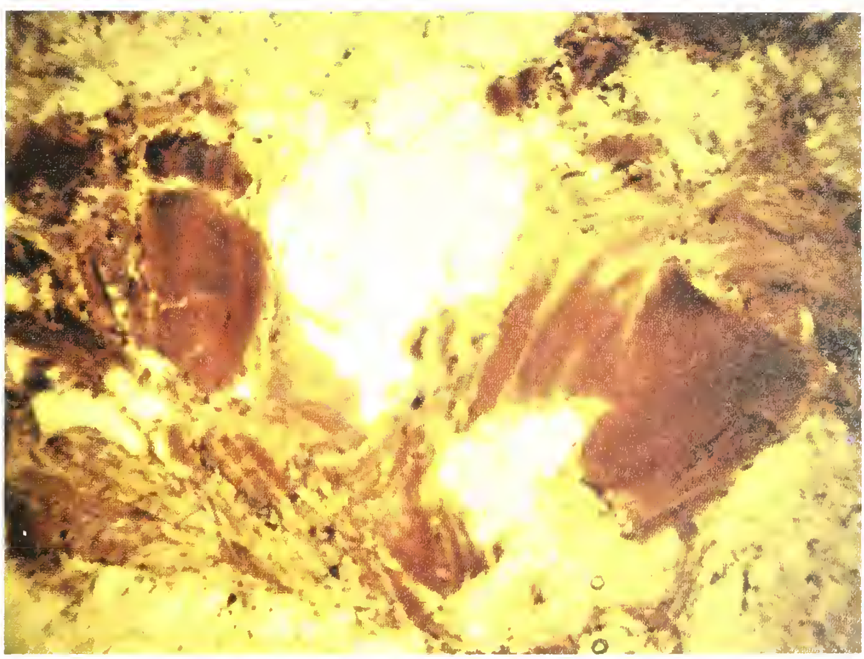

Figure 8.--Weathered biotite grains exhibiting iron oxide staining of adjacent feldspars and partial alteration of biotite to iddingsite and smectite. Magnification = 40X; plane light.

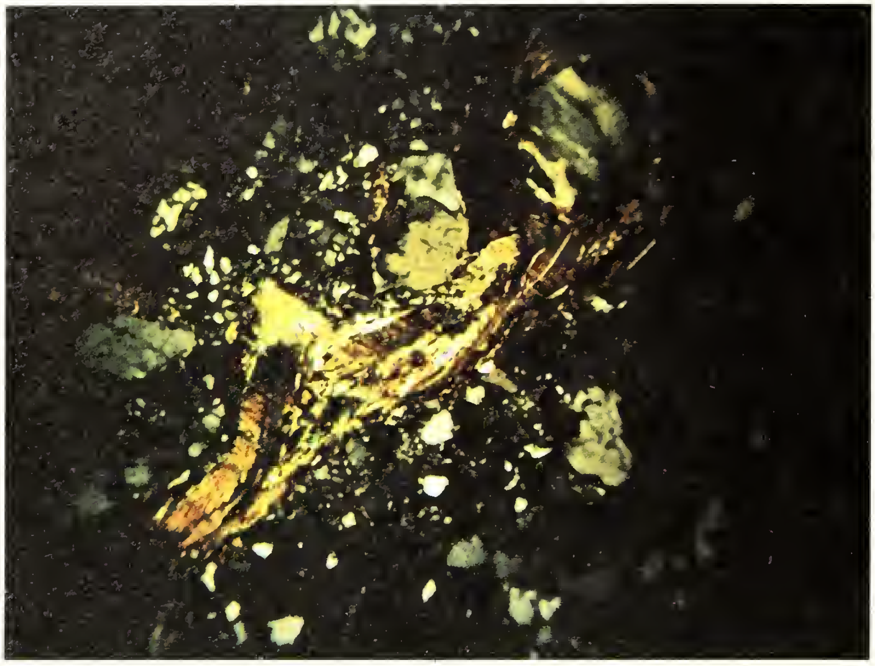

Figure 9.--Relatively complete sericite alteration of biotite in a rock weathering class 5. Magnification = 40X; nicols crossed.

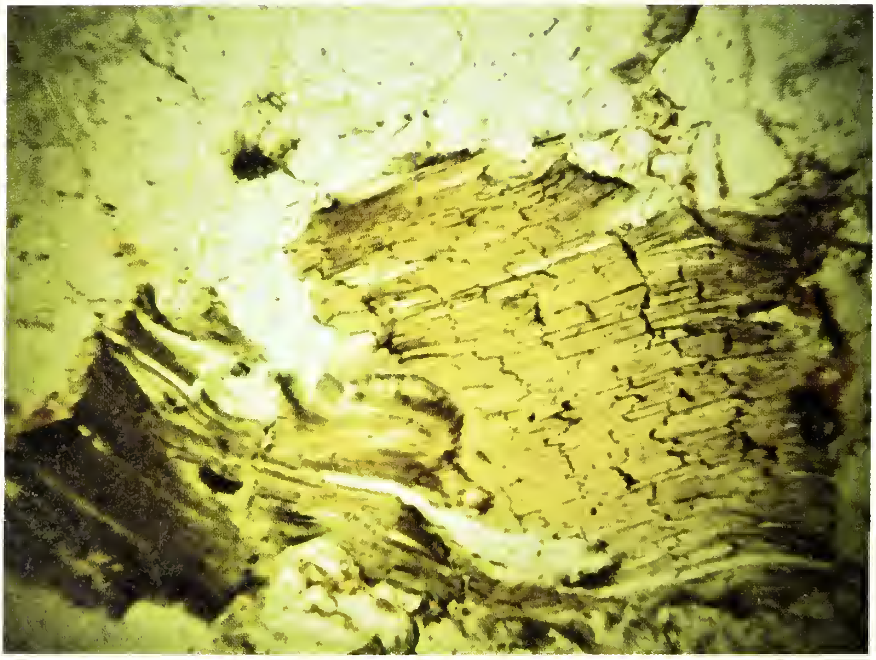

Figure 10.--Iron rich smectite-iddingsite alteration after biotite. Note oriented clay and iron oxide stains in microfractures of adjacent feldspar grain. Magnification = 100X; plane light. In a rock of weathering class 6.

In his summary of European and American research of biotite alteration in soil, Lucas (1962) described the principal transformations as either: (1) biotite to vermiculite and montmorillonite (both trioctahedral) by way of intermediate interstratified clays, or (2) biotite to chlorite, vermiculite and montmorillonite (all dioctahedral). Although all of these clay minerals have been reported in soils of the Idaho batholith (Clayton 1974), their presence is minor compared to kaolinite and illite. The dominance of kaolinite and illite would be expected on the basis of climate (Barshad 1966; Birkeland and Janda 1971; Clayton 1974).

FELDSPAR

It is often difficult to distinguish plagioclase feldspars from potassium feldspars in hand specimen. For this reason, the macroscopic descriptions of the feldspar weathering sequence combines all feldspars. Very fresh feldspars from weathering class 1 rock appear clear and transluscent. With increasing weathering (classes 2 through 4), feldspars become more opaque. Feldspars dye blue with p-aminophenol along their grain boundaries in weathering class 3 and darken to violet and pink as weathering increases. In weathering classes 5 and 6, the opaque appearance of the mineral grains changes to a powdery appearance and mechanical strength is greatly diminished.

One can work out the details of feldspar weathering by examining specimens in thin section. Most plagioclase crystals are in the range of Ab70 to Ab50, as determined by extinction angles of carsbad-albite twins (Kerr 1959). Plagioclase grains obviously are more argillized at lower weathering classes (3 and 4) than potassium feldspars. Kaolinite (or possibly halloysite) commonly forms pseudomorphs after plagioclase, distinguished by low relief and weak birefringence (fig. 11). Plagioclases in the Idaho batholith are commonly zoned and differential weathering of the more calcic core is frequently observed (fig. 12).

Sericitic mica (or perhaps illite) occurs as both an intergranular and a fine surficial replacement of plagioclase feldspar in thin section. The transition from plagioclase to illite is difficult to prove because sericitic mica is invariably present in the parent rock. Wilson (1975) points out that this transition is likely in confined saprolites because potassium is not removed by leaching.

Potassium feldspar argillation was not pronounced in weathering classes 1-3. In contrast, rather complete argillation of orthoclase was observed in higher weathering classes (fig. 13a, 13b, and 14). In places, orthoclase grains have extreme microbrecciation and partial argillation surrounded by a groundmass of primary quartz, orthoclase, and kaolinite. Large fractures are filled with chalcedony, suggesting hydrothermal water may have occupied the shear zone (fig. 15). Such extreme microbrecciation may result from strain associated with a localized shear zone, a common occurrence in the Idaho batholith.

Microcline is the common potassium feldspar in a few plutons within the Idaho batholith. Figures 16 and 17 show fresh and slightly weathered microclines from the Sawtooth Mountains, in the south-central part of the Idaho batholith. The minerals appear to be more susceptible to weathering along stress fractures.

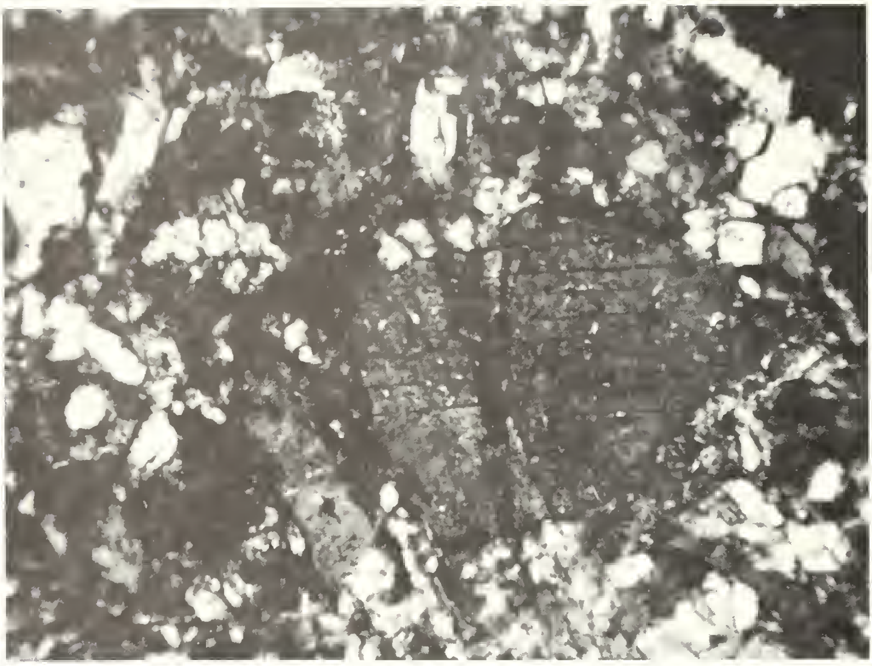

Figure 11.--Kaolinite pseudomorph after plagioclase showing relict twinning. Groundmass is highly fractured quartz, orthoclase, and altered biotite. Magnification = 40X; nicols crossed. Weathering class 5.

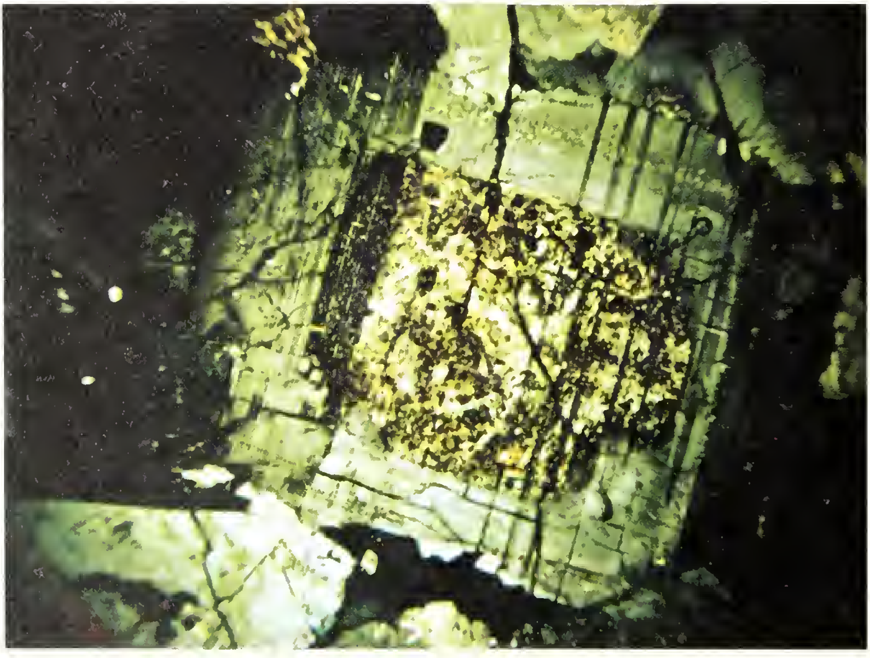

Figure 12.--Preferential weathering of the more calcic core of a plagioclase feldspar to kaolinite. Note relict twinning in the clay. Magnification = 40X; crossed nicols. Weathering class 4.

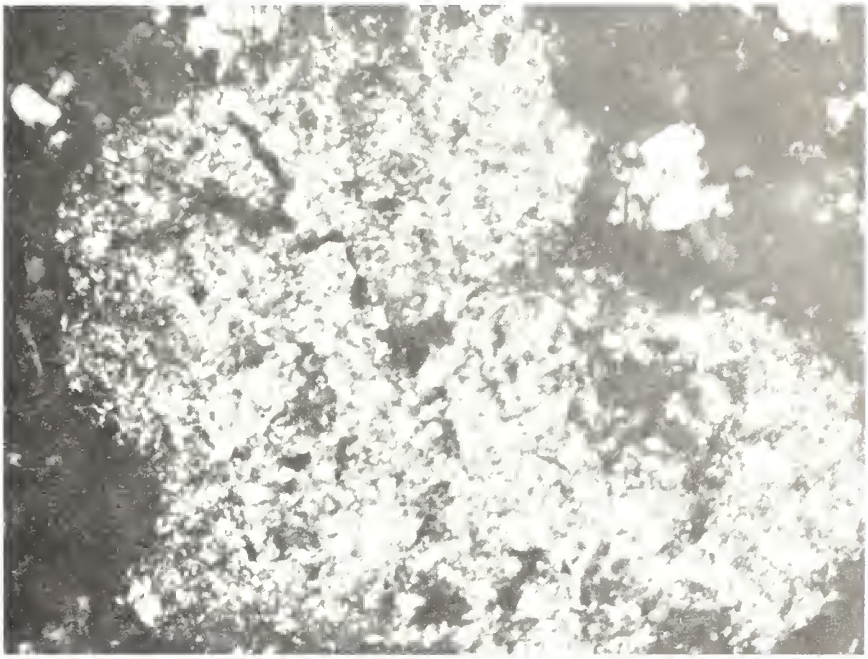

Figure 13a.--Complete argillation of a K-feldspar to kaolinite, an iron-rich smectite (?) and a venilet of iddingsite or iron oxide. Magnification = 100X; nicols crossed. Weathering class 6.

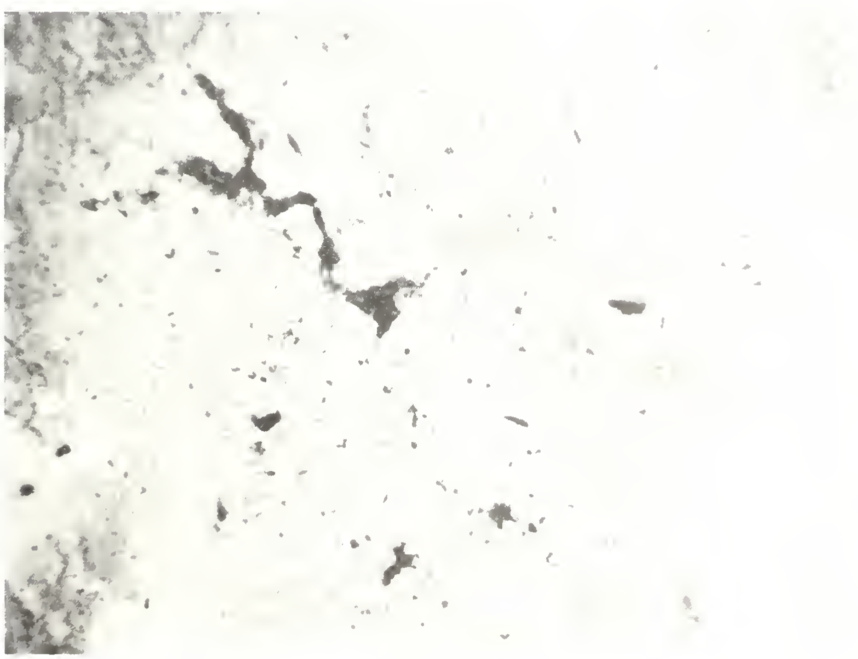

Figure 13b.--Same as figure 13a; plane light.

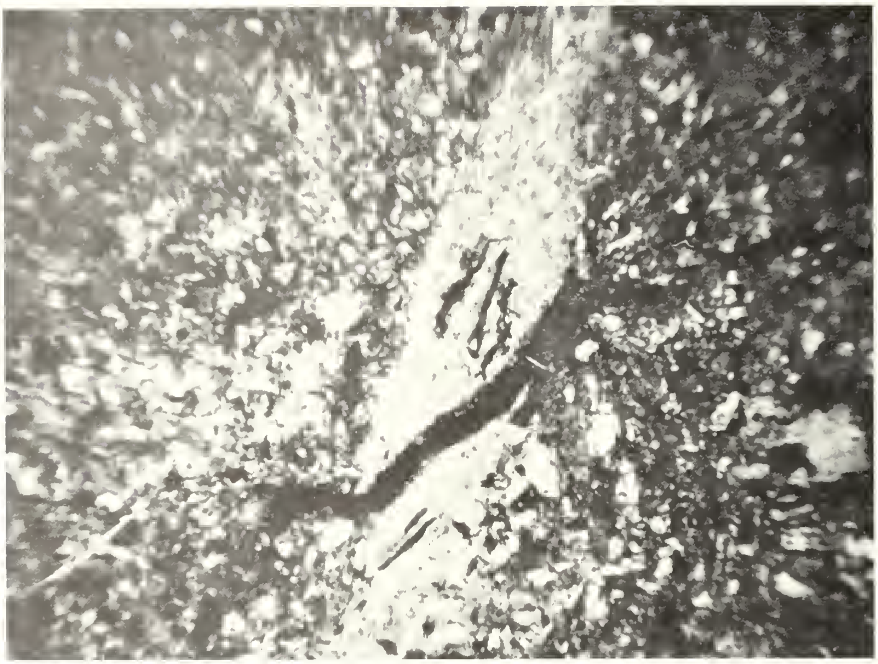

Figure 14.--A sericitized pseudomorph after orthoclase containing kaolinite, secondary mica, and iron oxide. Magnification = 40X; nicols crossed. Weathering class 5.

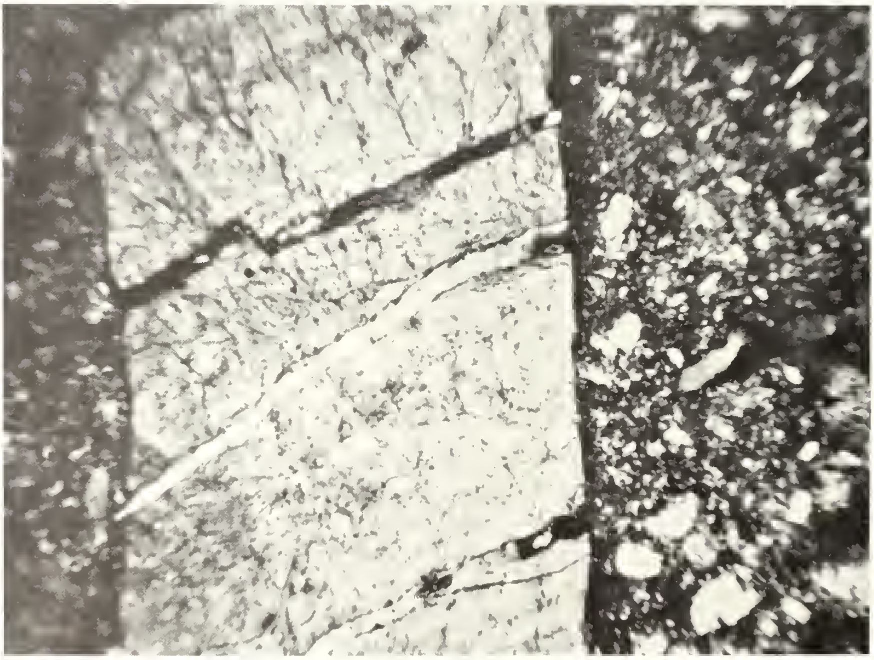

Figure 15.--A highly microbrecciated k-feldspar surrounded by a groundmass of primary quartz, orthoclase, and kaolinite. The large fractures are filled with chalcedony. Magnification = 40X; nicols crossed. Weathering class 5.

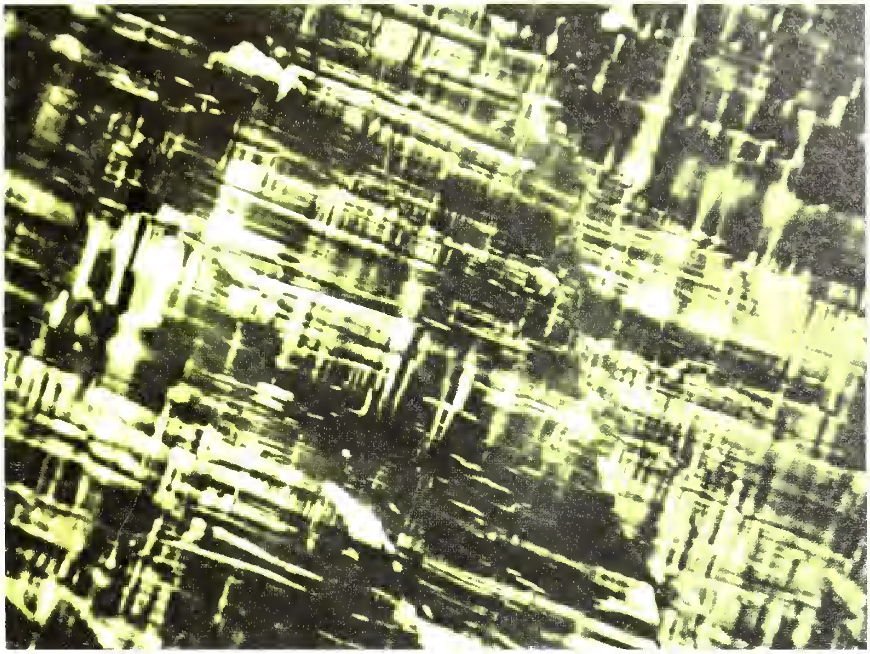

Figure 16.--Rather fresh microline exhibiting stress fracturing, but no chemical alteration. Magnification = 100X; nicols crossed. Weathering class 1.

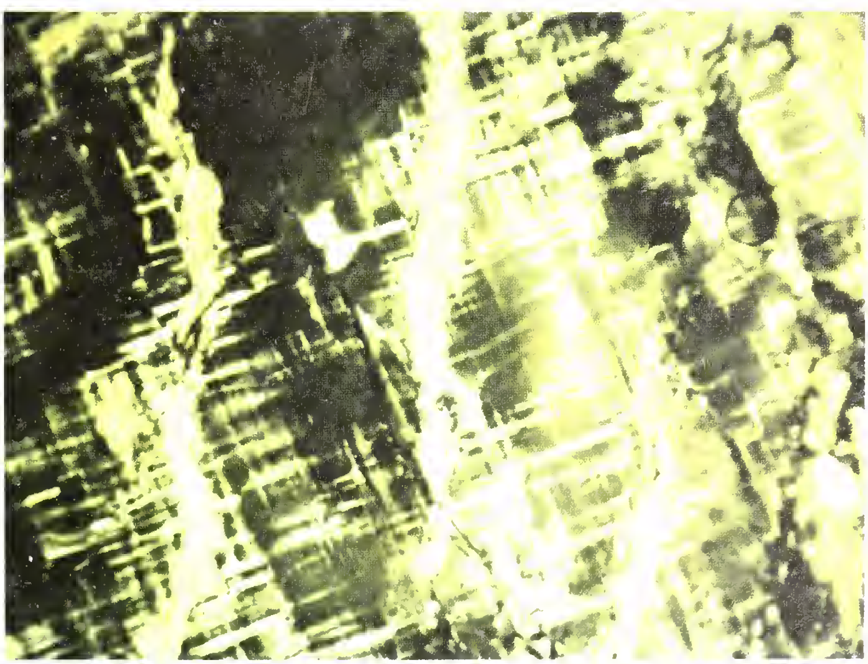

Figure 17.--Microcline crystal showing incipient alteration along stress fractures. Magnification = 100X; crossed nicols. Weathering class 3.

QUARTZ

Alterations in quartz grains appear to be mainly mechanical, at least through weathering class 6. This may be due in part to the lack of obvious secondary mineral replacement of quartz. Highly fractured quartz grains are common in shear zones. Most quartz grains have an undulose extinction pattern, presumably strain induced during magmatic cooling (fig. 18).

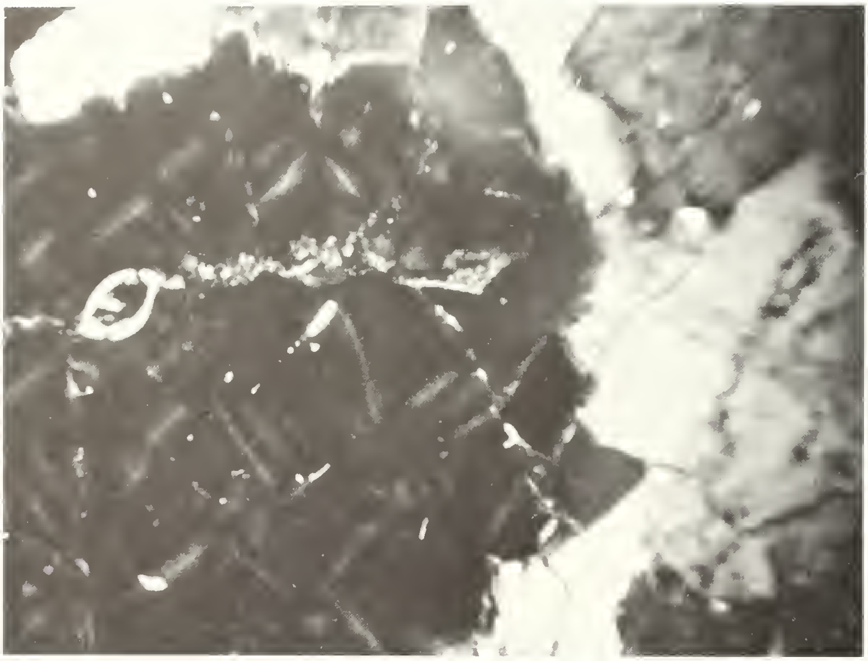

Figure 18.--Dark area at left is a large quartz grain near extinction (no transmission of polarized light). Light lines are strain induced and bound domains of crystal lattice deformation. This results in an undular extinction pattern when the microscope stage is rotated. Magnification = 100X; crossed nicols.

X-ray diffraction patterns from selected powdered rock samples show decreases in peak height and increases in peak diffuseness with increasing weathering (fig. 19). These changes are most apparent for plagioclase peaks from 3.16 to 3.26 Å (040 reflection), 3.66 Å (13$\bar{1}$), 3.78 Å (111) and at 4.04 Å (20$\bar{1}$). In general, the diffuseness (broad base, lack of symmetry) of the peaks is a better indicator of mineral weathering than peak height.

Slight changes in mineralogy of rocks of various weathering classes sometimes cause less distinct diffraction peaks, or the complete absence of a peak. For example, the 020 orthoclase reflection at 6.46 Å is absent in the class 1 sample (fig. 19), yet the $\bar{2}$01 reflection at 4.26 Å is present in all three samples.

Weathering class 1 rocks have a distinct 10 Å biotite peak. In contrast, class 7 rock has a 10 Å mica peak of equal intensity, but thin section observation indicates this to be entirely secondary mica, probably illite. Interestingly, rocks of intermediate weathering (classes 3 through 5) generally have less intense 10 Å peaks than either the fresh or highly weathered samples.

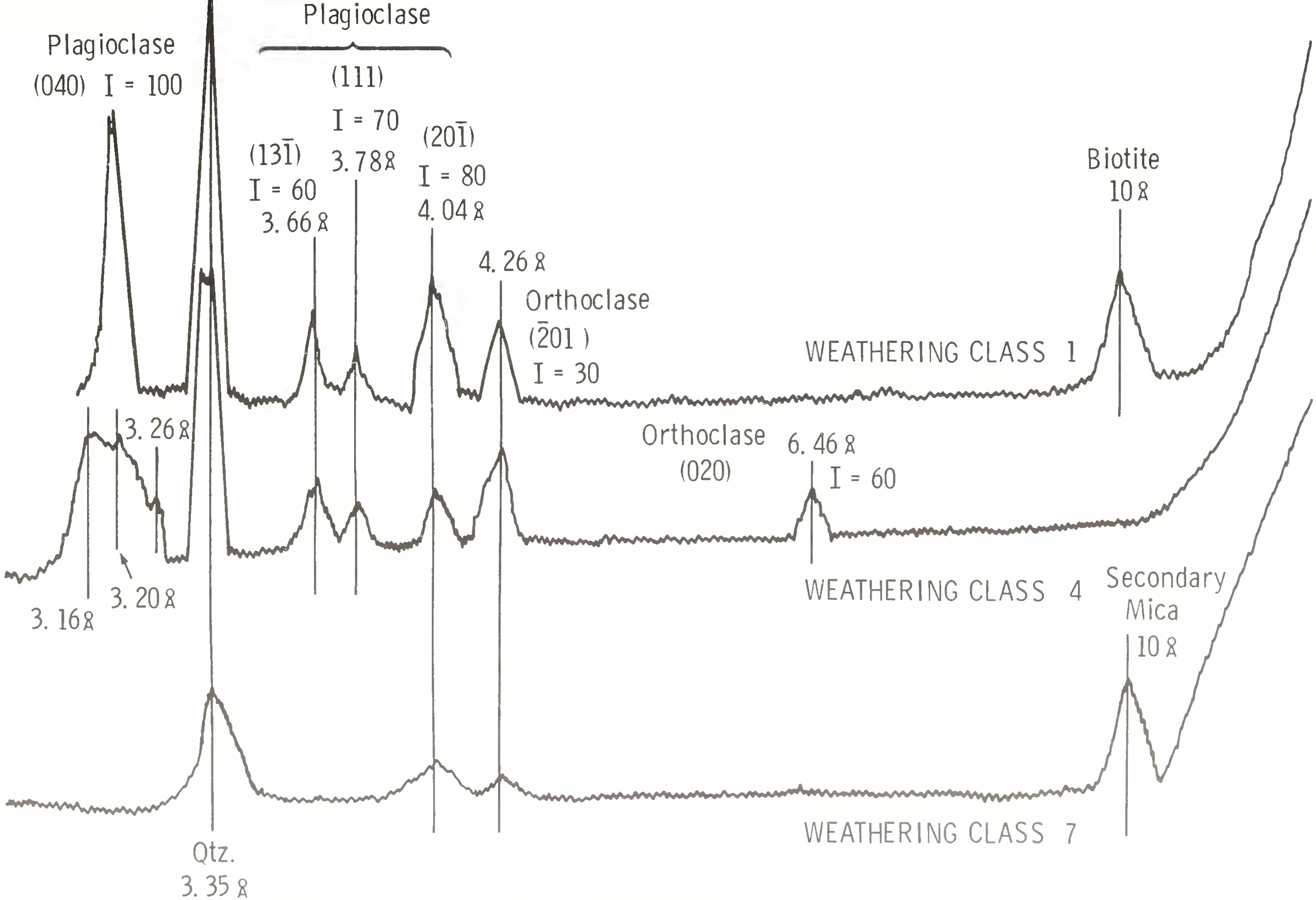

Figure 19.--X-ray diffractograms of powered bedrock showing differences in plagioclase feldspar peaks with increasing weathering. Note: d-spacing of crystal reflections are marked in angstroms. Miller indices of probable reflecting crystal faces are provided where appropriate. I-values are relative intensities; I-100 is the most intense peak.

Quartz peaks remain essentially unchanged through weathering class 5. There was some indication that the intensity of the quartz peak at 3.34 Å diminishes in weathering classes 6 and 7.

The only weathering products that appeared present in powdered rock diffraction patterns are 10 Å micas, although some mixed-layer clays are present in class 6 rock. We separated the clay fraction from soil and class 7 rock samples for x-ray examination, and class 7 rock are presented by Clayton (1974).

Weathering Progression the Idaho Batholith

Because of our studies of chemical, mineralogical, and physical changes brought about by physical and chemical weathering, we can propose typical weathering stages for batholithic rocks in Idaho. We feel that such a weathering progression would be similar for other batholiths with similar climates--winter freezing and summer dry periods. Such areas are extensive throughout the western United States and Canada.

Stage 1: Removal of overburden material.--Though not truly a weathering process, the rock expansion resulting from unloading associated with overburden removal forms small fissures large enough for water entry and subsequent weathering. This stage corresponds to weathering class 1. No chemical or mineralogic change has occurred in the rock, and bulk density is typically greater than 2.6 g/cc.

Stage 2: Initial chemical and physical weathering.--This stage is characterized by hydrolysis of iron and magnesium in biotites, oxidation of ferrous iron to ferric iron, loss of potassium, and a gain in water. Hydrolysis of calcic plagioclases is moderate, and initial hydrolysis of alkali feldspars is mild, but evident. Interstitial fracturing is evident in hand specimens, but rock is not spalling nor producing grus. Bulk density ranges from 2.3 to 2.5 g/cc. Stage 2 weathering corresponds to weathering classes 2 and 3.

Stage 3: Intense physical, moderate chemical weathering.--Following stage 2 weathering, the rock is "primed" for accelerated weathering because of the numerous pathways for water entry provided by stage 2 weathering. Physical weathering by cyclic freezing and thawing, and cyclic wetting and drying break down the weathered bedrock to grus. Processes of physical weathering have reached their apex in stage 3 weathering with appearance of thick spall rinds and ultimate grus formation. Spalling and formation of grus by granular disintegration requires that a rock surface be exposed to the atmosphere (Carroll 1970; Ollier 1969). Continued hydrolysis, oxidation and hydration of primary minerals, forms considerable quantities of clay minerals, allophane, and iron oxides. In hand specimen, feldspars appear powdery and stain blue and violet or pink with p-aminophenol. Clay pseudomorphs after feldspars, and micas and iddingsite alteration products, are commonly observed in thin section. Plagioclase feldspar x-ray peaks become diffuse and lose their intensity. Biotite peaks may disappear and secondary mica peaks show up in powdered rock x-rays. Stage 3 weathering involves the progression from weathering class 4 to weathering class 6, and bulk densities decrease ranging from 2.1 to 2.3 g/cc.

Stage 4: Intense chemical weathering.--Rocks that complete stage 3 weathering, but remain buried within or below a soil profile, are subject to intense *in situ* chemical weathering. In stage 4 weathering, the original rock fabric is preserved, but, with the exception of quartz, most other minerals have been altered to secondary weathering products. The result is a rock matrix of clays, crystalline and amorphous oxides of iron, silicon and aluminum, and embedded quartz grains. The rock is subject to plastic deformation when wet. Stage 4 weathering results in bedrock of weathering class 7. Bulk densitites of class 7 rock range from 1.8 to 2.1 g/cc.

HYDROTHERMAL ALTERATION OF BEDROCK AND SLOPE STABILITY

The geographical occurrence of bedrock of weathering class 7 was of considerable nterest to us because of the strong correlation between class 7 bedrock and mass ailures in the batholith (Megahan 1973; Day and Megahan 1976) Along the Middle Fork f the Payette River drainage in the southwestern Idaho batholith, 18 percent of 186 ass failures studied were associated with class 7 bedrock (unpublished data on file t the Intermountain Station's research laboratory, Boise). A generous estimate of he areal occurrence of class 7 rock in this drainage is 3 or 4 percent. In the learwater Forest in the northern Idaho batholith, Day and Megahan (1976) assigned 53 ercent of 441 slides to a weathering class similar to class 7 of this study.

X-ray diffraction studies of the clay fraction from selected sites containing lass 7 rock in the southern Idaho batholith show the expected clay mineral suites kaolinite-halloysite and illite) in some cases and unexpected mineral assemblages dominantly smectites and interstratified mixed-layer clays) in others. Clayton 1974) interpreted the smectite formation as a result of high silica potential and igh base status associated with impeded drainage. Corroborative evidence of impeded rainage includes the common association of lepidocrocite with the smectite clays, and olar silica:alumina ratios twice the value found in freely drained soils with the aolin-illite mineralogy.

Further field investigations revealed several sites fitting the field criteria or class 7 bedrock, but obviously occurring in gouge zones or localized shear zones. he clay alteration products often occur in seams within these zones, bounded by ighly fractured (but chemically and mineralogically less altered) rock. These observa- ions indicate that the clay is not a product of *in situ* weathering.

Boise State University, in cooperation with the Intermountain Station's research aboratory at Boise, investigated the mineralogical properties of several class 7 rock ites located in the southern Idaho batholith (Nichols and Nichols 1976)[4]. These ites included both shear zone locations with clay seams and locations where the rgillized material appeared to result from in situ weathering. Sampling sites for hese studies were concentrated in two areas, the Middle Fork of the Payette River in alley County, Idaho, and the North Fork of the Boise River in Boise County, Idaho.

The Payette River sites are located along a major linear structural trend (Day nd others 1974). Hot springs are located along this linear feature, often at the ntersection of it and secondary linear features. According to Nichols and Nichols 1976), deep fracture zones associated with these lineaments provide the "significant lumbing systems for the deep convective circulation which is responsible for the ydrothermal alteration" (p. 13).

In contrast, the linear structural trends that control the course of the North ork of the Boise River are more local in nature, and the width of the fractured rock nd associated alteration is much less extensive.

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[4]Nichols, Clayton R., and Ann M. Nichols. 1976. Mineralogical investigation of ydrothermally altered plutonic rocks of the southwestern Idaho batholith. Final Rep., oop. Agreement 12-11-204-113. Unpubl. Ms. on file, Intermt. For. and Range Exp. Stn., oise, Idaho, 30 p.

The alteration products observed along the Payette River are dominantly kaolinite and illite with minor mixed-layer illite-montmorillonite. Individual grains of quartz, orthoclase, and plagioclase "float" in a groundmass of kaolinite and illite. Orthoclase crystals are clouded and sericitized along fracture faces. Plagioclases have undergone extensive internal alteration to kaolinite and sericite.

The alteration products observed along the Boise River differ markedly from those observed along the Payette River. The dominant alteration products at the Boise River sites are montmorillonite and clinoptilolite, a zeolite similar to heulandite. The zeolite occurs in veinlets or fracture fillings in areas of more intense alteration associated with extreme microbrecciation. Plagioclase feldspars exhibit zoned internal alteration to sericite (probably montmorillonite). Orthoclase crystals are fractured, but otherwise appear fresh. Biotites are generally fresh with minor alteration to montmorillonite at grain boundaries.

Nichols and Nichols (see footnote 4) consider the kaolinite-illite alteration along the Payette River to be more vigorous than the montmorillonite-clinoptilolite alteration along the Boise River. Their judgement is based upon the greater desilication and relative alumina enrichment and cation removal required for kaolin formation. In turn, they relate this more vigorous alteration to the more extensive fracture system associated with the large regional linear features along the Middle Fork of the Payette and the attendant hot water leaching.

Valley width is greater and the relief ratio is smaller along the Payette than along the Boise. Gentler sideslopes and deeper soils result, probably because of more extensive surface weathering. The resultant clay mineralogy is that expected from surface weathering and presumed to be in equilbrium with present-day pedogenic processes.

The above is not in disagreement with the hypothesis that the more extensive fracture system associated with a major lineament has resulted in more vigorous alteration. This does leave open the hypothesis that hydrothermal alteration in combination with subsequent surface weathering produced the kaolinite-illite suite.

The mass erosion problems associated with weathering class 7 bedrock appear to be related to poor soil drainage and loss of strength along the contact between class 7 rock and the adjacent less-altered rock. The high clay content of class 7 rock and lack of distinct jointing and fracturing result in a lower hydraulic conductivity than that in the overlying sandy soils and adjacent weathered bedrock. Most failures occur during spring snowmelt or long-duration rainstorms. The overlying soils become saturated after large volumes of water percolate to and are detained by the clay zone. Often the failure plane of the mass failure is at or directly adjacent to the clay zone.

Debris avalanches and rotational slumps are the common mass failures associated with class 7 rock, occurring in a 60:40 ratio, respectively (data on file at the Intermountain Station's research laboratory, at Boise). We feel that orientation of the clay seam or zone with respect to the slope is important. The hazard increases as dip angles increase and where the strike parallels the sideslope.

We have not observed inherent differences in slope stability associated with mineralogy. One might expect montmorillonitic clay zones to be less stable than kaolinitic zones because of the shrink-swell capabilities of montmortillonite. The more pervasive alteration of the kaolinite-illite clay zones along the Middle Fork of the Payette River may have masked any differences in erodibility associated with the clay mineralogy.

SOIL GENESIS AND MORPHOLOGY

Soils formed on slopes in the Idaho batholith are characteristically shallow to oderately deep, coarse textured, and either gravelly or stony. Typical soil profile ave A and oxidized C horizons underlain by weathered granitic bedrock. Coarse loamy and and coarse sandy loam textures predominate. In residual soils, B horizons are ncommon on steep sideslopes. On gently sloping upland slopes that could be remnants f old erosion surfaces (see footnote 2), erosion rates are probably relatively low nd cambic B horizons often are present. Argillic B horizons are weak and generally estricted to soils formed on alluvium or colluvium, and to slope gradients of less han 10 percent.

The common orders and suborders of soils that have been mapped in the Idaho atholith are (nomenclature follows Soil Survey Staff 1975):

Entisols

- Orthents
- Psamments
- Fluvents

Inceptisols

- Umbrepts
- Ochrepts
- Andepts

Alfisols

- Boralfs
- Xeralfs

Mollisols

- Borolls
- Xerolls

Important family differentiae in the Idaho batholith include the following classes:

(1) Particle size: sandy, sandy-skeletal, loamy-skeletal, coarse loamy, medial

(2) Mineralogy: mixed

(3) Temperature: frigid, mesic

(4) Depth: shallow

(5) Bedrock contact: lithic, paralithic

Of the state factors of soil formation presented by Jenny (1941), topography ppears to most strongly influence soil morphology on slopes in the Idaho batholith. rosion rates on the steeper slopes are sufficiently high that other state factors, uch as climate, biota, and parent material, are not allowed maximal expression for edogenic development over time. The topgraphic limitations result in "soils without ormal profiles" (Jenny 1941). "This condition," he wrote, "is related to slope in uch a manner that the greater the slope--as compared with the 'normal' slope--

the fewer the number of characteristic profile features and the more feeble their design. Soils of mountainous regions furnish the most conspicuous examples of this type."

We can better understand the reasons for these weakly developed soils by examining annual erosion and sedimentation rates from undisturbed, forested sites in the Idaho batholith. (Annual erosion and sedimentation rates expressed in cubic yards or tons per square mile per year have been adjusted to cm/1,000 years to clarify the following discussion.)

Megahan and Kidd (1972a) report annual erosion figures from erosion plot data ranging from 0.16 to 0.67 cm/1,000 years, for 2 years and 13 stations, in the west central batholith. We have erosion plot data (on file in the research laboratory at Boise) ranging from 0.02 to 5 cm/1,000 years, with a mean erosion loss of 0.86 cm/1,000 years. These figures are based on data collected over 4 years on 25 stations in the southwestern Idaho batholith. Much higher erosion has been observed (several cm per storm) during high intensity summer rainstorms or during rapid snowmelt (Megahan and Kidd 1972b).

In a study of sediment yields from small watersheds in the southern Idaho batholith Megahan (1975) published figures on probable annual sedimentation rates indicating a 50 percent chance occurrence of 0.39 cm/1,000 years. A 10 percent chance occurrence event would yield a sedimentation rate of 1.5 cm/1,000 years. Sedimentation rates at these study sites, however, average less than one-half the erosion rates in the batholith. This discrepancy may be due in part to aggradation during valley building above the dams where the sediment is collected.

In any case, erosional losses exceeding 1 cm/1,000 years are to be expected in the batholith under present climatic stresses.

Marchand (1971) points out that major alluviations in valleys of the western cordillera (and hence erosional events on mountain slopes) occur during glacial rather than interglacial periods, even in unglaciated basins. Therefore, our short-term records of erosion rates are minimums when considered over a period of several tens of thousands of years.

These erosion rates take on considerable significance when time for pedogenic processes is considered. Birkeland (1974) indicated that the time required for steady state expression (maximal development) of A horizons ranges from 100 to 1,000 years, for cambic horizons several thousand to 100,000 years, and for argillic horizons, is greater than several hundred thousand years. Time for initial expression of these horizons would be one or two orders of magnitude less. It is readily apparent that the time required for even modal development of B horizons is simply not available on slopes losing 1 cm or more of soil each 1,000 years, when the total soil depth averages 50 to 60 cm.

Sampling and Laboratory Studies

Descriptive soil morphology and a variety of laboratory analyses were performed to meet the original study objectives of relating soil properties to bedrock weathering and fracturing characteristics and to geomorphological considerations. Sampling procedures assured variety in bedrock characteristics and geographic and climatic diversity. The necessity of sampling roadcut faces tended to bias sampling to ridgelin

Several soil properties reflecting degree of soil profile development were examined. These properties were considered from the standpoint of topographic and climatic variables and slope stability (and thus age). Properties included: horizonation, color, amount of clay and clay mineralogy, free silica and alumina in the clay fraction, free iron oxides, water retention, percent organic matter, heavy mineral grain morphology, and pH. We were particularly interested in relating degree of soil development to weathering and fracture density characteristics of the underlying parent rock. Where topographic influences (steep slopes) are not the limiting factor in soil development, rates of bedrock weathering are limiting. These rates are also a function of climate and biota. Of secondary interest was the influence of topographic and climatic variables on soil genesis and bedrock weathering and alteration.

Soil Characteristics and Rock Weathering Relationships

The degree of horizonation and the distinctness of soil horizons are related to weathering classes. For example, two of three sites underlain by class 1 (hard, unweathered) rock have no soil formation except an accumulation of surface litter (01 horizon). The third site has a shallow A1 horizon and a transitional AC horizon containing 60 percent stone and rock. Bedrock at this site is highly fractured and the greater soil development (the presence of both an A1 and AC horizon) is likely attributable to the high density of fractures.

In contrast, soils overlying bedrock of weathering classes 4 through 6 generally have A11 and A12 horizons and two or more C horizons transitional to the bedrock. Soils usually exhibit paralithic contacts with bedrock.

The boundary between the C horizon and bedrock becomes less distinct as the weathering class of the underlying bedrock increases. Hence, soils overlying weathering class 1 or 2 bedrock have a much more distinct C-R horizon boundary than soils overlying bedrock of weathering class 5 or 6; however, as the weathering class of underlying bedrock increases, A-B, A-C, and B-C horizon boundaries often are clearer and more distinct.

Clarity and distinction of horizon boundaries is a function of time available for morphologic expression of pedogenic processes. Hence, we intuitively feel that soil formation has progressed over a longer period of time on well-weathered parent materials. Further, this explains why soils formed on more highly weathered bedrock have progressed further morphogically than soils of similar age on unweathered bedrock.

X-ray diffraction studies were carried out on the <2 μm fraction of all soils sampled and on selected bedrock samples ground to a fine powder. Clay mineralogy of the soils was found to be principally influenced by climate (and microclimate) (Clayton 1974). The 1:1 minerals (kaolinite and halloysite) predominate in well-drained soils of moderate or better development.

X-ray samples of bedrock indicate a variety of secondary minerals in weathering classes 6 and 7; however, only weathering class 7 samples gave sharp, distinct kaolin peaks. Sericitic mica (illite?), present as a fine surficial and intergranular alteration product of plagioclase feldspar and mixed-layer montmorillonite-illite are the common secondary silicates found in weathering class 6.

Although illite commonly appears in the clay fraction of soils (Clayton 1974) the mixed-layer clays are notably absent. We must presume that these mixed-layer clays are transformed in the soil, either to allophane, kaolin clays or to illite.

Free silica and alumina were determined in the clay fraction of soils. Stratifying the soils into dominantly kaolinitic clays versus dominantly montmorillonitic clays showed a marked difference in amounts of silica and alumina. Kaolinite clays average 1.6 times more silica and three times more alumina than montmorillonite clays (Clayton 1974); however, the molar silica/alumina ratio is 1.8 times greater in the montmorillonite clays relative to kaolinite clays. The larger ratio was explained by the greater solubility of silica relative to alumina and by the fact that in well-drained soils insufficient silica potential exists for montmorillonite formation.

We adjusted the percent of free silica and alumina in the clay fraction by bulk density and clay content of the soil to express the sum of the two in grams per cubic centimeter of soil. There is a generally increasing trend in free silica plus alumina per unit volume of soil, ranging from 0.002 g/cc in soils formed on weathering class 1 to 0.005 g/cc in soils formed on weathering class 7 rock. This increase is attributable to the slightly higher clay content of soils formed on rocks in higher weathering classes, particularly class 7.

Soil color and free iron oxide content of soils were analyzed to see if any relationships exist with degree of bedrock weathering. Zinke and Colwell (1963) found color to be the most obvious field characteristic indicative of the degree of weathering in upland soils in California. They found that color progresses from grayish brown to reddish brown with increasing soil development. This color progression is related to a progressive increase in free Fe_2O_3 content in the soil.

Birkeland and Shroba (1974) used the hue of Cox and B horizons to indicate intensity of oxidation (and hence age) in dating Quaternary soils. The hue progression is from 2.5Y or 5Y to 10YR to 7.5YR with time. This hue change is a progression from yellow to red and again reflects increasing iron oxide content in the C horizon.

In all of our soils the dominant hue in the oxidized C horizon is 10YR. Taking colors in weathered granitic rock is very subjective, however, because of the salt and peppery appearance due to the coarse grain size and differing colors of the constituent minerals. We did find a trend of increasing chroma from 1 or 2 to 4 with increasing weathering class of parent rock for soils of similar petrology. This relationship did not hold up universally in the soils we studied. As explained, free Fe_2O_3 content and iron oxide staining of bedrock appears to be related to the amount of biotite in the rock, not just to the degree of weathering.

Heavy mineral grain etching has been used to indicate degree of soil development or stage of weathering (Birkeland 1974). We separated heavy minerals in the fine sand and very fine sand fractions of selected soils for microscopic observation. Amphiboles and pyroxenes are almost completely absent in Idaho batholith rocks sampled; so we have no useful data on heavy mineral etching.

The pH of the soils studied shows a decreasing trend with increasing bedrock weathering class (fig. 20). We omitted A horizons from this analysis to diminish the confounding effect of organic matter. Decreasing pH with increasing weathering class can be expected due to the greater hydrolysis and subsequent leaching of released bases. Seventy percent of the variance in subhorizon pH can be explained by bedrock weathering class in this linear regression. The standard error of estimate is 0.29 pH units.

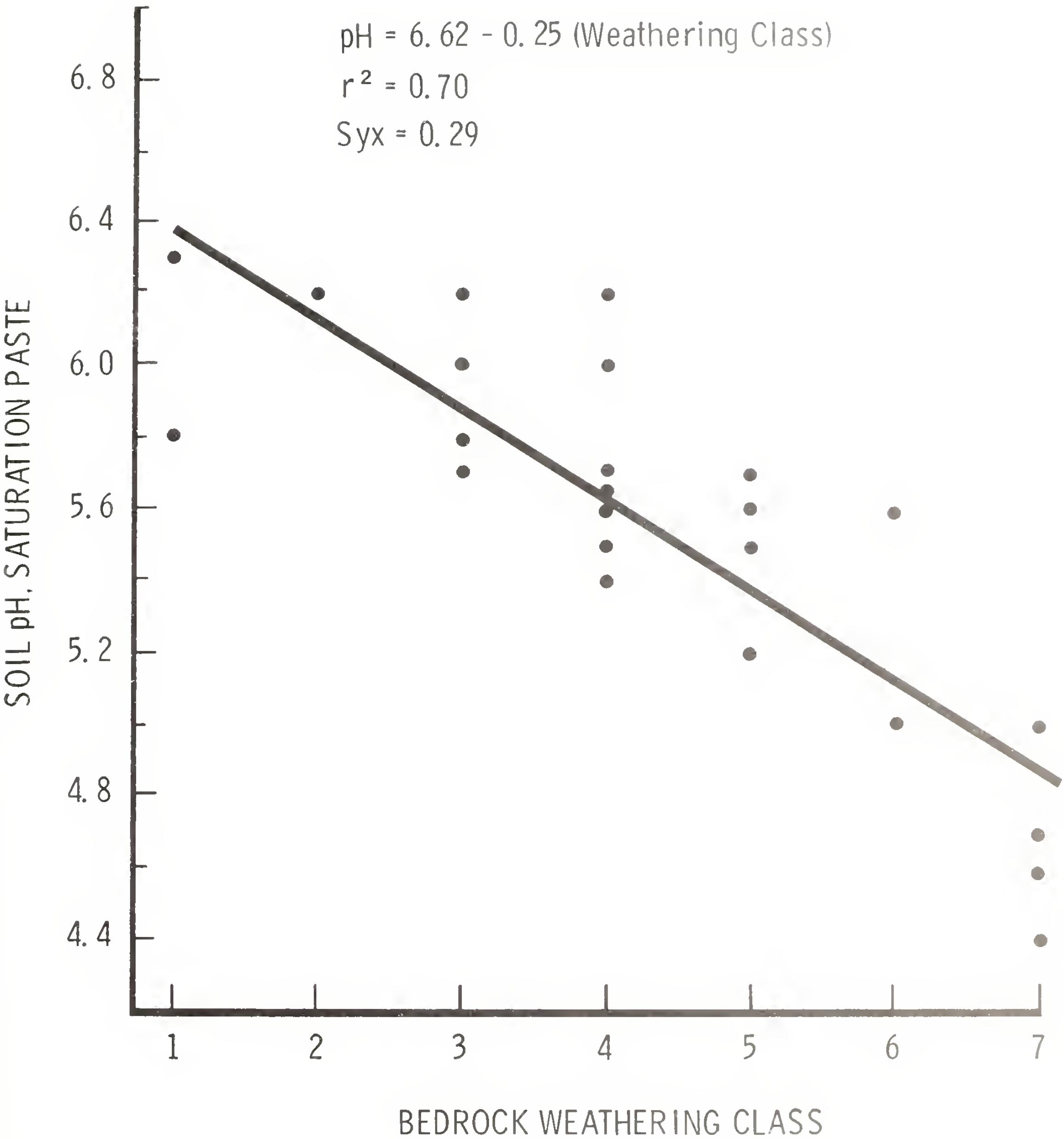

Figure 20.--pH of B or C horizons as a function of bedrock weathering class.

SUMMARY

The degree of weathering of batholithic rocks, as described by a previously devised seven-class system, appears to reasonably reflect physical and mineralogic changes in bedrock. We have described these changes as observed in hand specimen, thin section, and through chemical, physical, and x-ray analyses of fresh and weathered bedrock from the Idaho batholith.

After the unloading associated with overburden erosion, initial hydrolysis and oxidation of biotites provide sufficient pathways for water entry, a necessary precursor to physical weathering. Rocks at or near the ground surface then progressively weather to grus, with physical weathering processes dominating chemical weathering. At depth, chemical weathering processes assume greater importance and the products of chemical weathering are better preserved. Biotites commonly weather to a degraded mica, then to a smectite-iddingsite product, and eventually to a 10 Å clay probably illite. Sericitic weathering products and, ultimately, kaolinization of feldspars are common.

Relationships between soil morphologic properties and bedrock weathering in the Idaho batholith are for the most part obscured by climatic and topographic influences, such as precipitation patterns, slope steepness, and internal soil drainage.

Slope steepness affects erosion rates and erosion strongly controls the time for pedogenic processes to differentiate soil horizons. Batholith soils are predominatly entisols, inceptisols, and weakly developed alfisols and mollisols, all reflecting lack of pedogenic development due to high erosion rates.

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Field Weathering Guide

The weathering classification of intrusive rocks pub-
hed previously by Clayton and Arnold (1972) has been used
ensively by land managers, primarily for relating bedrock
thering characteristics to slope stability. The research
orted in this paper has provided for minor refinement and
expansion of this classification to include relationships
ween rock strength and weathering classes. In addition,
weathering stages published in this paper are related to
thering classes, providing a conceptual framework for the
esis of the various classes of weathered granitic bedrock.

Weathering classes are recognized in the field by the
lowing criteria:

1. Change in rock color from that of the unweathered condition.

2. Mechanical strength of rock (how easily it can be broken manually)

3. Ease with which roots penetrate the rock matrix or fractures

4. How distinctly original jointing is preserved

5. The sound a rock hammer makes when striking the rock

6. Whether or not the rock is spalling (crumbling)

7. Whether or not the rock is plastic in nature when wet.

The above criteria should be used to identify the
lowing classes:

Class 1, Unweathered Rock.--Unweathered rock will ring from a hammer blow; cannot be dug by the point of a rock hammer; joint sets are the only visible fractures; no iron stains emanate from biotites; joint sets are distinct and angular; biotites are black and compact; feldspars appear to be clear and fresh.

Class 2, Very Weakly Weathered Rock.--Very weakly weathered rock is similar to class 1, except for visi iron stains that emanate from biotites; biotites may also appear to be "expanded" when viewed through a hand lens; feldspars may show some opacity; joint set are distinct and angular.

Class 3, Weakly Weathered Rock.--Weakly weathered roc gives a dull ring from a hammer blow; can be broken with moderate difficulty into "hand-sized" rocks by a hammer; feldspars are opaque and milky; no root penetration; joint sets are subangular.

Class 4, Moderately Weathered Rock.--Moderately weath rock may be weakly spalling. Except for the spall ri if present, rock cannot be broken by hand; no ring from hammer blow; feldspars are opaque and milky; bio usually have a golden yellow sheen; joint sets are in tinct and rounded to subangular.

Class 5, Moderately Well Weathered Rock.--Moderately well weathered rock will break into small fragments or sheets under moderate pressure from bare hands; usually spalling; root penetration is limited to fractures, unlike class 6 rock where roots penetrate through the rock matrix; joint sets are weakly visibl and rounded; feldspars are powdery; biotites have a light-golden sheen.

Class 6, Well-weathered Rock.--Well-weathered rock ca be broken into sand-sized particles (grus); usually it is so weathered that it is difficult to determine whether or not the rock is spalling; roots can penetrate between grains; only major joints are preserved and filled with grus; feldspars are powdery; biotites may appear as thin silver or white flakes.

Class 7, Very Well Weathered Rock.--Very well weather rock has feldspars that have weathered to clay mineral rock is plastic when wet; no resistance to roots.

The four stages of weathering of granitic rock that ar recognized in the Idaho batholith are based upon intensity type of weathering (predominantly physical or predominantly

cal). The following stages are related to weathering class
o decreases in bulk density and unconfined compressive
gth as described below:

tage 1: Removal of overburden material.--Though not truly a weathering process, the rock expansion resulting rom unloading associated with overburden removal forms nall fissures large enough for water entry and subsequent eathering. This stage corresponds to weathering class 1. here is no chemical or mineralogic change in the rock, nd bulk density is typically greater than 2.6 g/cc; unonfined compressive strength is greater than 14,000 psi.

tage 2: Initial chemical and physical weathering.--This tage is characterized by the hydrolysis of iron and magesium in biotites, the oxidation of ferrous iron to ferric ron, a loss of potassium, and a gain in water. Hydrolysis f calcic plagioclases is moderate and initial hydrolysis f alkali feldspars is mild, but evident. Interstitial racturing is evident in hand specimens, but rock is not palling nor producing grus. Bulk density is in the range .3 to 2.5 g/cc; unconfined compressive strength ranges rom 4,000 to 14,000 psi. Stage 2 weathering corresponds o weathering classes 2 and 3.

tage 3: Intense physical, moderate chemical weathering.--ollowing stage 2 weathering, the rock is "primed" for ccelerated weathering due to the numerous pathways for ater entry provided by stage 2 weathering. Physical eathering by cyclic freezing and thawing, and cyclic etting and drying break down the weathered bedrock to rus. Processes of physical weathering have reached their pex in stage 3 weathering with appearance of thick spall inds and ultimate grus formation. Continued hydrolysis, xidation, and hydration of primary minerals form considrable quantities of clay minerals, allophane, and iron xides. Stage 3 weathering involves the progression from eathering class 4 to weathering class 6. Bulk densities ecrease to the range 2.1 to 2.3 g/cc; unconfined compresive strength ranges from 1,000 to 4,000 psi.

Stage 4: Intense chemical weathering.--Rocks that comple stage 3 weathering but remain buried within or below a soil profile are subject to intense *in situ* chemical weat ering. In stage 4 weathering, the original rock fabric i preserved, but, with the exception of quartz, most other minerals have been altered to secondary weathering produc The result is a rock matrix of clays, crystalline and amorphous oxides of iron, silicon and aluminum, and embed quartz grains. The rock is subject to plastic deformatic when wet. Stage 4 weathering results in bedrock of weath ering class 7. Bulk densities of class 7 rock range from 1.8 to 2.1 g/cc; unconfined compressive strength is less than 2,000 psi.

Published as part of Research Paper INT-237, and as a refinement and expansion of the weathering classification in Clayton and Arnold (1972).

Clayton, James L., Walter F. Megahan, and Delon Hampton.
1979. Soil and bedrock properties: weathering and alteration products and processes in the Idaho batholith. USDA For. Serv. Res. Pap. INT-237, 35 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Weathering processes and products, hydrothermal alteration and soil genesis in the Idaho batholith are described. Stages of weathering are proposed and related to a previously published classification of rock weathering in the batholith. The relationships between weathering and hydrothermal alteration and hydrothermal alteration and various rock strength parameters are also described. Soil properities were not found to be strong related to bedrock weathering in the Idaho batholith.

KEYWORDS: Idaho batholith, rock weathering, hydrothermal alteration, soil formation, slope stability

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KEYWORDS: Idaho batholith, rock weathering, hydrothermal alteration, soil formation, slope stability

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 250 million acres, or 90 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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GROWTH CHARACTERISTICS OF PINYON-JUNIPER STANDS IN THE WESTERN GREAT BASIN

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GROWTH CHARACTERISTICS OF PINYON-JUNIPER STANDS IN THE WESTERN GREAT BASIN

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RESEARCH SUMMARY

Stem analyses in singleleaf pinyon (*Pinus monophylla*)-Utah juniper (*Juniperus osteosperma*) stands in Nevada and eastern California indicate that tree age does not directly affect either diameter or height growth rates. Diameter growth rates are governed primarily by competition, and height growth rates depend largely on genetic characterictics and approach to a site-dependent maximum height. Rates of stand basal area increment vary among stands, but tend to be constant with time within closed stands. Because of its constancy and direct relationship to productivity, stand basal area increment may provide a good index of site quality in closed stands. Total aboveground biomass accumulation rates tend to increase with time, even in older stands. In the absence of perturbations, biomass in pinyon-juniper stands would probably continue to accumulate at nearly constant or slightly increasing rates for several centuries.

CONTENTS

INTRODUCTION

A study of tree growth and stand development in pinyon-juniper (*Pinus monophylla-Juniperus osteosperma*) woodlands of the Great Basin was initiated in 1977. Meeuwig and Budy (1979)[1] measured, analyzed, and reported on three pinyon plots in the Sweetwater Mountains, 130 km (80 mi) south-southeast of Reno, Nevada. During the summer of 1978, five more plots were measured: three in the Paradise Range 190 km (120 mi) east-southeast of Reno, one in the Monitor Range 300 km (190 mi) east-southeast of Reno, and one more in the Sweetwater Mountains. These plots were located on firewood sale areas, but on sites with no evidence of recent cutting or other disturbance. Except for one plot in the Paradise Range, the plots were located in the oldest undisturbed stands that could be found in the sale areas. All five plots were predominately pinyon, but contained some juniper. Understory was sparse on all five plots.

METHODS

The procedures followed in 1978 were essentially the same as those of the previous year, except no trees were weighed. The plots were 30 m square. A crown map was prepared for each plot, showing locations of all trees taller than 1 dm.

All trees taller than 2 m were felled and their total height was measured with a tape. Stump height was about 15 cm unless limbs or other irregularities made it necessary to cut above or below this height. On all felled trees, stem sections were taken at the stump, at about 3 cm diameter on the dominant leader and at two intermediate points on the dominant stem. The ages of these sections were determined by annual ring count and height-age curves were plotted for each tree. These curves were extrapolated to ground level to estimate tree age, and interpolated to determine past height at any particular time.

Stump diameters outside bark (d.o.b.) were measured with a diameter tape. A few trees had more than one stem at stump height. Equivalent diameters of these were calculated by taking the square root of the sum of the squared diameters of the individual stems.

Total aboveground biomass, foliage mass, and mass of wood in stems and limbs larger than 3 inches (76 mm) diameter were calculated for each tree using regression equations developed from data obtained in another study (Miller, Budy, and Meeuwig, in preparation). These equations are defined in appendix A.

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[1]Meeuwig, Richard O., and Jerry D. Budy. 1979. Pinyon growth characteristics in the Sweetwater Mountains. USDA For. Serv. Res. Pap. INT-227, 26 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Past diameters of each stumpsection were determined by measuring ring widths (to the nearest 0.1 mm) along a radial that appeared to best represent diameter growth. Stump diameters outside bark (D_t) at any time (t) in the past was calculated by

$$D_t = (\text{d.o.b.})\ \Sigma ri_t / \Sigma ri_p$$

in which d.o.b. is present diameter outside bark, Σri_t is the sum of ring widths from the pith to time t, and Σri_p is the sum of all ring widths along the radial. If there was more than one stem at stump height, ring widths were measured on the largest stem and the calculated equivalent diameter was used for d.o.b.

Basal area and total aboveground biomass of each tree were calculated by decades from 1860 to 1970 and also for 1965 to 1975, using the calculated past diameters and interpolated heights as inputs to regression models described in appendix B.

Stand basal area and biomass per hectare from 1860 to 1978 were calculated by summing the values of the individual trees and dividing by plot area (0.09 ha).

RESULTS AND DISCUSSION

Elevation, slope, and aspect of the plots are listed in table 1. All eight plots are on skeletal soils derived from igneous parent material. Sweetwater plots S1, S2, and S3 were measured in 1977 and reported by Meeuwig and Budy (1979); and Sweetwater plot S4 was measured in 1978. Plots P1, P2, and P3 are in the Paradise Range near Gabbs, Nevada; and M1 is in House Canyon in the Monitor Range.

Except for plot P3, the stands sampled in 1978 were considerably older than the three sampled in 1977 (table 2). They apparently escaped the extensive cutting that took place in the Nevada woodlands during the latter half of the 19th century. Four plots showed no evidence of tree harvesting, other than some juniper-post cutting, even though they were surrounded by woodland that apparently had been cut over in the 19th century.

Table 1.--*Elevation, slope and aspect of the eight plots*

Plot	Elevation	Slope	Aspect
	m	*Percent*	
S1	2 200	5	N 80° E
S2	2 100	20	N 40° E
S3	2 300	15	S 60° E
S4	2 030	25	N 15° W
P1	2 060	5	N 6° W
P2	2 040	15	N 55° E
P3	2 190	5	N 85° E
M1	2 220	20	S 60° E

Table 2.--*Age distribution of trees taller than 2 m on the eight plots*

Age class	S1	S2	S3	S4	P1	P2	P3	M1
Years								
41-60	1	--	1	--	1	--	--	--
61-80	17	6	9	--	--	--	4	--
81-100	10	9	9	1	6	1	6	--
101-120	--	9	5	5	10	2	8	1
121-140	1	6	2	2	12	2	5	3
141-160	3	14	1	1	6	1	16	2
161-180	--	12	3	2	2	2	10	6
181-200	1	1	--	2	1	--	--	9
201-220	--	--	--	2	3	1	1	6
221-240	--	--	--	1	5	2	--	5
241-260	--	--	2	1	6	2	--	4
261-280	--	--	1	2	4	6	--	15
281-300	--	--	--	2	1	2	--	9
301-320	--	--	--	4	1	3	--	4
321-340	--	--	--	--	2	--	--	1
341-360	--	--	--	2	1	4	--	1
361-380	--	--	--	4	1	1	--	--
381-400	--	--	--	1	--	1	--	--
401-420	--	--	--	1	--	--	--	--
421-440	--	--	1	--	--	--	--	--
Total	33	57	34	33	62	30	50	66

The fifth plot (P3) was selected in a younger stand. Its age structure was nearly identical to that of plot S2 and similar to the other two Sweetwater plots measured in 1977.

On the basis of age structure, the eight plots can be divided into two groups: four relatively young and four relatively old. The four older plots have an all-age structure, but few young trees. The younger plots show a tendency toward all-age structure. Plot S3 is considered young even though it had four old trees that apparently had been left when it was cut over in the 19th century.

Canopy cover varied from 36 percent in plot S4 to 64 percent on plot S2 (table 3). Stand basal area ranged from 23.4 m^2/ha on plot S1 to 38.4 m^2/ha on plot S4. Stand basal area growth from 1966 through 1975 varied from 2.2 m^2/ha/decade on plot M1 to 5.3 m^2/ha/decade on plot S1.

Total aboveground biomass, wood mass, and foliage mass in metric tons per hectare on each plot, and the rate of total aboveground biomass accumulation are also presented in table 3. The figures for wood are based on the mass of ovendry wood (bark excluded) in stems and limbs larger than 76 mm (3 inches) diameter and provide an indication of the amount of cordwood. One cord contains about 1 metric ton of ovendry wood, not counting bark.

Crown maps and tree data for the five plots measured in 1978 are in appendix C and appendix D. For crown maps and tree data for plots measured in 1977, see Meeuwig and Budy (1979).

Height Growth

In general, the plots sampled in 1977 showed appreciable variation in rates of height growth among trees, even among dominants; but each tree grew in height at a fairly constant rate throughout most of its life. There was little indication that height growth slowed down as the trees aged. The plots sampled in 1978 showed even more variation in height growth rates among dominants, but few of the dominants have straight-line height growth curves (fig. 1 and 2). Some have the typical curve, exemplified by tree No. 48 on plot P1, in which height growth rate decreases as height increases. Some, like tree No. 43 on plot P1, grow rapidly at first and then slow down to a lower rate of height growth that is sustained for one or two centuries. Others have erratic rates of height growth that may, like that of tree No. 5 on plot S increase with time.

Table 3.--*Canopy cover, stand basal area, biomass, and growth rates on the eight plots*

	Plot							
	S1	S2	S3	S4	P1	P2	P3	M1
Canopy cover (%)	49	64	60	36	52	56	58	40
Stand basal area (m^2/ha)	23.4	35.4	34.8	38.4	33.0	32.1	29.9	29.1
Total aboveground biomass (MT/ha)	80	116	121	118	86	102	96	60
Wood (MT/ha)	30	47	54	55	33	42	35	19
Foliage (MT/ha)	13	15	14	10	10	13	13	9
Decadal growth (1966-1975)								
Stand basal area (m^2/ha/10 yrs)	5.3	3.6	3.8	2.5	2.7	2.7	3.4	2.2
Total aboveground biomass (MT/ha/10 yrs)	20.8	12.3	13.4	9.3	8.4	10.6	13.4	5.5

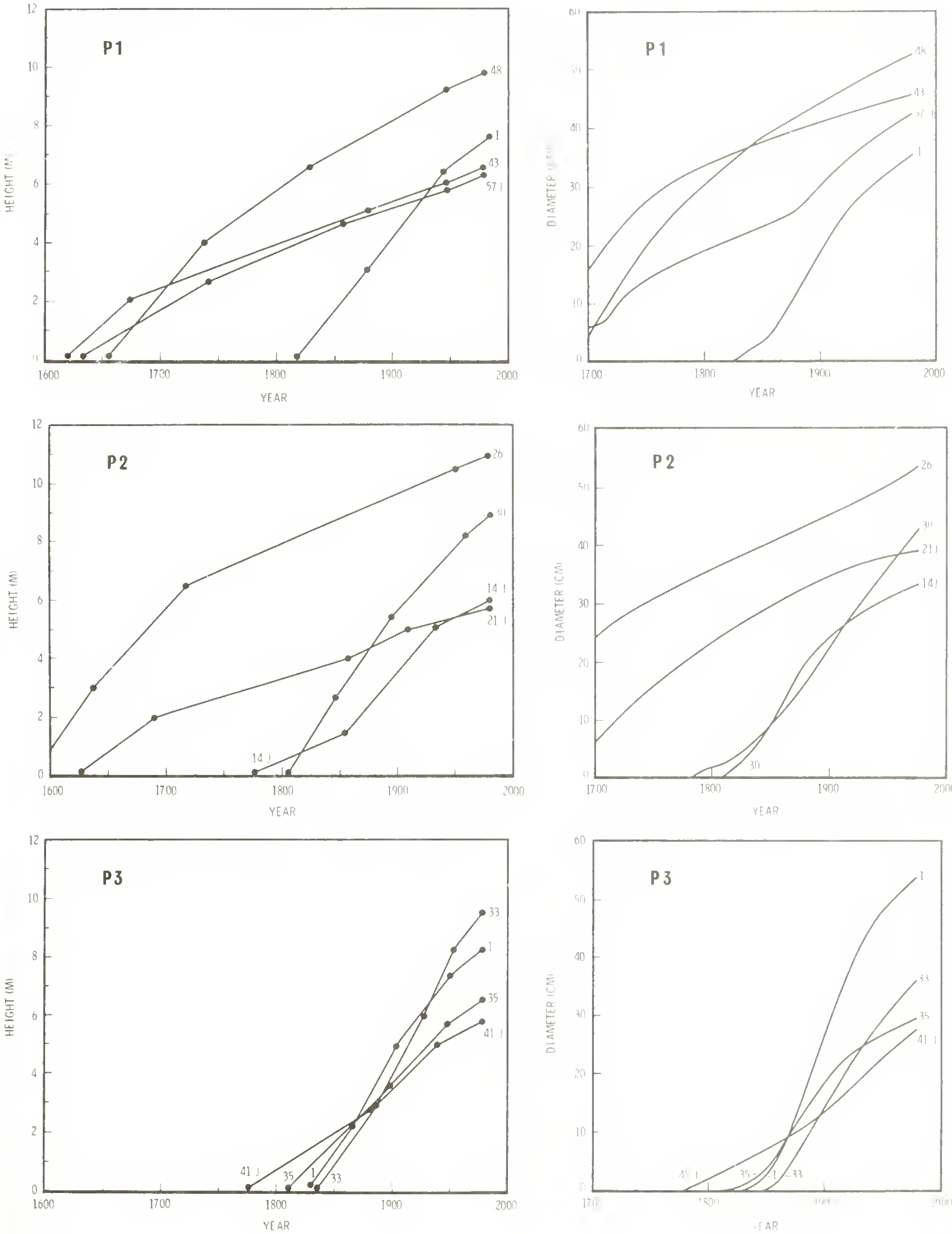

Figure 1.--Heights and stump-height diameters through time of selected trees on the plots in the Paradise Range. Selected trees include the oldest and tallest pinyons and the oldest and tallest junipers on each plot. Junipers are identified by the letter J.

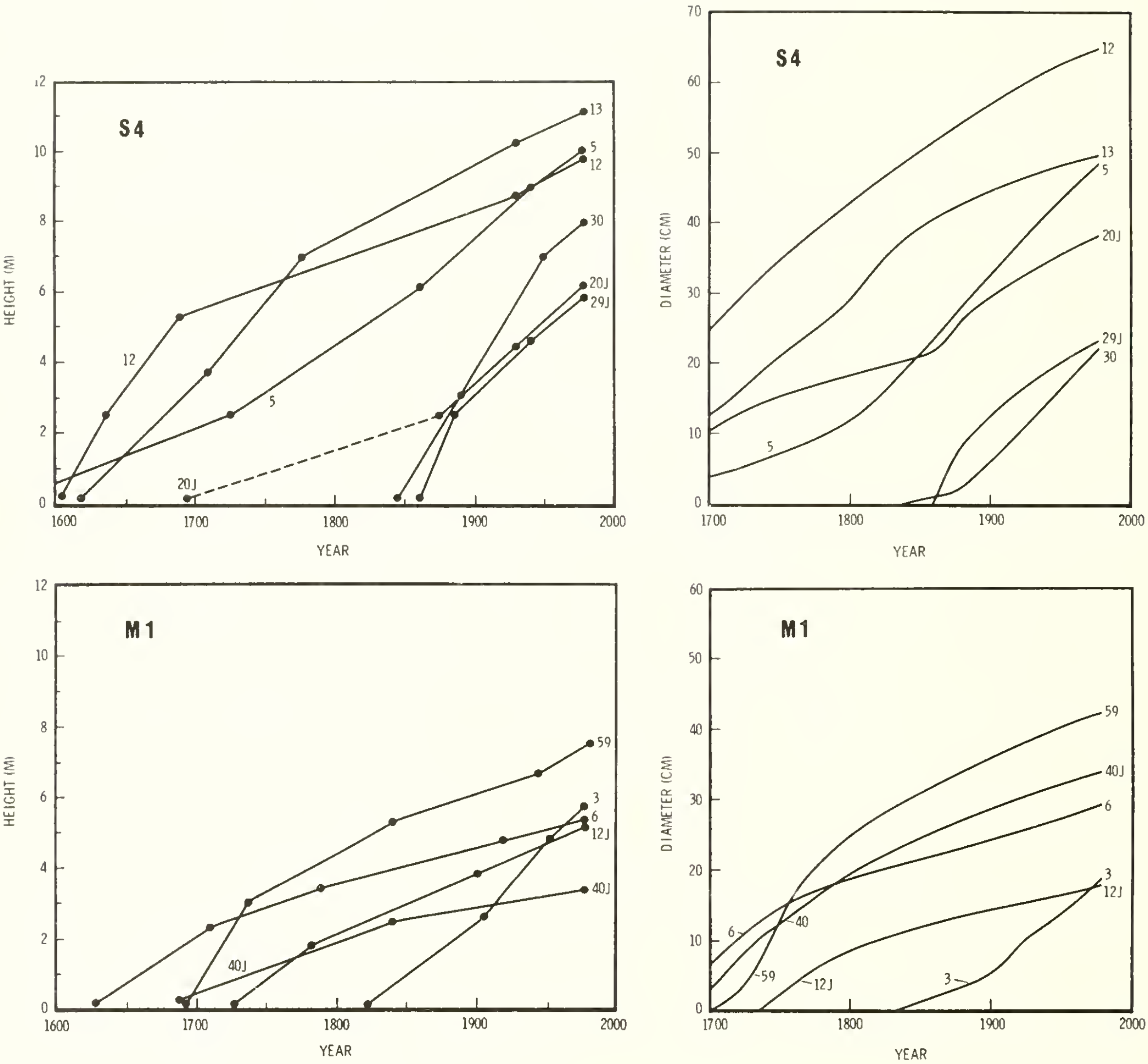

Figure 2.--Heights and stump-height diameters through time of selected trees on plots S4 and M1. Selected trees include the oldest and tallest pinyons and the oldest and tallest junipers on each plot. Junipers are identified by the letter J.

Junipers tended to have lower height growth rates than pinyon, but the two junipers in plot S4 show that juniper is capable of height growth rates comparable to pinyon. A post had been cut from the main stem of juniper No. 20 on this plot about 100 years ago and the present top is a lateral branch that took over. Its height growth rate equaled that of the much younger juniper No. 29.

Diameter Growth

As reported for the 1977 plots, diameter growth rates did not decrease appreciably with age in truly dominant trees. Reductions in diameter growth were caused by competition.

Tree No. 5 on plot S4 (fig. 2) is particulary interesting. In 1750, it was severely suppressed, about 200 years old, only 26 dm tall, only 8 cm diameter at stump height, and nearly dead. It was gradually released from suppression sometime between 1750 and 1800. It recovered slowly and eventually became one of the fastest growing dominants in the stand. What happened to the suppressing overstory back in the 18th century is unknown; there was no evidence of fire damage to the surviving trees. Similar, but less spectacular, responses to release have been observed in other pinyons.

Stand Basal Area

Radial growth of the individual trees on the plots fluctuated and generally decreased as competition increased, but, once the trees fully dominated, stand basal area growth on each plot became remarkably constant (fig. 3). The magnitude of this constant rate is determined by site quality.

Theoretically, there is a maximum basal area for each stand, and, as this maximum is approached, stand basal area increment decreases through reduction in growth of individual trees and through mortality. Other than seedlings and a few saplings, there has been no evident mortality on six of the plots in the past 100 years or so. The other two plots, S4 and P2, each had one pinyon snag. These trees were 220 and 280 years old at time of death and had stump diameters of 25 and 30 cm. Both had been growing very slowly for more than 100 years prior to death and apparently died because of localized overcrowding.

All of the sampled stands, even the oldest ones, are well below maximum basal area. There are no indications of impending reduction in basal area increment on any of the plots, except possibly two of the younger plots, S2 and P3.

The four younger plots all have higher basal area growth rates than the four older plots. This is because they are on better sites, not because young stands grow faster than old ones. All available evidence indicates that basal area growth rates on the older plots were no greater when they were young. It would be desirable to sample older stands on better sites, but none have been found so far. Virtually all accessible good sites must have been cut over in the 19th century.

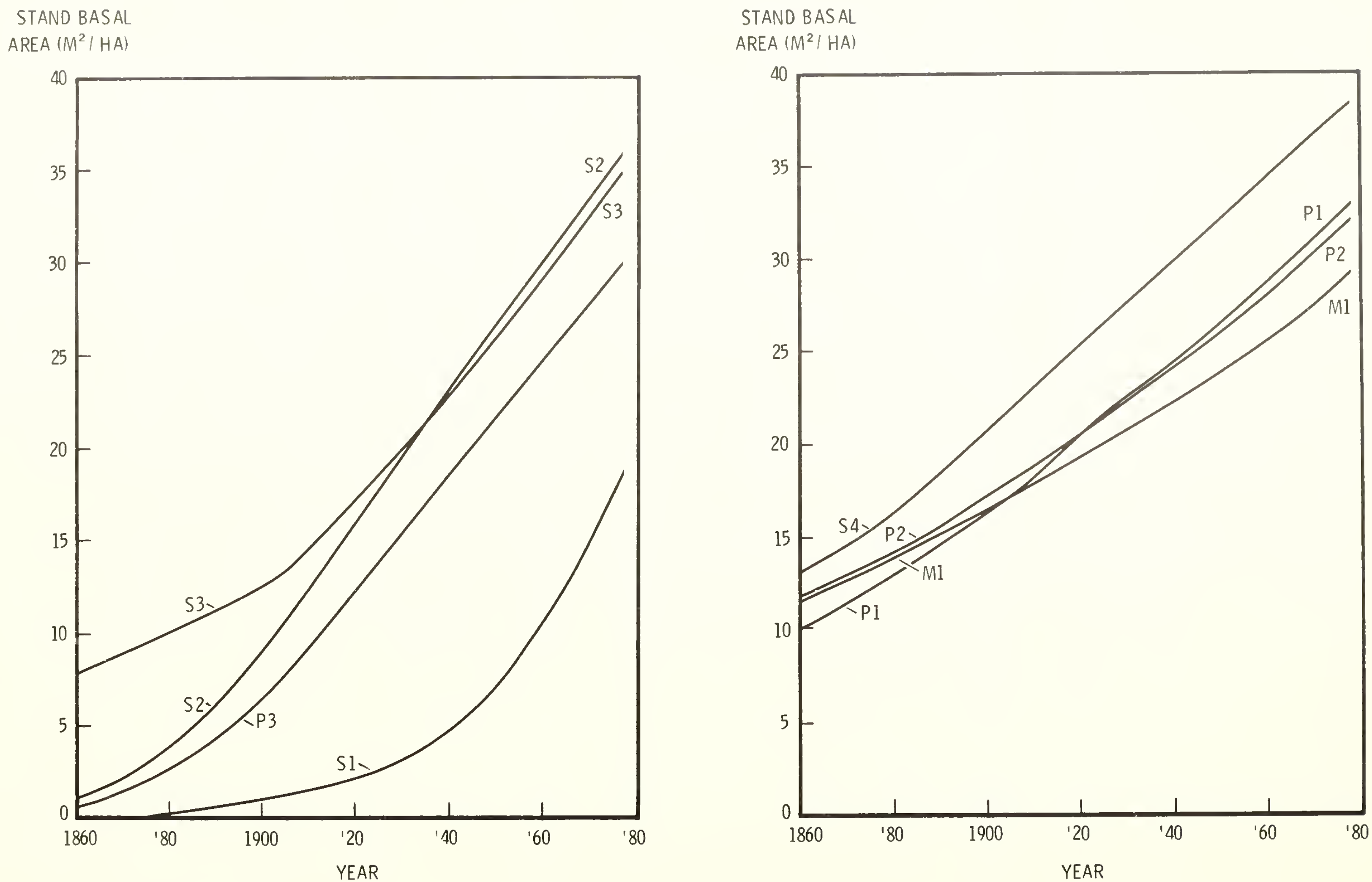

Figure 3.--Stand basal area on the eight plots from 1860 to 1978.

Total Aboveground Biomass

Stand biomass curves (fig. 4) follow patterns similar to basal area curves (fig. 3). e main differences are in the relative positions of the curves and the tendency for ntinuing increases in biomass growth rate after basal area increment has stabilized. e changes in relative positions of the curves are caused mainly by differences in tree ight characteristics. Plots P1, P2, and M1 are very close in basal area, but P2 has e tallest trees and M1 has the shortest; hence the separation of their biomass curves. e tendency for biomass growth rate to continue to increase after basal area increment ases to increase is due to continued height growth.

Regardless of age structure, all plots have been accumulating biomass at an creasing rate; however, biomass accumulation rates must eventually decline. On the sis of these plots, the time when that decline would begin is unpredictable. Mortaty must increase appreciably to bring about a decline in biomass accumulation rate.

CONCLUSIONS

The plots measured in 1977 were all in relatively young, pure pinyon, stands on od sites. Except for plot P3, the plots measured in 1978 were in older stands, conining some juniper, on poorer sites. Except for the determinations pertaining to ight growth, the conclusions of Meeuwig and Budy (1979) that were based on the 1977 ots, were supported by the data from the 1978 plots. More complex height growth tterns were found in the older stands. Competition may have a greater effect on ight growth rates than we surmised from the 1977 plot data. The existence of a te-dependent maximum height on the 1978 plots was also indicated. The trees on the 77 plots must have been well below maximum height for their sites because no indicaon of approach to maximum height was discernible.

Based on information obtained on the eight plots intensively measured so far, the llowing conclusions are offered:

1. Height growth rates depend on a complex combination of site quality, tree height, tree form, and competition. Height growth rates decrease as height approaches a site-dependent maximum. Height growth is usually slower in trees with a shrubby form and multiple leaders, which may be due to genetic make-up, insects, disease, approach to maximum height, or a combination of these. Competition affects height growth, but to a much lesser degree than it affects diameter growth.

2. Age has no direct effect on height growth rates. Some old trees have maintained constant height growth rates for the past century or more. Reduction in height growth rates in older trees is caused by approach to maximum height or, sometimes, by competition, insects or disease.

3. Diameter growth rates are regulated primarily by competition. The effects of site quality and genetic make-up on diameter growth of individual trees are obscured by competition and are probably much less important. As with height growth rates, diameter growth rates are not directly affected by age.

4. There are indications that, in the absence of competition, juniper is capable of more rapid diameter growth than pinyon and may be capable of more rapid height growth as well. However, junipers appear to be more sensitive to competition; they were dominated by pinyons on all five plots on which they occurred. Therefore, their true potentials could not be accurately evaluated.

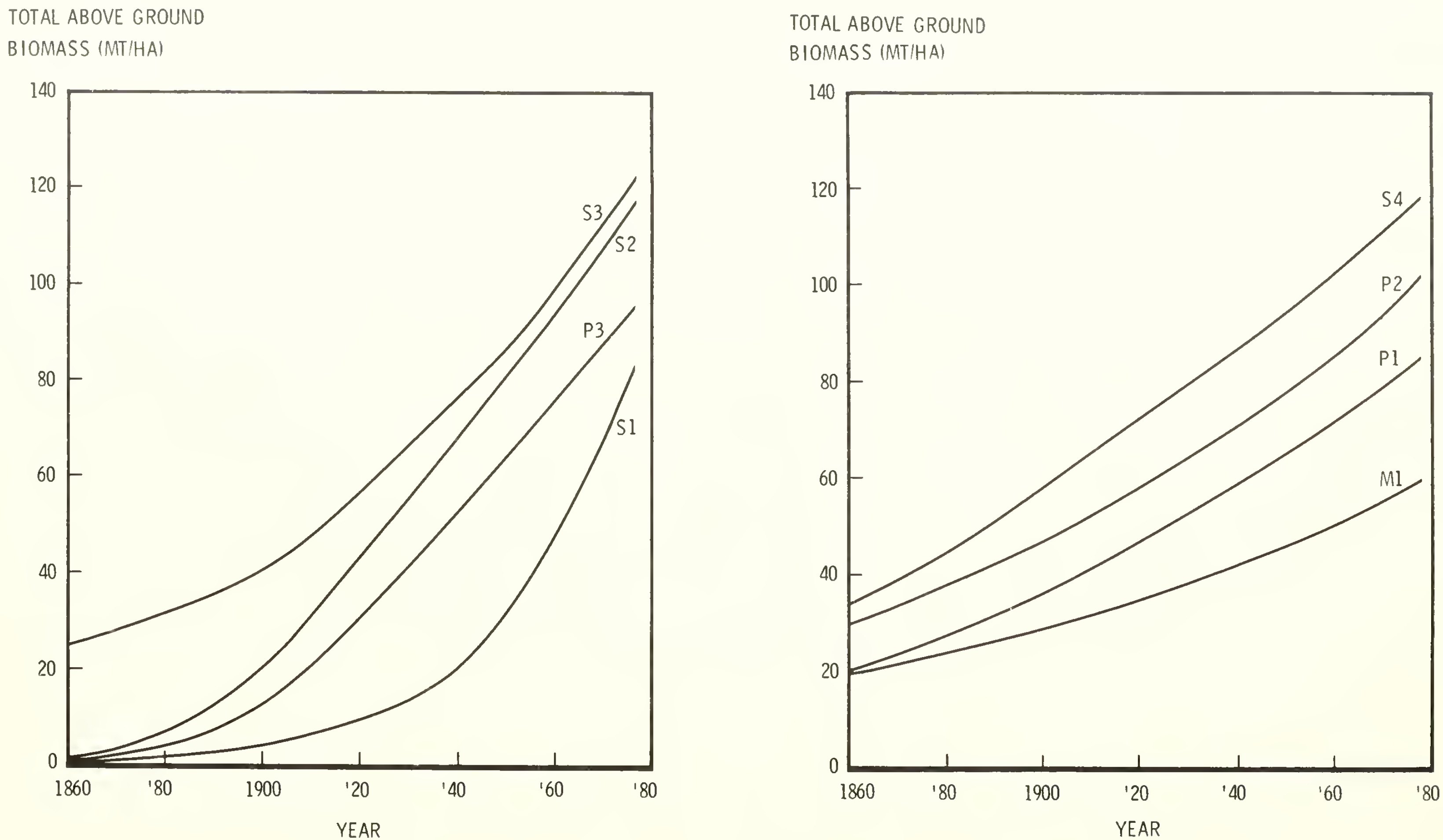

Figure 4.--Total aboveground biomass on the eight plots from 1860 to 1978.

5. Pinyon is capable of fully recovering from rather severe suppression.

6. Stand basal area increment had been remarkedly constant on all but the youngest plot for the past 60 years or more. The only plots with any indication that stand basal area increment might have been beginning to decline were, surprisingly, two of the younger plots. Because of its constancy and direct relationship to productivity, stand basal area increment appears to be a good index of site quality in closed stands.

7. Total aboveground biomass accumulation rates follow a pattern similar to stand basal area increment, but, because of continued height growth, there is a tendency for the rates to continue to increase even in the oldest stands. Since competition rarely kills larger pinyon and juniper, biomass accumulation can be expected to continue at nearly constant or slightly increasing rates for several centuries, barring tree cutting, fires, or epidemics.

These conclusions are tentative and subject to modification when more data are acquired. The conclusions pertaining to juniper are rather tenuous because few junipers were on the plots. Conclusions concerning effects of age on growth should be tested by measuring old stands on better sites, if such stands can be found.

APPENDIX A: EQUATIONS OF ESTIMATING BIOMASS

The regression equations in this appendix and in appendix B were derived from data obtained by Miller, Budy, and Meeuwig (manuscript in preparation). These equations are based on 68 pinyon and 30 juniper trees on 13 sites throughout Nevada and 3 sites in eastern California. Biomasses are expressed in kilograms ovendry basis.

Symbols

Y_1 = Ln [total aboveground biomass]

Y_2 = Ln [wood (bark excluded) larger than 76 mm diameter]

Y_3 = Ln [foliage]

X_1 = Ln [diameter outside bark at stump height (cm)]

X_2 = Ln [total height (dm)]

X_3 = Ln [maximum crown diameter (dm)]

X_4 = Ln [average crown diameter (dm)]

X_5 = Ln [foliage class (defined in appendix D]

SDR = Standard deviation from regression

Pinyon

$$Y_1 = 2.416X_1 + 0.463X_2 + 1.776X_3 - 0.243X_1X_3 - 8.429$$

$R^2 = 0.988$ SDR = 0.148

$$Y_2 = 3.167X_1 + 2.827X_2 - 0.408X_1X_2 + 0.120X_1X_3 - 14.141$$

$R^2 = 0.991$ SDR = 0.163

$$Y_3 = 0.486X_1 + 0.470X_2 + 1.287X_4 + 0.396X_5 - 5.504$$

$R^2 = 0.936$ SDR = 0.267

Juniper

$$Y_1 = 0.850X_1 + 0.642X_2 + 1.392X_4 - 5.805$$

$R^2 = 0.969$ SDR = 0.199

$$Y_2 = 1.366X_2 + 0.336X_1X_4 - 6.289$$

$R^2 = 0.957$ SDR = 0.279

$$Y_3 = 0.137X_1X_2 + 1.278X_4 - 3.053$$

$R^2 = 0.919$ SDR = 0.258

APPENDIX B: PROCEDURE FOR CALCULATING PAST BIOMASS

Diameter and height can be used to estimate past biomass because they can be determined for any time in the past by stem analysis. Crown parameters cannot be used as they were for present biomass because their past values cannot be estimated accurately. The following equations were developed to estimate past biomass:

Pinyon

$$Y = 2.695X_1 + 0.670X_2 - 0.0806X_1X_2 - 5.258$$

$R^2 = 0.978$ SDR $= 0.205$

Juniper

$$Y = 4.155X_1 + 2.435X_2 - 0.5473X_1X_2 - 11.504$$

$R^2 = 0.926$ SDR $= 0.308$

The natural log of total aboveground biomass (kg), ovendry basis is Y. Natural logs of stump diameter and total height (determined by stem analysis as described in the Methods section) are X_1 and X_2.

The last term (the intercept) in the equations was not used in the calculation of past biomass. A new intercept was calculated for each tree such that biomass calculated for 1978 equaled the estimated biomass as calculated by the more accurate equations in appendix A. For the pinyon equation, the proper intercept term (I) was calculated by:

$$I = Y_1 - 2.695X_1 - 0.670X_2 + 0.0806X_1X_2$$

in which Y_1 is the natural log of total aboveground biomass in the particular tree as calculated by the first equation in appendix A and X_1 and X_2 are logs of stump diameter and height measured in 1978. Intercept values for juniper trees were calculated similarly.

APPENDIX C: CROWN MAPS

Crown maps for the five plots measured in 1978 are shown in figures 5 through 9. The plots are 30 m square. Pinyon stem centers are designated by an "x." An asterisk "*" indicates a juniper stem center.

All trees taller than 2 m are numbered and their crown outlines are shown. Locations and heights of trees between 1 dm and 20 dm are marked on the map, but they are not numbered and their crown outlines are not shown. Heights of these trees are given in decimeters. For example, "J13" signifies a juniper 13 dm tall.

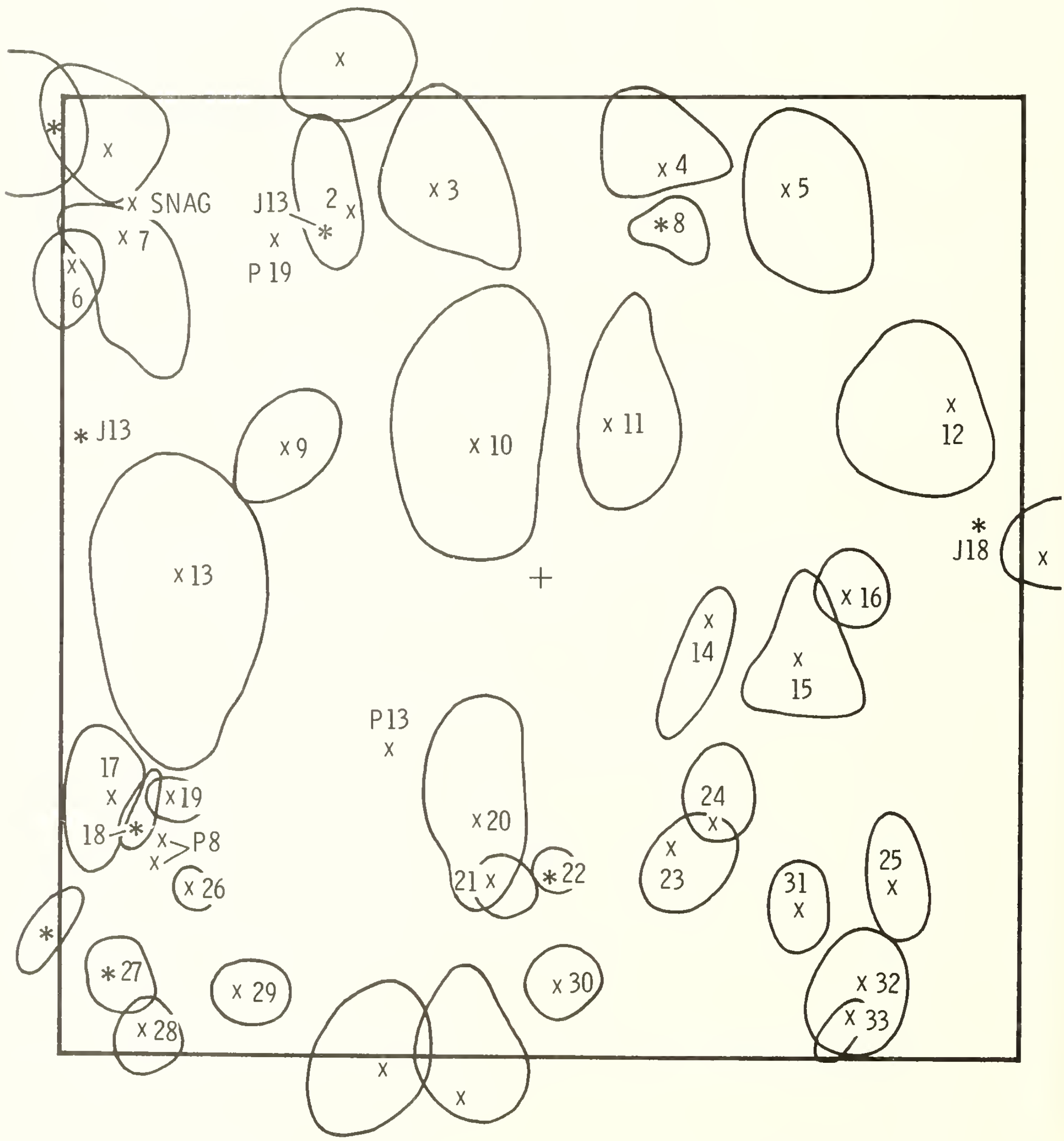

Figure 5.--Crown map of plot S4.

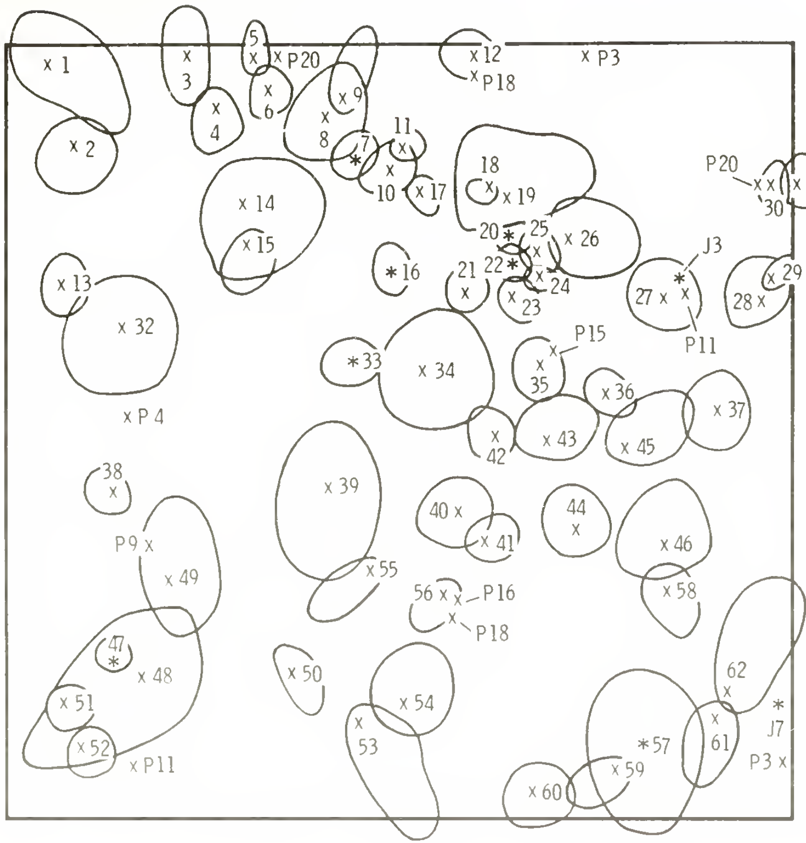

Figure 6.--Crown of plot P1.

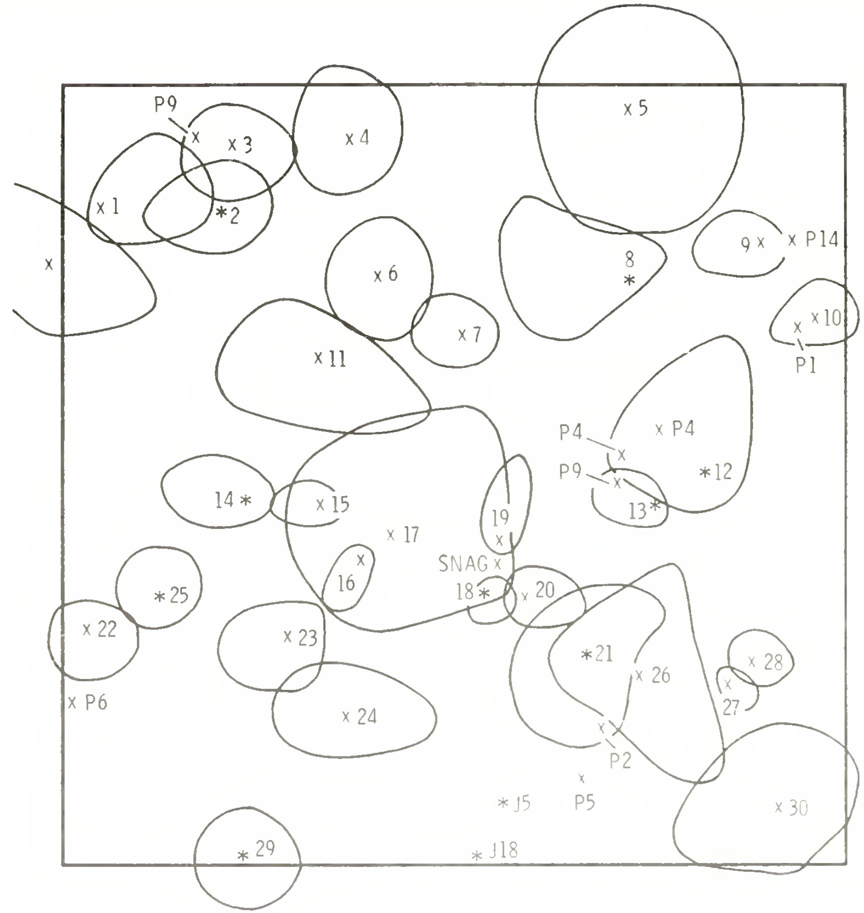

Figure 7.--Crown map of plot P2.

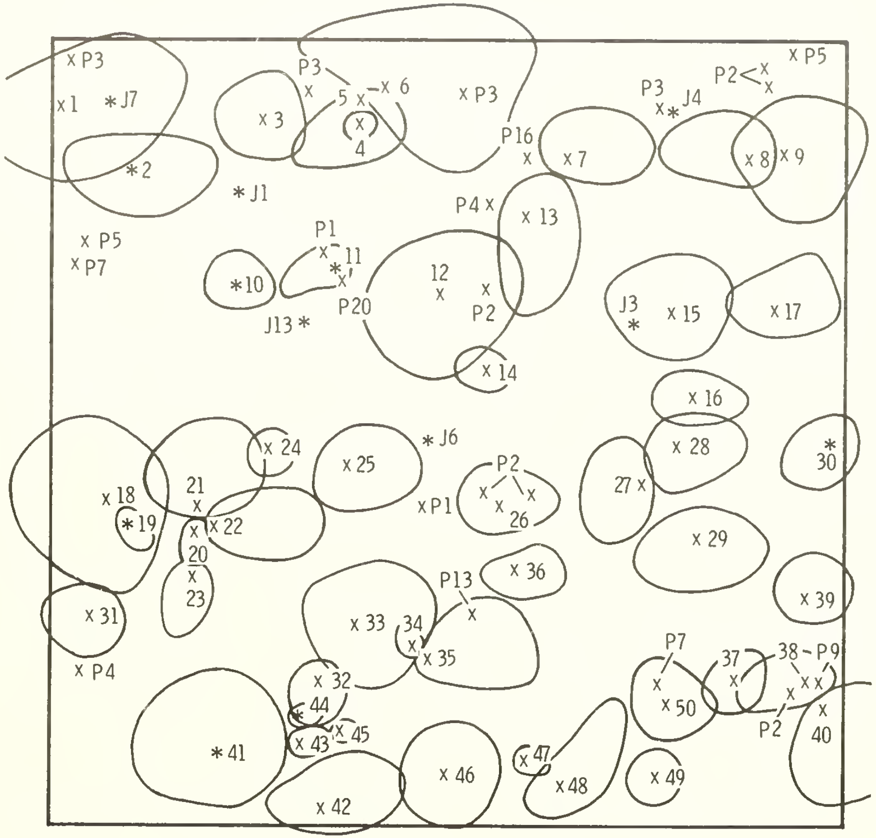

Figure 8.--Crown map of plot P3.

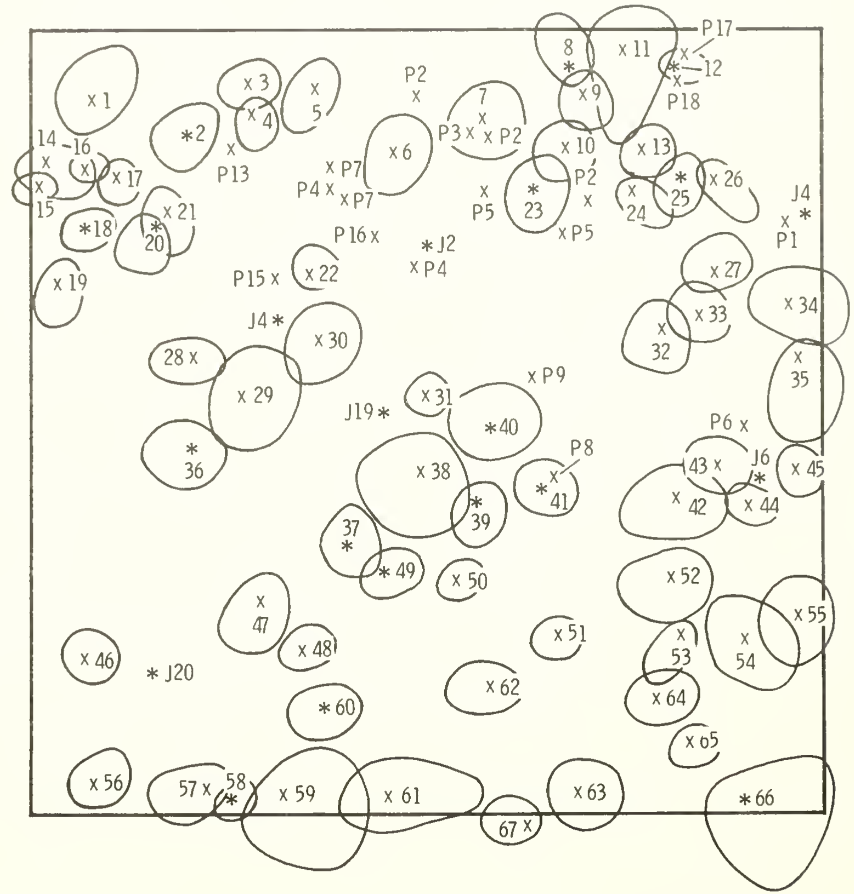

Figure 9.--Crown map of plot M1.

APPENDIX D: TREE DATA

The measured and calculated data for trees taller than 2 m on the five plots easured in 1978 are in tables 4 through 8. The first column is tree number as shown n the crown maps. The second column is species: P for *Pinus monophylla* and J for *uniperus osteosperma*. The third column is diameter measured outside bark at stump eight (15 cm). The fourth column is total height. Maximum crown diameter is in olumn 5. The crown diameter perpendicular to the axis of maximum crown diameter is n column 6.

Foliage class is an ocular estimate of foliage density on a scale of 1 to 9. A ree with dense foliage on all sides would be rated 9 and a tree with few live branches ould be rated 1.

Total age was estimated by extrapolating the height age curves to the ground surace. Height growth rates of seedlings are generally low; so the extrapolation procedure may slightly underestimate total age.

The biomasses in the next three columns were calculated with the regression quations in appendix A. The last column is diameter growth during the 10 years from 966 through 1975.

Table 4.--*Dimensions, ages, biomasses, and decadal diameter growth rates of trees on plot S4*

Tree number	Species[1]	Diameter	Height	Crown Max.	Crown Min.	Foliage class	Age	Biomass Foliage	Biomass Wood	Biomass Total	Diameter growth
		cm	*dm*	- - *dm* - -			*Years*	- - - - - *kg*	- - - -		*mm/10 yrs*
1	P	42	78	46	38	3	348	37	165	385	6
2	p	44	76	48	17	2	365	19	170	410	9
3	P	50	94	60	42	3	369	56	326	679	11
4	P	40	88	44	33	3	314	33	166	353	17
5	P	48	100	60	42	4	420	63	322	653	21
6	P	30	47	33	20	2	290	11	35	129	8
7	P	49	107	64	32	1	342	33	377	736	9
8	J	15	38	24	19	2	164	9	4	21	7
9	P	28	72	37	25	3	280	19	64	165	11
10	P	64	98	84	50	3	377	89	625	1 265	10
11	P	49	111	70	28	3	364	50	408	801	6
12	P	44	78	56	50	4	278	57	190	477	18
13	P	62	107	100	55	3	383	107	691	1 414	18
14	P	31	50	51	13	2	180	12	50	214	22
15	P	57	91	44	33	3	319	41	334	620	13
16	P	24	54	24	21	2	243	9	25	72	8
17	P	31	72	46	24	3	318	23	83	234	9
18	J	28	62	25	10	3	280	11	11	34	8
19	P	12	48	16	14	5	116	5	5	14	10
20	P	45	84	67	33	3	307	46	238	596	15
21	P	13	48	20	20	4	108	7	6	21	19
22	J	8	42	13	12	3	81	4	2	7	15
23	P	30	78	34	24	4	193	21	75	169	20
24	P	31	87	30	23	3	212	18	93	174	12
25	P	32	74	39	19	3	215	18	85	211	16
26	P	14	27	15	12	4	105	3	2	12	21
27	J	23	58	23	21	3	121	14	12	44	14
28	P	22	80	22	21	3	137	12	40	71	24
29	P	26	71	24	20	2	145	10	45	94	20
30	P	19	46	23	22	3	115	9	12	43	16
31	P	30	66	27	18	2	185	11	55	129	12
32	P	46	82	40	32	2	242	27	188	389	15
33	P	15	46	22	10	3	115	5	8	29	23

[1]The letter P represents *Pinus monophylla* and the letter J stands for *Juniperus osteosperma.*

Table [illegible]

Tree number	Species[1]	Diameter	Height	Crown Max.	Crown Min.	Foliage class	Age	[illegible] Foliage	[illegible] Wood	[illegible]	[illegible]
		cm	dm	dm			years				
1	P	35	[illegible]	60	33	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	P	19	58	30	28	1	159	[illegible]	[illegible]	66	[illegible]
3	P	25	75	37	18	3	157	13	[illegible]	[illegible]	12
4	P	24	61	25	21	3	132	11	[illegible]	[illegible]	[illegible]
5	P	14	53	21	9	3	123	1	[illegible]	[illegible]	11
6	P	20	60	19	16	3	140	7	19	[illegible]	[illegible]
7	J	9	28	20	16	[illegible]	98	3	[illegible]	[illegible]	[illegible]
8	P	23	64	40	25	3	143	17	58	[illegible]	[illegible]
9	P	15	54	36	14	2	137	7	12	[illegible]	[illegible]
10	P	16	60	24	19	[illegible]	131	8	13	68	[illegible]
11	P	12	39	13	10	[illegible]	130	2	3	[illegible]	[illegible]
12	P	11	32	23	19	[illegible]	123	3	2	[illegible]	[illegible]
13	P	10	30	23	16	[illegible]	95	1	2	[illegible]	[illegible]
14	P	39	70	50	45	3	213	10	[illegible]	348	[illegible]
15	P	16	29	24	17	[illegible]	207	5	1	[illegible]	[illegible]
16	J	12	28	19	14	3	116	5	2	10	[illegible]
17	P	16	48	15	12	1	123	3	8	21	[illegible]
18	P	10	23	11	9	2	123	1	1	4	[illegible]
19	P	25	64	54	39	3	190	29	50	189	[illegible]
20	J	7	26	13	11	3	98	3	1	1	11
21	P	21	54	17	16	2	221	6	17	40	5
22	J	7	36	14	12	2	88	3	1	6	13
23	P	12	44	19	15	3	130	5	5	17	9
24	P	10	39	12	10	3	118	2	2	7	12
25	P	28	66	19	15	2	257	7	43	83	4
26	P	22	78	37	30	4	157	23	47	120	26
27	P	14	36	30	28	4	113	10	5	32	20
28	P	20	66	30	24	4	118	15	27	74	22
29	P	11	47	16	10	2	83	3	4	12	18
30	P	11	44	19	14	2	110	4	3	13	14
31	P	13	40	20	17	3	108	5	4	18	18
32	P	38	61	48	44	3	206	35	98	301	21
33	J	13	34	24	18	3	113	8	3	17	17
34	P	35	64	48	44	3	257	35	90	277	4
35	P	10	20	24	20	3	132	4	1	11	7
36	P	9	22	21	18	3	95	4	1	8	18
37	P	14	32	30	25	3	108	8	4	32	36
38	P	28	58	20	16	1	226	6	35	80	4
39	P	38	86	61	39	3	262	44	171	433	12
40	P	27	88	30	27	2	250	16	71	135	9
41	P	13	56	21	17	3	153	6	8	24	9
42	P	14	58	21	18	2	224	6	10	26	9
43	P	46	66	34	25	2	365	19	133	307	7
44	P	32	64	29	24	2	254	14	60	147	9
45	P	35	74	38	26	2	275	19	99	236	7
46	P	41	76	41	35	2	271	27	142	329	12
47	J	5	24	13	13	2	56	3	1	3	13
48	P	52	99	86	45	1	325	49	436	978	5
49	P	32	83	55	26	3	253	29	114	307	8
50	P	18	60	31	15	3	222	9	19	63	9
51	P	10	20	18	18	3	163	3	1	7	12
52	P	16	48	19	18	3	153	6	8	26	6
53	P	42	69	58	26	1	333	20	150	433	10
54	P	40	70	36	32	3	258	26	113	268	25
55	P	14	42	35	15	3	125	8	7	43	14
56	P	36	68	23	15	1	236	7	75	152	4
57	J	42	64	65	45	3	352	66	83	271	13
58	P	30	70	30	20	2	265	13	63	148	9
59	P	13	34	27	17	3	112	6	4	25	10
60	P	16	39	27	23	5	115	10	7	36	35
61	P	32	76	34	19	3	290	17	84	191	5
62	P	33	85	56	30	3	304	33	129	336	13

[1]The letter P represents *Pinus monophylla* and the letter J stands for *Juniperus osteosperma*.

Table 6.--*Dimensions, ages, biomasses, and decadal diameter growth rates of trees on plot P2*

Tree number	Species[1]	Diameter	Height	Crown Max.	Crown Min.	Foliage class	Age	Biomass Foliage	Biomass Wood	Biomass Total	Diameter growth
		cm	*dm*	- - *dm* - -			*Years*	- - - - - *kg*	- - - - -		*mm/10 yr*
1	P	28	68	48	39	3	265	30	65	206	14
2	J	20	59	48	36	3	126	29	20	93	32
3	P	27	64	46	37	4	170	30	52	177	30
4	P	36	70	48	42	4	221	40	107	299	23
5	P	54	86	94	83	4	267	128	415	1 038	23
6	P	32	77	46	42	3	303	34	98	257	12
7	P	37	70	34	28	2	309	19	95	224	5
8	J	22	41	65	50	3	244	40	20	127	18
9	P	26	61	35	25	4	255	19	42	129	17
10	P	25	52	35	28	3	231	16	30	111	15
11	P	55	87	80	48	3	376	73	399	934	16
12	J	41	57	68	54	3	341	73	81	300	15
13	J	35	50	31	21	3	350	20	19	69	11
14	J	33	60	44	29	3	207	33	33	118	6
15	P	26	70	27	18	2	294	10	47	108	6
16	P	19	50	28	15	3	275	8	15	55	9
17	P	69	97	94	88	3	350	141	733	1 487	15
18	J	14	31	19	17	3	268	7	3	14	9
19	P	29	67	36	16	3	263	14	59	160	14
20	P	31	95	32	22	3	305	19	102	184	12
21	J	39	58	71	53	3	355	70	75	282	5
22	P	17	44	34	32	5	117	16	11	55	22
23	P	39	92	42	40	3	273	37	166	333	13
24	P	44	96	63	35	3	292	48	268	593	14
25	J	22	34	33	29	6	83	17	8	48	57
26	P	53	110	82	62	3	395	96	500	1 011	23
27	P	14	28	20	13	1	150	3	3	18	7
28	P	12	33	25	20	4	105	7	3	20	34
29	J	29	44	41	38	3	128	30	21	99	19
30	P	43	90	76	55	4	175	78	251	642	33

[1]The letter P represents *Pinus monophylla* and the letter J stands for *Juniperus osteosperma*.

le 7.--*Dimensions, ages, biomasses,* [illegible]

ree ber	Species[1]	Diameter	Height	Crown Max.	Crown Min.	Foliage class	Age	Biomass Foliage	Biomass Wood	Biomass Total	Diameter growth
		cm	*dm*	- - *dm* - -			*Years*	- - - - -	*kg*	- - - -	*mm/10 yrs*
	P	54	83	78	51	4	156	81	359	872	29
	J	32	56	58	34	3	152	41	38	150	14
	P	19	55	36	35	5	96	21	19	74	22
	P	7	33	11	10	2	104	2	1	5	7
	P	31	86	45	27	4	156	29	104	245	14
	P	39	88	90	65	3	143	82	221	647	17
	P	24	64	42	31	3	122	21	39	133	20
	P	34	80	44	30	3	149	28	114	275	25
	P	36	82	52	50	4	140	50	134	338	21
	J	16	35	27	22	4	83	11	5	26	24
	J	13	52	29	17	3	106	10	6	26	14
	P	36	86	64	52	3	164	54	160	424	15
	P	30	92	55	31	3	146	33	116	288	17
	P	10	27	21	17	4	65	4	1	10	21
	P	25	54	46	42	3	136	26	37	152	19
	P	25	70	36	21	2	137	14	49	134	8
	P	22	64	42	30	3	118	20	36	123	15
	P	42	84	70	60	4	155	75	212	560	26
	J	8	34	18	13	2	115	4	2	7	12
	P	18	64	18	11	3	141	5	17	36	13
	P	36	84	47	38	3	159	36	141	328	19
	P	27	81	45	28	2	168	21	77	199	7
	P	14	45	30	19	4	120	9	7	36	14
	P	9	36	18	18	3	81	4	2	9	19
	P	38	68	42	22	3	165	22	105	279	20
	P	29	76	38	26	2	160	18	73	181	12
	P	21	59	41	28	3	128	17	27	104	24
	P	34	80	38	31	3	161	26	104	233	19
	P	32	68	41	35	3	163	27	77	216	17
	J	8	36	33	25	3	69	10	3	19	10
	P	22	56	33	28	3	116	15	26	88	17
	P	25	80	26	23	3	150	15	53	103	10
	P	36	96	49	48	4	144	51	166	352	23
	P	12	42	13	9	2	112	2	4	11	6
	P	30	66	48	34	3	171	27	68	218	14
	P	22	64	33	22	3	147	14	31	93	8
	P	16	64	31	24	4	101	14	18	55	19
	P	27	80	39	21	3	163	18	71	172	10
	P	26	67	29	28	2	142	14	42	107	13
	P	28	74	80	44	2	165	39	86	340	6
	J	28	58	58	53	4	210	51	42	185	18
	P	23	54	42	31	4	153	22	30	122	14
	P	8	28	17	12	4	80	3	1	6	15
	J	7	30	13	8	3	85	2	1	4	12
	P	5	25	10	10	2	65	1	--	1	9
	P	27	71	40	39	3	163	26	58	162	19
	P	8	33	14	10	2	105	2	1	5	3
	P	36	91	55	24	3	164	31	166	389	13
	P	10	42	21	21	5	88	7	3	14	23
	P	22	65	34	31	3	159	18	33	99	15

[1]The letter P represents *Pinus monophylla* and the letter J stands for *Juniperus osteosperma*.

Table 8.--*Dimensions, ages, biomasses, and decadal diameter growth rates of trees on plot M1*

Tree number	Species[1]	Diameter	Height	Crown Max.	Crown Min.	Foliage class	Age	Biomass Foliage	Biomass Wood	Biomass Total	Diameter growth
		cm	*dm*	- - *dm* - -			*Years*	- - - - -	*kg*	- - - -	*mm/10 yrs*
1	P	20	52	37	26	4	158	16	19	82	19
2	J	16	45	29	21	4	190	12	7	32	7
3	P	18	57	23	19	3	161	9	17	46	21
4	P	15	46	20	14	3	125	5	7	25	15
5	P	21	48	30	18	3	280	10	17	67	7
6	P	30	53	33	24	3	356	16	43	139	7
7	P	24	54	30	29	3	196	15	27	90	17
8	J	11	31	32	30	3	219	12	3	25	4
9	P	23	43	29	20	3	285	10	18	74	7
10	P	12	36	23	20	3	173	6	3	19	10
11	P	37	75	53	36	4	334	42	131	366	8
12	J	18	52	18	13	2	256	7	6	20	6
13	P	16	38	21	20	3	266	7	6	27	7
14	P	25	61	30	20	3	287	13	37	105	10
15	P	11	30	16	10	2	192	2	2	10	10
16	P	11	28	15	11	3	166	3	1	9	7
17	P	13	34	17	16	2	187	4	3	14	8
18	J	14	31	20	16	3	240	7	3	14	6
19	P	22	47	27	19	2	276	8	19	69	5
20	J	15	28	23	23	4	202	9	3	20	9
21	P	22	58	26	20	3	271	11	24	69	6
22	P	8	31	20	18	4	101	4	1	8	10
23	J	12	40	30	24	4	239	11	5	26	5
24	P	16	41	24	16	2	178	5	7	32	7
25	J	20	48	26	18	3	223	12	8	33	5
26	P	17	58	30	15	2	263	7	16	55	10
27	P	19	54	26	21	3	275	10	17	53	8
28	P	30	65	28	18	3	288	13	56	135	10
29	P	35	69	41	33	4	308	30	95	251	9
30	P	36	64	32	27	3	309	20	81	200	8
31	P	22	51	17	16	2	234	6	18	44	5
32	P	22	49	27	25	3	245	12	19	66	11
33	P	14	46	25	22	4	184	9	7	28	12
34	P	33	72	37	27	3	287	22	83	206	6
35	P	34	51	39	29	2	315	18	58	199	8
36	J	13	24	30	27	3	180	10	3	22	8
37	J	18	33	27	23	3	280	12	5	29	7
38	P	31	66	45	41	3	270	30	73	222	8
39	J	12	33	25	20	3	197	8	3	18	9
40	J	34	34	36	29	3	305	22	14	72	10
41	J	20	42	24	20	4	251	11	7	31	9
42	P	30	58	41	30	3	293	22	54	179	6
43	P	15	38	27	22	3	187	8	6	33	11
44	P	11	36	20	16	3	126	4	3	13	18
45	P	24	45	20	17	3	280	8	18	56	18
46	P	15	22	22	20	1	294	3	2	19	2
47	P	30	54	33	24	4	295	18	44	139	10
48	P	22	45	20	18	1	232	5	15	48	11
49	J	12	31	23	17	4	203	7	2	15	9
50	P	17	38	19	16	3	182	5	7	27	10
51	P	16	42	20	17	4	132	7	8	29	21
52	P	24	51	35	27	3	265	15	27	103	11
53	P	16	34	27	15	3	244	6	6	34	8
54	P	32	66	42	31	4	270	28	75	217	10
55	P	29	59	33	28	4	266	20	47	139	10
56	P	24	58	27	22	3	280	12	28	81	6
57	P	25	58	30	21	2	267	11	34	102	7
58	J	7	28	19	13	4	149	4	1	6	5
59	P	42	76	49	46	3	288	43	162	401	9
60	J	12	36	27	21	2	175	9	30	20	11
61	P	37	68	53	27	4	297	32	114	336	7
62	P	20	57	31	21	3	192	12	21	71	13
63	P	21	60	29	27	4	220	16	26	76	19
64	P	17	33	27	21	3	208	8	6	37	11
65	P	14	37	19	17	2	206	4	4	20	17
66	J	28	35	54	50	1	265	37	20	122	3

[1]The letter P represents *Pinus monophylla* and the letter J stands for *Juniperus osteosperma*.

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KEYWORDS: *Pinus monophylla*, *Juniperus osteosperma*, silvics, site index, biomass

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KEYWORDS: *Pinus monophylla*, *Juniperus osteosperma*, silvics, site index, biomass

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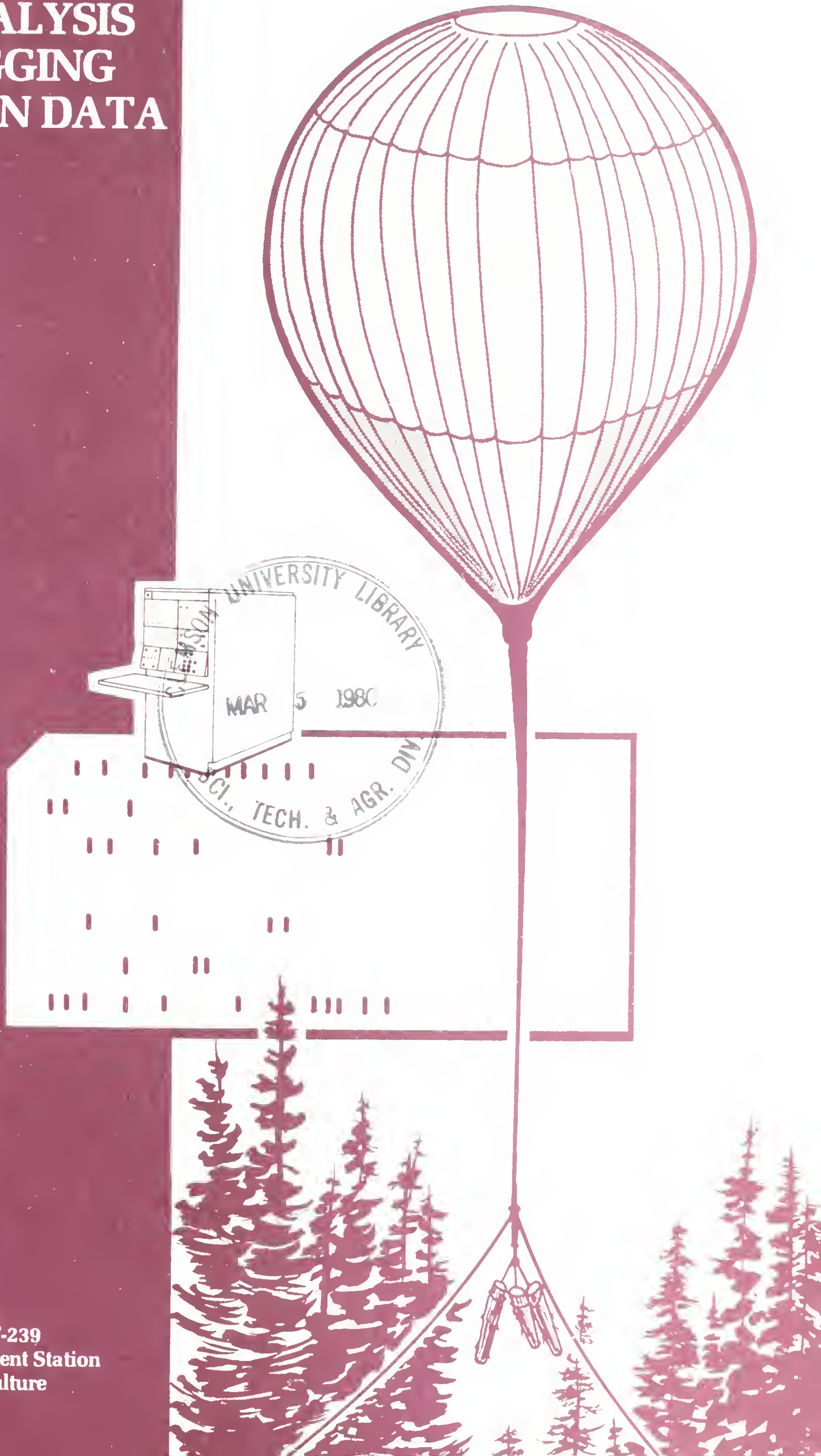
M S. HARTSOG
CASS



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STATISTICAL ANALYSIS OF BALLOON LOGGING TIME AND MOTION DATA

William S. Hartsog

James Cass

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

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JAMES CASS received a bachelor's degree in psychology in 1973 and an M.S. in mathematics (statistics option) in 1975, both from Montana State University. While doing graduate work at Montana State, he did the statistical analysis for this study. He is presently employed as a statistician with the Montana Department of Revenue in Helena, Montana.

RESEARCH SUMMARY

Time and motion studies were conducted on an experimental balloon logging show in the Idaho batholith during 1973. The objective of the study was to determine the variables affecting production and to develop models for estimating production rates. A data collection technique and a method of statistical analysis are presented for others involved in analyzing balloon logging operations.

Selected variables were divided into three classes: those involving the time required for each portion of the logging cycle (dependent variables), factors directly related to the yarding operation (independent variables), and coded independent variables (such as surface type and condition, operator skill, and landing size).

Variables were then partitioned into four groups so that easy comparisons could be made between predictive models. A statistical program was used to determine and quantify the most important variables for each model. The resulting regression equations serve as limited guidelines for predicting time requirements for the various portions of the balloon logging cycle and identify factors that have a significant influence on this cycle.

CONTENTS

INTRODUCTION

Flying logs from the stump to a landing area using a balloon is a relatively new chnique to minimize the environmental impacts of logging. Little data are available balloon logging production and the factors affecting production rates.

This report presents the results of a 1975 time and motion study of a balloon gging experiment in the Idaho Batholith. The results may be useful for foresters or gineers estimating logging production rates, and for analyzing proposed balloon gging operations. A data collection technique, a method of statistical analysis, d the relative importance of different measured variables involved in balloon logging udies are presented. These should help avoid the wasted time and effort which rmally occur when starting a study on any new logging system. It must be recognized at these results are narrow in scope when one examines the wide range of variables ssible in terrain conditions, timber harvesting techniques, climate, logging set nfigurations, volume of timber per acre, and log size, to mention a few.

Details of the balloon logging system, timber harvest prescription, terrain nditions, environmental constraints, and cost data are described in Forest Service search Paper INT-208, "Balloon Logging in the Idaho Batholith: A Feasibility udy," by William S. Hartsog (1978). The paper provides valuable information on the nctioning of the balloon logging system, information necessary for understanding the plicability of time and motion data.

METHODS

The first task of the time and motion study was to observe carefully the balloon stem operation and factors affecting production rates. Selection of variables to be asured during the data collection phase was based on these observations. Time quired to complete a logging cycle (turn) was determined to be the dependent variable nce it indicated production and seemed to be affected by many of the other factors. rn time was partitioned into five elements. Since total turn time equaled the sum these five elements, all six are dependent variables. The dependent variables are lly defined, along with the independent variables, in a later section.

Data Sheets

Data sheets were designed to collect information on those factors selected in the itial observations; these were to serve as variables in a multiple regression analy- s. Three data sheets were used for collecting field data: Site/Terrain Information, rding Data, and Scaling Data. The Site/Terrain Information sheets (fig. 1) were ed to record information pertinent to site description, site conditions, and the gging subsystem (balloon yarding in this case). Yarding Data sheets (fig. 2) were ed to record the time required for each element within the turn and other physical asurements important to the study. Scaling Data sheets (fig. 3) were used to record e measurements of each log so that volume and weight could be calculated for each rn of the ballon yarding subsystem. For a detailed description of the data collection thods, see the publication "Time Study Techniques for Logging Systems Analysis" ibson and Rodenberg 1975).

SITE/TERRAIN INFORMATION FORM

SITE DESCRIPTION

Logmaking ____________ Location
Skidding ____________ Timber Sale ____________
Yarding 102 Forest Boise, Garden Valley R.D.
Loading ____________ Type of Cut Overstory
Hauling ____________ Contractor Boise Cascade
Data Collection Date 7/11/73 Start Time 7:00 a.m. Stop Time 12:00
Comments Broken Gear in Planetary

SITE CONDITIONS

	Rating				
Surface Type	1	2	(3)	4	Comments very brushy
Surface Condition	(1)	2	3		Comments
Operator	1	(2)	3		Comments
Landing	1	2	(3)	4	Comments gusty winds & small landing
Deck	(1)	2	3	4	Comments

Temperature 75 degrees Elevation map feet
Wind 5 velocity S.W. direction Precipitation 0 inches ____________ form

SUBSYSTEM INFORMATION

Logmaking Comments ____________
Crew Members
____________, Comments ____________
____________, Comments ____________
Saw or Feller
Make ____________ Type ____________ Equipment Owner ____________
Model ____________ Size ____________ Payment (Method & Amount) ____________

Skidding/Yarding Comments ____________
Crew Members
operator, foreman, Comments ____________
headrigger, unhooker, Comments ____________
2 hookers, knot bumper, Comments ____________
Skidder or Yarder
Make Washington Type ____________ Equipment Owner Boise Cascade
Model 608 Aero Size ____________ Payment (Method & Amount) ____________

Loading Comments ____________
Crew Members
____________, Comments ____________
____________, Comments ____________
Loader
Make ____________ Type ____________ Equipment Owner ____________
Model ____________ Size ____________ Payment (Method & Amount) ____________

Hauling Comments ____________
Crew Members
____________, Comments ____________
____________, Comments ____________
Truck and Trailer
Make ____________ Type ____________ Equipment Owner ____________
Model ____________ Size ____________ Payment (Method & Amount) ____________

Figure 1.--Site/terrain information form.

YARDING DATA – TURN ELEMENT TIME STUDY FORM AND KEYPUNCH TRANSCRIBING FORM
Snapback Reading

Subsystem (1)	Equipment & Method (2–3)	Code No. (4–6)	Turn No. (7–9)	1 Trav. Un. (10–12)	2 Trav. Lat. (13–15)	3 Hook Ch. (16–18)	4 Trav. Load. (19–21)	5 Un-hook Ch. (22–24)	Foreign Element (25–32)	Dist. (FT) (33–36)	Slope (%) (37–40)	Lat. Di. (FT) (41–42)	No. of Logs (43–44)	Species (45)	MVR (MBF/A) (46–47)	Trees/Acre (Tens) (48–50)	TCV (FT³/A) (51–52)	Surface T. (53)	Surface C. (54)	Operator (55)	Landing (56)	Deck (57)	I.D. (58)	Additional Data (59–79)	Continue (80)
3	60	102	1	1.9	2.3	2.5	5.8	1.0		1200	-65	99	2	2				3	1	2	3	1			
			2	2.9	2.3	3.8	5.3	1.5	24 1.3 1.4	1200	-65	99	3	2											
			3	1.1	1.0	3.7	3.5	.5	25 .5 1.2	1000	-65	15	3	2											
			4	1.3	2.4	3.4	3.9	1.0		1000	-65	70	3	3											
			5	1.3	1.4	2.0	2.0	.8		1000	-65	70	3	2											
			6	.9	.4	2.3	2.4	1.1		1000	-65	20	3	3											
			7	1.7	1.1	.9	2.7	.7		1000	-65	60	4	3											
			8	1.7	1.0	.9	2.6	.4		1000	-65	70	3	3											
			9	2.9	.9	1.7	2.8	1.0		1000	-65	50	3	3											
			10	1.5	1.4	1.3	1.6	1.0		800	-65	40	1	2											
			11	1.4	.9	4.2	1.5	.5		800	-65	40	2	3											
			12	1.5	.8	1.3	4.0	.2		800	-65	50	3	3											
			13	1.8	1.0	1.2	1.9	1.5	25 .8 1.0	700	-65	40	4	3											
			14	1.6	1.2	2.4	1.9	.9		600	-65	20	3	3											
			15	1.9	.9	1.3	2.2	.5	24 1.0 .9	600	-65	30	2	3											
			16	2.3	1.0	1.1	2.3	.3		600	-65	30	3	3											
			17	1.3	1.1	.9	1.3	1.0		600	-65	40	4	3											
			18	1.1	.9	.8	1.5	.6		600	-65	40	1	3											
			19	1.3	.9	1.7	2.4	.4	25 5 2.4 1.2	500	-65	40	3	3											
			20	1.7	.5	2.0	3.4	.4		400	-65	40	3	2											
			21	2.4	2.1	2.9	2.0	.7	23 2.5 4.6	400	-65	75	4	3											
			22	1.7	2.2	3.2			34 .0	400	-65	60	0	-											
			22						31 .099.0																

Figure 2.--Yarding data sheet.

SCALING DATA

DATE 7/11

MATCH WITH TIME STUDY FORM CODES 101, 102, ____

CODE NO.	TURN NO.	NO. OF LOGS	LOG 1			LOG 2			LOG 3			LOG 4			LOG 5			LOG 6			LOG 7			LOG 8			LOG 9			LOG 10			LOG 11			LOG 12		
			D_1	D_2	L	D_1	D_2	L	D_1	D_2	L	D_1	D_2	L	D_1	D_2	L	D_1	D_2	L	D_1	D_2	L	D_1	D_2	L	D_1	D_2	L	D_1	D_2	L	D_1	D_2	L	D_1	D_2	L
1 2 3	4 5 6	7 8	9 10	11 12	13 14	15 16	17 18	19 20	21 22	23 24	25 26	27 28	29 30	31 32	33 34	35 36	37 38	39 40	41 42	43 44	45 46	47 48	49 50	51 52	53 54	55 56	57 58	59 60	61 62	63 64	65 66	67 68	69 70	71 72	73 74	75 76	77 78	79 80
102	1	2	8	20	33	20	22	24																														
	2	3	10	22	33	10	20	24	20	22	16																											
	3	3	10	12	33	10	18	33	12	20	33																											
	4	3	8	12	33	10	16	24	16	24	29																											
	5	3	8	16	14	18	18	18	24	28	25																											
	6	3	20	24	39	12	14	33	10	12	33																											
	7	4	8	12	20	12	18	24	12	16	33	10	12	37																								
	8	3	8	12	24	8	12	24	12	20	33																											
	9	3	8	20	31	8	12	33	12	20	24																											
	10	1	28	30	8																																	
	11	2	8	10	25	24	36	20																														
	12	3	10	16	35	8	12	35	20	24	33																											
	13	4	8	14	35	8	16	35	8	14	33	10	14	29																								
	14	3	14	24	35	10	20	33	10	22	33																											
	15	2	10	12	10	10	16	20																														
	16	3	10	20	39	10	24	39	12	14	33																											
	17	4	14	20	33	10	12	33	16	20	33	8	12	33																								
	18	1	10	14	25																																	
	19	3	16	20	33	16	18	33	8	12	25																											
	20	3	22	24	16	16	18	33	18	22	33																											
	21	4	12	18	25	18	24	25	12	24	35	12	16	33																								
	22																																					
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Figure 3.--Scaling data sheet.

Definition of Variables

Variables were divided into three classes: dependent variables (measurement of time), independent variables (factors directly related to the operation of the yarding subsystem), and coded independent variables (qualitative independent variables with only a few levels). The dependent variables were defined as follows (the abbreviation following the variable will be used throughout this report):

1. Travel unloaded (TU).--Time, in minutes, required for the balloon to travel from the log landing area to the general area of the felled logs.

2. Travel laterally out (TLO).--Time, in minutes, required for the choker setter to drag the tagline from a point directly beneath where the balloon stopped to the felled logs.

3. Hook chokers (HC).--Time, in minutes, required for the choker setter to hook the tagline to the preset chokers and scramble clear of the travel path of the logs.

4. Travel loaded (TL).--Time, in minutes, required for the yarder to yard the load of logs and place them on the landing.

5. Unhook chokers (UC).--Time, in minutes, required to unhook the chokers.

6. Total turn time (TT).--Total time, in minutes, for one complete logging cycle (TT = TU + TLO + HC + TL + UC).

The first five dependent variables are the elements from which component models were constructed. The sixth variable, total turn time (TT), is the dependent variable used in the model for predicting the time required to complete a logging cycle.

Measurements of time were also taken on foreign elements, delays in the logging cycle due to an event which was not a normal occurrence during the yarding operation. Foreign elements were not included in the analysis as they proved to be random.

The independent variables were defined as follows (the abbreviation following the variable will be used throughout this report):

1. Number of logs (NL).--Total number of logs carried on each turn.

2. Volume (VOL).--Volume, in board feet (Scribner scale), of the logs carried on each turn.

3. Weight (WT).--Weight, in pounds, calculated from measurements of the logs carried on each turn.

4. Distance (DI).--Slope distance (along the ground surface), in feet, from the landing area to where the balloon stopped to pick up a load of logs.

5. Slope (SLO).--A decimal number defined as the vertical distance from the yarder to the logs, divided by the horizontal distance from the yarder to the logs (slope is positive for yarding downhill and negative for yarding uphill).

6. Lateral distance (LDI).--The lateral distance, in feet, from where the tagline touched the ground to the choker on the felled logs.

7. Lateral slope (LSLO).--A decimal number determined by the vertical distance from the ground beneath the tagline to the logs, divided by the horizontal distance from the tagline to the logs.

8. Temperature (TEMP).--The highest daily temperature (°F) taken while the yarding crew was working.

9. Wind velocity (WINVEL).--The highest daily wind velocity (mi/h) taken while the yarding crew was working.

Measurements were also taken on precipitation but most of the measurements were zero or trace levels so this provided little useful information.

The coded independent variables were defined as follows:

1. Surface type.--Coded from one (little surface obstruction) to three (severe surface obstruction).

2. Surface condition.--Coded from one (dry, firm soil) to three (wet, muddy soil).

3. Operator.--Coded from one (below average) to three (above average).

4. Landing.--Coded from one (spacious landing) to three (limited landing).

5. Deck.--Coded from one (easy to land logs and unhook chokers) to three (difficult to land logs and unhook chokers). A four indicates this variable was not applica

A more complete description of the criteria for the classification system is contained in Gibson and Rodenberg (1975).

ANALYSIS

Model building was partitioned into four classes so that easy comparisons could be made. The first class was composed of the independent variables, except TEMP and WINVEL. The second class also was composed of the independent variables, except TEMP and WINVEL, but interactions were allowed. The third was composed of all the independent variables. The fourth class was composed of all the independent variables plus interactions. These four classes were then used to compare the simple models (no interaction terms) and the interaction models since the physical constraints of the system implied that most of the independent variables were linear. The effect of TEMP and WINVEL was analyzed separately since there were a few levels (many repeated values of these two variables; estimates were based on only a few unique observations. TEMP and WINVEL were included in the final analysis, but their contribution to the regressions was weak since there were only a few levels of each variable.

The coded independent variables were eliminated from the final model building because no significant correlations with the dependent variables were found. Analysis using graphs and dummy variables indicated there was not enough range in the observations at each level to meaningfully measure the association between the coded independent and dependent variables. The analysis and field observations also indicated a need for a more quantitative method of rating the coded variables. The authors define the coded variables in this report because they could be important on other logging studies if the variable levels were better defined and the range of conditions was sufficiently large.

The four classes of models were used to form predictive equations for TT and for the components TU, TLO, HC, TL, and UC. A statistical program, BMD02R from the U.C.L. Biomedical package, was used to determine the most important variables within each class during model selection.

The criteria used to judge a model as "best" were: (1) check of normality and independence assumptions, (2) check of variables against the physical constraints of the system, (3) R-squared (coefficient of determination), (4) the F value being four times the value of the selected percentage point of the F distribution (Wetz 1966), (5) ease of use of these models, and (6) smallest variance.

The normality assumptions were checked by plotting the dependent variable and the residuals for each model constructed. Plots of observed values versus residuals and predicted values versus residuals were used to check for any predictive faults in the models. Plots of the order of the observation as recorded versus the residuals were used to check for lack of independence. The criterion of Wetz' as discussed in Draper and Smith (1966), "suggests that in order that an equation should be regarded as a satisfactory predictor (in the sense that the range of response values predicted by the equation is substantial compared with the standard error of the response), the observed F ratio (regression mean square)/(residual mean square) should exceed not merely the selected percentage point of the F distribution, but about four times the selected percentage point."[1]

During the model building process many mathematical forms of the variables were screened in order to improve the regression equations. Three of the independent variables, SLO, LD1, and LSLO had quadratic relationships. This was verified with plots of the data and other physical relationships determined from studying the logging system. These three quadratic forms appear in many of the selected models along with various combinations of interaction terms. The following discussion presents a summary of the best model for each element and presents other models which were close contenders.

RESULTS

Five good TT models (fig. 4) were found using the six criteria discussed above. None of the five models violated the normality or independence assumptions. In fact, the plots for each model were quite similar, and no one model could be judged "better" than the others. Since the five models were composed of two dominant variables, DI and LD1, model number one was chosen as the "best" model because of its simplicity:

$$TT = 3.43 + 0.0039 1D1 + 0.0036 LD1$$

with an R-squared of 42.69 percent.

Other variables were not included in the final model because they did not have a strong enough influence on the cumulative R-squared. Note that distance and lateral distance are the only variables that are included. Other expected relationships such as number of logs, volume in board feet, weight, and slope were found not to be significant in the total model.

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[1] Draper, N. R., and H. Smith. 1966. Applied regression analysis. p. ed. John Wiley and Sons, Inc: New York, London, Sidney.

Model #1

$TT = 3.43 + 0.00391DI + 0.0036LDI$

Variable	Cumulative R-squared (%)	Increased in R-squared (%)
DI	30.43	30.43
LDI	42.69	12.26

$R^2 = 42.69\%$, $\sigma^2 = 3.37$, $F = 58.10$, $4(x)F^{.05} = 12.28$

Model #2

$TT = 3.18 + 0.00413DI + 0.0330LDI - 0.95LSLO$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
DI	30.43	30.43
LDI	42.69	12.26
LSLO	43.62	0.93

$R^2 = 43.62\%$, $\sigma^2 = 3.34$, $F = 39.97$, $4(x)F^{.05} = 10.72$

Model #3

$TT = 2.67 + 0.00796DI + 0.1297LDI \cdot SLO^2 - 12.80SLO + 5529.46SLO/DI - 0.000222WT \cdot LSLO$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
DI	30.43	30.43
$LDI \cdot SLO^2$	40.80	10.37
SLO	43.41	2.62
SLO/DI	47.74	4.32
WT·LSLO	49.08	1.34

$R^2 = 49.08\%$, $\sigma^2 = 3.06$, $F = 29.49$, $4(x)F^{.05} = 9.16$

Model #4

$TT = 7.42 + 0.00424DI + 0.0307LDI - 0.0737WINVEL - 0.0327TEMP - 2.38LSLO^2$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
DI	30.43	30.43
LDI	42.69	12.26
WINVEL	44.35	1.66
TEMP	45.77	1.42
$LSLO^2$	46.63	0.85

$R^2 = 46.63\%$, $\sigma^2 = 3.20$, $F = 26.73$, $4(x)F^{.05} = 9.16$

Model #5

$TT = 7.59 + 0.00233DI + 0.0289LDI - 0.00282TEMP \cdot WINVEL + 0.000102DI \cdot WINVEL - 4.38LSLO^2$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
DI	30.43	30.43
LDI	42.69	12.26
TEMP·WINVEL	47.08	4.39
DI·WINVEL	51.01	3.94
$LSLO^2$	53.83	2.81

$R^2 = 53.83\%$, $\sigma^2 = 2.77$, $F = 35.67$, $4(x)F^{.05} = 9.16$

Figure 4.--Total turn time (TT) statistics

Four of the best TU models (fig. 5) were examined. In each case, none of the odels violated the normality assumptions. Again the differences between models were light. Model number one was chosen as the "best" model since it was an easy model to se and had a relatively high R-squared and F value:

$$TU = -7.60 + 0.01173DI - 0.01958DI \cdot SLO + 16.01SLO$$

ith an R-squared of 61.68 percent. In this model, distance, slope, and distance imes slope were important regression predictors of travel unloaded, and these factors re reasonable from a physical standpoint. Other factors such as number of logs and eight were eliminated in the regression analysis, as one would expect, since the carriage s not loaded during the TU element.

Model #1

$TU = -7.60 + 0.01173DI - 0.01958DI \cdot SLO + 16.01SLO$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
DI	44.00	44.00
DI•SLO	52.48	8.48
SLO	61.68	9.19

$R^2 = 61.68\%$, $\sigma^2 = 0.37$, $F = 83.17$, $4(x)F^{.05} = 10.72$

Model #2

$TU = 11.21 + 0.00144DI - 36.37SLO + 31.47SLO^2$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
DI	44.00	44.00
SLO	47.52	3.52
SLO^2	51.57	4.05

$R^2 = 51.57\%$, $\sigma^2 = 0.47$, $F = 55.01$, $4(x)F^{.05} = 10.72$

Model #3

$TU = 12.80 + 0.00150DI - 39.65SLO - 0.0121TEMP + 34.99SLO^2$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
DI	44.00	44.00
SLO	47.52	3.52
TEMP	51.57	4.05
SLO^2	54.32	2.75

$R^2 = 54.32\%$, $\sigma^2 = 0.45$, $F = 45.77$, $4(x)F^{.05} = 9.8$

Model #4

$TU = -8.79 + 0.01425DI - 0.02096DI \cdot SLO + 17.98SLO - 0.000022DI \cdot TEMP$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
DI	44.00	44.00
DI•SLO	52.48	8.48
SLO	61.68	9.19
DI•TEMP	67.94	6.26

$R^2 = 67.94\%$, $\sigma^2 = 0.32$, $F = 81.60$, $4(x)F^{.05} = 9.8$

Figure 5.--Travel unloaded (TU) statistics

It is obvious that for short yarding distances the prediction models can result in unreasonable times. Forcing the models through the origin in order to correct this deficiency was tried but this resulted in significantly lower R-square values and higher variances. Logs were not generally yarded with the balloon system unless they were several hundred feet from the yarder. Therefore, not much data were available for the shorter distances during the model building. As with any regression equation, care should be exercised when using the equation for predictive purposes. Use of short distances should be avoided, especially since they are not normal balloon yarding range.

Of the TLO models built, four were approximately the same in reference to the six criteria (fig. 6). Since they were approximately the same, model number one chosen. It was fairly easy to use and did not depend on the limited temperature (TEMP) and wind velocity (WINVEL) data. The resulting equation:

$$TLO = 0.10 + 0.0123LDI - 0.386LSLO + 0.541LSLO^2 + 0.000073LDI^2$$

has an R-squared of 58.44 percent. Only the first two variables, LDI and LSLO, normally would be included in the model for predictive purposes since the last two variables add little to the cumulative R-squared. Plots of the data and the physical situation, however, showed a definite quadratic relationship with LDI and LSLO. The contribution of the quadratics to the predictive equation is significant only at long lateral yarding distances (LDI) and steep lateral slopes (LSLO). Extension of the data on these variables could be used to verify and refine the model. The variables used in model number one had a physical relationship to the TLO element and were the only variables left after the regression screening process.

The HC variable was found to be best explained by its mean:

HC = 1.01, with a variance of 0.606 as shown below:

Mean	1.01
Median	.70
Variance	.606
Skewness	2.3632.

None of the independent variables were significant predictors of the time required to hook the chokers. The number of logs per turn would normally be expected to affect the time for HC, but in balloon logging, the chokers are preset so that the hooking operation only requires attaching the choker rings to the tagline.

Four satisfactory TL models were found using the six criteria. Model number one (fig. 7) was selected as the "best" model, due to its relative simplicity and lack of dependence on WINVEL:

$$TL = 1.28 + 0.00138DI + 0.0000868WT - 1.151LSLO - 1.626LSLO^2 + 0.00508LDI$$

with an R-squared of 27.86 percent.

Only the first three variables need to be included for predictive purposes; the last two variables ($LSLO^2$ and LDI) add little to the R-squared value. Travel loaded is a function of distance and weight as would be expected. Involvement of lateral slope and lateral distance arise from the first operation in the TL component, wherein the logs are yarded from their position to the side of the skyline before they can be yarded along the skyline. All the independent variables, except distance, contribute relatively small values to the R-squared; however, these additional variables improve the residual plots at the extremes. Hopefully, the R-squared value could be increased by trying the model on a larger range of data from another balloon logging site.

Model #1

$TLO = 0.10 + 0.123LD1 - 0.386LSLO + 0.541LSLO^2 + 0.000073LD1^2$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
LDI	54.12	54.12
LSLO	57.30	3.18
$LSLO^2$	57.86	0.56
$LD1^2$	58.44	0.59

$R^2 = 58.44\%$, $\sigma^2 = 0.22$, $F = 54.15$, $4(x)F^{.05} = 9.8$

Model #2

$TLO = 0.01 + 0.0184LD1 - 0.000173LSLO \cdot LDI^2 + 1.65LSLO^2 - 0.0267LD1 \cdot LSLO^2$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
LD1	54.12	54.12
$LSLO \cdot LD1^2$	57.96	3.84
$LSLO^2$	58.97	1.01
$LD1 \cdot LSLO^2$	59.69	0.71

$R^2 = 59.69\%$, $\sigma^2 = 0.22$, $F = 56.99$, $4(x)F^{.05} = 9.8$

Model #3

$TLO = 1.40 + 0.0072LDI - 0.0267WINVEL - 0.0074TEMP + 0.000113LD1^2$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
LDI	54.12	54.12
WINVEL	61.39	7.27
TEMP	62.67	1.28
$LD1^2$	64.02	1.34

$R^2 = 64.02\%$, $\sigma^2 = 0.19$, $F = 68.49$, $4(x)F^{.05} = 9.8$

Model #4

$TLO = 0.76 + 0.0090LDI - 0.00033TEMP \cdot WINVEL + 0.0000012LD1 \cdot TEMP$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
LD1	54.12	54.12
TEMP·WINVEL	62.49	8.37
LD1·TEMP	63.81	1.33

$R^2 = 63.81\%$, $\sigma^2 = 0.19$, $F = 91.11$, $4(x)F^{.05} = 10.72$

Figure 6.--Travel laterally out (TLO) statistics

Model #1

$TL = 1.28 + 0.00138DI + 0.0000868WT - 1.151LSLO - 1.626LSLO^2 + 0.005076LDI$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
DI	16.39	16.39
WT	19.94	3.56
LSLO	24.47	4.52
$LSLO^2$	26.71	2.24
LDI	27.86	1.15

$R^2 = 27.86\%$, $\sigma^2 = 0.75$, $F = 11.82$, $4(x)F^{.05} = 9.16$

Model #2

$TL = 1.63 + 0.00139DI - 0.000268WT \cdot LSLO - 8.14SLO^2 \cdot LSLO^2 + 0.0672LDI \cdot SLO^2$
$- 0.114LDI^2/DI$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
DI	16.39	16.39
$WT \cdot LSLO$	22.80	6.41
$SLO \cdot {}^2LSLO^2$	27.14	4.34
$LDI \cdot SLO^2$	29.79	2.65
LDI^2/DI	31.68	1.89

$R^2 = 31.68\%$, $\sigma^2 = 0.71$, $F = 14.19$, $4(x)F^{.05} = 9.16$

Model #3

$TL = 1.61 + 0.00158DI + 0.000087WT - 1.10LSLO - 1.94LSLO^2 - 0.0145WINVEL$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
DI	16.39	16.39
WT	19.94	3.56
LSLO	24.47	4.52
$LSLO^2$	26.71	2.24
WINVEL	27.96	1.25

$R^2 = 27.96\%$, $\sigma^2 = 0.75$, $F = 11.88$, $4(x)F^{.05} = 9.16$

Model #4

$TL = 1.81 + 0.00205DI - 0.000157WT \cdot LSLO - 0.0361TEMP \cdot SLO^2 - 0.00051TEMP \cdot WINVEL$
$+ 0.06535WT/DI$

Variable	Cumulative R-squared (%)	Increase in R-squared (%)
DI	16.39	16.39
$WT \cdot LSLO$	22.80	6.41
$TEMP \cdot SLO^2$	27.47	4.67
$TEMP \cdot WINVEL$	30.78	3.31
WT/DI	33.46	2.69

$R^2 = 33.46\%$, $\sigma^2 = 0.70$, $F = 15.39$, $4(x)F^{.05} = 9.16$

Figure 7.--Travel loaded (TL) statistics

The unhook chokers model was found to be best explained by its mean

UC = 0.88, with a variance of 0.323

as shown below:

Mean	0.88
Median	.70
Variance	.323
Skewness	2.8166.

None of the independent variables were found to be significant predictors of this component, probably because of the highly variable conditions and locations of the log decks.

CONCLUSIONS

An alternate method of predicting total turn time (TT') was formed by summing the component models:

TT' = TU + TLO + HC + TL + UC.

The "best" component models for TU, TLO, and TL were used to predict the time required for these factors. Time required for HC and UC was estimated using their mean values. The correlation between the summed component predictors and the observed data was calculated and then squared. This psuedo R-squared was 0.4264; the standard error of the predicted values was 1.829. These statistics for TT' were then compared with TT model number one (fig. 4) which had an R-squared of 0.4269 and standard error of 1.836. Since the additive model built from the components was more complex than the TT model, it was concluded that the TT model was the best total turn time model for this study. The similarity of the two sets of statistical values indicates that the models were properly selected for both the components and the total turn.

As a final check, the TT model was tested using 15 observations which had been randomly selected prior to the analysis and set aside for this purpose. The psuedo R-squared (defined in the same way as in the preceding paragraph) was 0.4262, and the standard error was 1.837. These agree very well with the statistics for the best TT model. This implies that the model is doing a reasonable job of predicting the response variable, total turn time.

The variables in the models developed in this analysis do not explain as much as the variation in the dependent variables as was initially expected. The R squared values for the dependent variables were: 42.69 percent for TT, 61.68 percent for TU, 58.44 percent for TLO, and 27.86 percent for TL. The authors feel that a more quantitative method of rating the coded independent variables would increase the R-squared values. This conclusion was based on observations made over a wide range of conditions as compared to the conditions encountered during the relatively short stay of the time study crew. The models also could be improved by expanding the range of the independent variables. This would require many more observations, however, because of the number of combinations of variables and the possibility of interactions between the variables.

There are other possible sources of error in the equations which would be obvious to anyone who has worked or studied logging operations, but those presented are felt to be most important.

There are intangible human factors that affect operator and logging crew efficienc on a daily basis. The data from this study easily could have been influenced by the method logging crews were paid. Payment strictly for the number of hours worked gives little incentive to increase production. Payment based on production (i.e., logs yarded/day or MBF/day) tends to increase production as long as the rates are fair. On the balloon logging job, payment was on an hourly basis plus a bonus for each log yarde above a daily quota. This sounds like a satisfactory method of payment and it did work well most of the time. Occasional difficult logging conditions, however, made it extremely difficult for the crew to surpass their daily quota no matter how hard they worked. This tended to discourage the crew and production decreased. At the other extreme, under ideal logging conditions the crew could greatly surpass their daily quota. The crew would then produce enough logs to receive a bonus, but not enough so that the company raised their quota for bonus pay. The problem of how to set quotas could be aided by time and motion studies such as this.

The statistics for the various models provide basic information about the relative importance of various factors for those studying balloon logging operations. The regression equations serve as guidelines for predicting time required to complete various portions of the balloon logging cycle. Persons using the equations should familiarize themselves with balloon logging and keep in mind the limitations of the equations that have been presented here.

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Hartsog, William S., and James Cass.
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Time and motion studies were conducted on an experimental balloon logging show in the Idaho Batholith during 1973. Selected variables were divided into three classes: those involving the time required for each portion of the logging cycle, factors directly related to the yarding operation, and independent variables. Variables were then partitioned into four groups so that easy comparisons could be made between predictive models. The resulting regression equations serve as limited guidelines for predicting time requirements for the various portions of the balloon logging cycle.

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-K, A FUNCTION FOR THE MODELER

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e^{-K}, A FUNCTION FOR THE MODELER

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RESEARCH SUMMARY

Manipulating the parameters of e^{-K}, a variant of the Normal function, generates a great variety of bell-shaped curves. These curves, or portions thereof, are useful in developing mathematical descriptors for graphed hypotheses of the relations between continuous variables (regression relations). Like the Normal, e^{-K}, responds sigmoidally to departures from a pivotal value in X and to changes in the point of inflection within the X-range. Slope of the sigmoidal face at the inflection point varies additionally with change in power of the negative exponents for the e-components. All sigmoids are forced to zero at the extremities of the applicable range (the pivot point, X_p, $\pm X_p$) to enhance control of the curve system by the modeler. Within this range, e^{-K} varies from zero to one and the appropriate form of e^{-K} can be scaled to the value of the objective curve at X_p. Along with curves of the class X^n, e^{-K} is particularly useful in developing mathematical descriptors for curves with unique shapes and/or those involving complex interactions. A five-dimensional application is shown.

CONTENTS

INTRODUCTION

The December 1975 issue of Biometrics featured "A Review of Response Surface Methodology from a Biometrics Viewpoint" by R. Mead and D. J. Pike. Along with methods review, the authors examined applications in current biological literature and identified a variety of statistical improprieties. The formulation of weak hypotheses is one of these. It was noted that, when transformations are used, simple polynomials predominate and that "Polynomials seem to be used as the simplest readily available smoothing curve, without any appeal to their theoretical properties as approximations to the true response function," (p. 816-817). In the presence of adequate incentive for analysts to follow technical direction, this finding would suggest lack of emphasis on hypothesis development in statistical texts and in the curriculums of statistical schools. In any event, a brief discussion of hypothesis development is in order here as support for the presentation of e^{-K}, a family of curves designed to facilitate mathematical characterization of hypotheses that have been established graphically.

HYPOTHESIS DEVELOPMENT

A condition for valid statistical evaluation of hypotheses is that they be developed independently of the data sets used for evaluation. Analysts, then, must rely on knowledge, intuition, and conjecture to establish their concepts of the underlying forms of the relations being considered. When expressed graphically, possibly the usual case, mathematical descriptors for these relations must be established as the hypotheses to be evaluated.

There is perhaps little reason to search for exact mathematical forms to represent conceptual models regarded as weak by the analysts generating them. Descriptors based on low-degree polynomials will probably suffice.

But, as conceptual models elicit more confidence, they should be more accurately represented by mathematical hypotheses. This could necessitate a time-consuming search for appropriate *existing* functions, possibly contained in a list similar to that provided by Mead and Pike (p. 817). Direct *development* of suitable functions by the analysts, however, may prove to be a more satisfying and perhaps even a more efficient alternative. The exact nature and reliability of the graphed hypotheses are emphasized in this process and full control of the form of the descriptor is achieved by the analyst. Mathematical descriptors should meet the acceptance criteria of the analysts involved (Bartlett 1947; Draper and Hunter 1969). The parent function, e^{-K}, provides a versatile base from which to develop mathematical descriptors for forms of widely differing shapes.

Data sets reserved for evaluation of hypotheses and excluded as sources of information in the development thereof may contain information beyond that included in the original hypotheses. After evaluation, analysts are free to exhaust such data sets of new information graphically or by any means available and to incorporate these findings into advanced hypotheses. These may give rise to further research and to new data with which to evaluate advanced hypotheses.

Methods for exhausting data of information directly are shown by Jensen and Homeyer (1970, 1971) and Jensen (1973). And again e^{-K} is a transformation alternative that can be used in developing mathematical expressions for graphed hypotheses of the relations between continuous variables.

e^{-K}: ITS DERIVATION, CAPABILITIES AND LIMITATIONS

The new function, simply identified as e^{-K}, provides the analyst with a finite sour of versatile transformations for use when it is inefficient to search for alternatives or when alternatives are inadequate. While e^{-K} is not a panacea for all the problems modelers face in developing functional relationships, it along with curves of the class X^n $(n \geq 1)$, does serve a broad spectrum of transformation needs with no particular limi tations as to curve shapes for which it is most useful. Methods for developing mathematical descriptors using these functions have been treated by Jensen and Homeyer (1970 1971), and Jensen (1973, 1976).

A variant of the normal, the new function is defined as:

$$e^{-K} = \frac{e^{-\left|\frac{(X/X_p) - 1}{(X_I/X_p) - 1}\right|^n} - e^{-\left|\frac{1}{(X_I/X_p) - 1}\right|^n}}{1 - e^{-\left|\frac{1}{(X_I/X_p) - 1}\right|^n}} \quad , \; 0 \leq X \leq 2X_p$$

where,

e = natural logarithm base.

X_p = pivot point in X, for e^{-K}.

I = point of sigmoidal inflection in X.

X_I = absolute departure of I from zero to X_p or, from $2X_p$ to X_p.

n = power of negative exponents for e.

The divisor X_p is retained throughout the equation for e^{-K} to preserve correspondence with the proportional X-format of the descriptor development system associated with e^{-K} in Jensen and Homeyer (1970).

The left numerator, like the Normal, generates a system of bell-shaped curves abou X_p. These curves reach the maximum value of 1.0 at X_p, decline sigmoidally and symmetrically on either side of X_p with increasing absolute departure of X from X_p, and reach zero at ~~$X_p \pm X_p$~~. Sigmoids on either side of X_p are forced into different areas of two-dimensional space by shifting I, the point of inflection, and the slope of the sigmoidal face at I, changes with n.

User control of the curve system is enhanced if all curves of the set range in value from zero to one within a finite domain of X. To achieve this property, curves generated by the left numerator have been forced through zero at $X_p \pm X_p$ as follows:

Let the left numerator = e^{-T} and let $e^{-T_O} = e^{-T}$ at $X = 0$ or $\pm X_p$. Consider the residuals generated by $1-e^{-T}$. Expanded by the inverse $(1-e^{-T_O})^{-1}$ and subtracted from one, we have

$$e^{-K} = 1-(1-e^{-T_O})^{-1}(1-e^{-T})$$

which simplifies to the final form,

$$e^{-K} = (e^{-T} - e^{-T_O})(1-e^{-T_O})^{-1}$$

Then, the right numerator and the denominator serve to force curves of the left numerator through zero at $X_p \pm X_p$. This domain, along with X_p, can be altered to accommodate skewed conceptual models by adding constants (+ or -) to the X-scale. The apparent complexity of e^{-K} is much reduced by the fact than in application the right numerator and the denominator reduce to constants or approach zero and can be deleted.

Sample arrays of curves from the left half of this function (a mirror image of the right half) are shown in figure 1. Sets are shown for n = 1.5, 3.0, 5.0, and 10.0. Each set has curves progressing from X_I/X_p = 0.1 at the left to 0.9 at the right. It is evident that a great variety of sigmoid (and bell-shaped) curves can be generated with e^{-K}. These curves or any portions thereof provide an almost endless potential for matching graphed curves and describing them mathematically. Given that Y_p is the peak value of Y (the dependent variable) on the objective curve, the selected e^{-K} function may be scaled to that curve through multiplication by Y_p.

A descriptor (X_T), adopted as a hypothesis in its entirety, may be fitted to pertinent data by least squares in the simple model,

$Y = \beta X_T + \varepsilon$, where the ε are NID $(0, \sigma^2)$, constant variance, and $\hat{\beta} = \Sigma X_T Y / \Sigma X_T^2$

Weighted regression procedures are recommended where the variance about regression is *not* uniform over the ranges of the independent variables. In such cases, reasonable success in achieving constant variance has been obtained by solving for departures $(Y_i - \hat{Y}_i)^2$ or d_i^2 as a suitable function of the related $\hat{Y}_i$ in $d^2 = b\hat{Y}^n$. Then the weight, w, for each observation is set equal to $1/\hat{Y}^n$ and a weighted β in $Y = \beta\hat{Y}$ is estimated as $\hat{\beta} = \Sigma w\hat{Y}Y/\Sigma w\hat{Y}^2$.

More complex, generally iterative fitting procedures, such as the Newton-Raphson method, can be used to arrive at statistical estimates of internal model parameters (*see* Damaerschalk and Kozak 1977; Draper and Smith 1966).

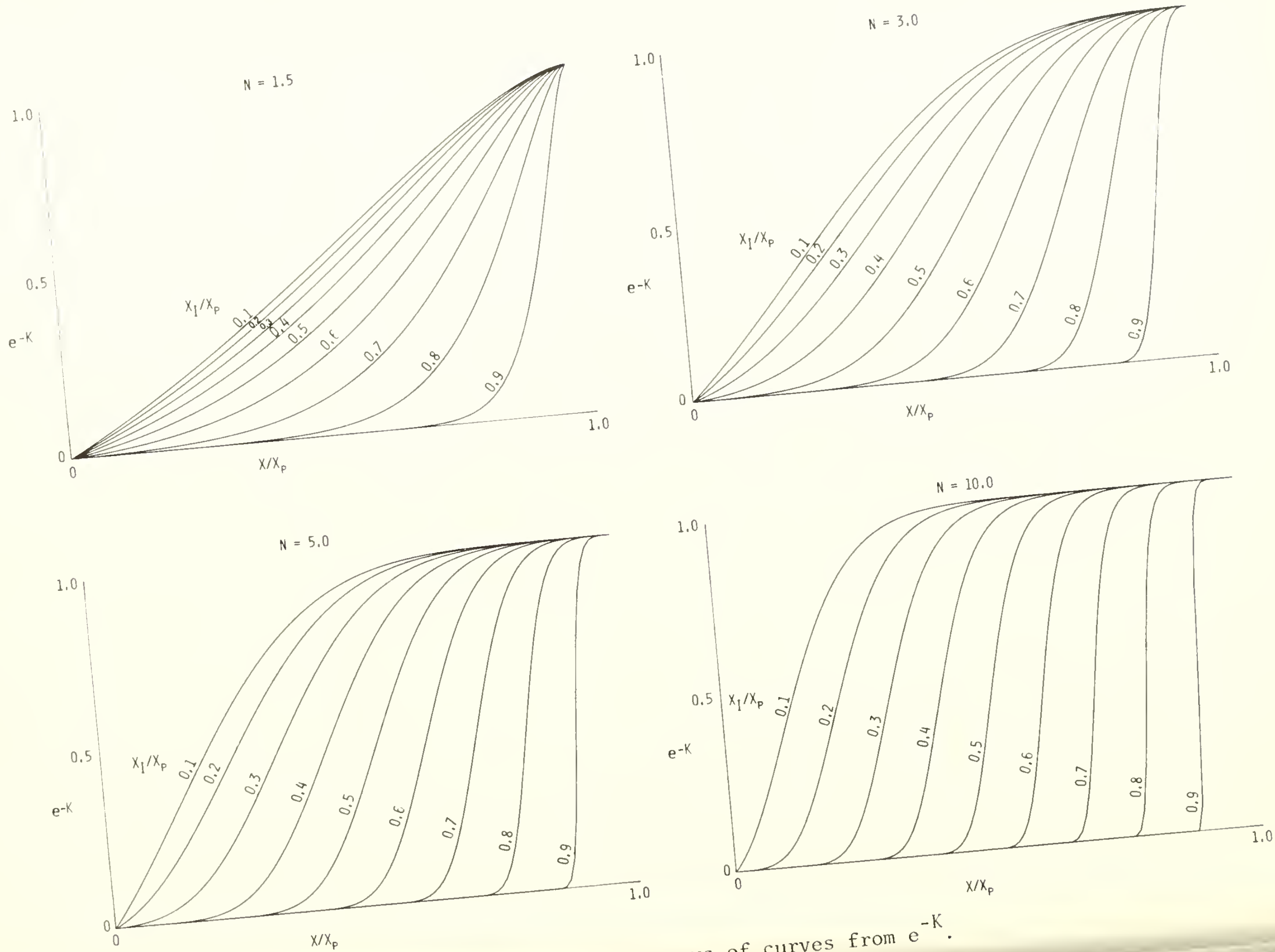

Figure 1.--Sample arrays of curves from e^{-K}.

e^{-K}: A FIVE-DIMENSIONAL APPLICATION

The flexibility of e^{-K} in representing a complex relation is evident in the five-dimensional interaction pictured in figure 2. Here an index to intensity of deer use of forest openings created by clearcutting in western Montana is expressed as a function of opening size, height of new vegetation, depth of slash in the opening, and depth of dead and down timber adjacent to the opening. (Data were provided by L. Jack Lyon, Wildlife Research Biologist, Forestry Sciences Laboratory, Intermountain Forest and Range Experiment Station, Missoula, Montana).

The data at hand, however, were initially committed to statistical evaluation of the linear effects of the above and other independent variables on the intensity index. These were virtually the simplest regression hypotheses that could have been developed. In this case, the evaluation provided only weak support for expected results and yielded little new information.

At this point, an advanced hypothesis was developed for the set of four independent variables above judged to be of high utility to the land maanger. Prior knowledge on the forms of the relations, including interactions, between these variables was summarized. Subject to these constraints and adhering to the data-fitting principles of "least deviations" (Karst 1958), the data were then graphically exhausted of associated curve form and scaling information and appeared to provide strong support for the dynamic interaction anticipated. Procedures specified by Jensen and Homeyer (1970, 1971), and Jensen (1973, 1976) were used to develop a functional form X_T for the graphed interaction. This was refitted to the data by least squares in the model $PGR = \beta(X_T) + \varepsilon$ and $\beta = 0.9721$. The adjusted model is specified below:

$$PGR = f\ (VI,\ SI,\ SO,\ Acres)$$

where,

PGR = number of deer pellet groups per acre inside the opening.

VI = height of vegetation in feet, inside the opening.

SI = depth of logging slash in feet, inside the opening.

SO = depth of dead and down timber, in feet, outside the opening.

Acres = size of opening in acres.

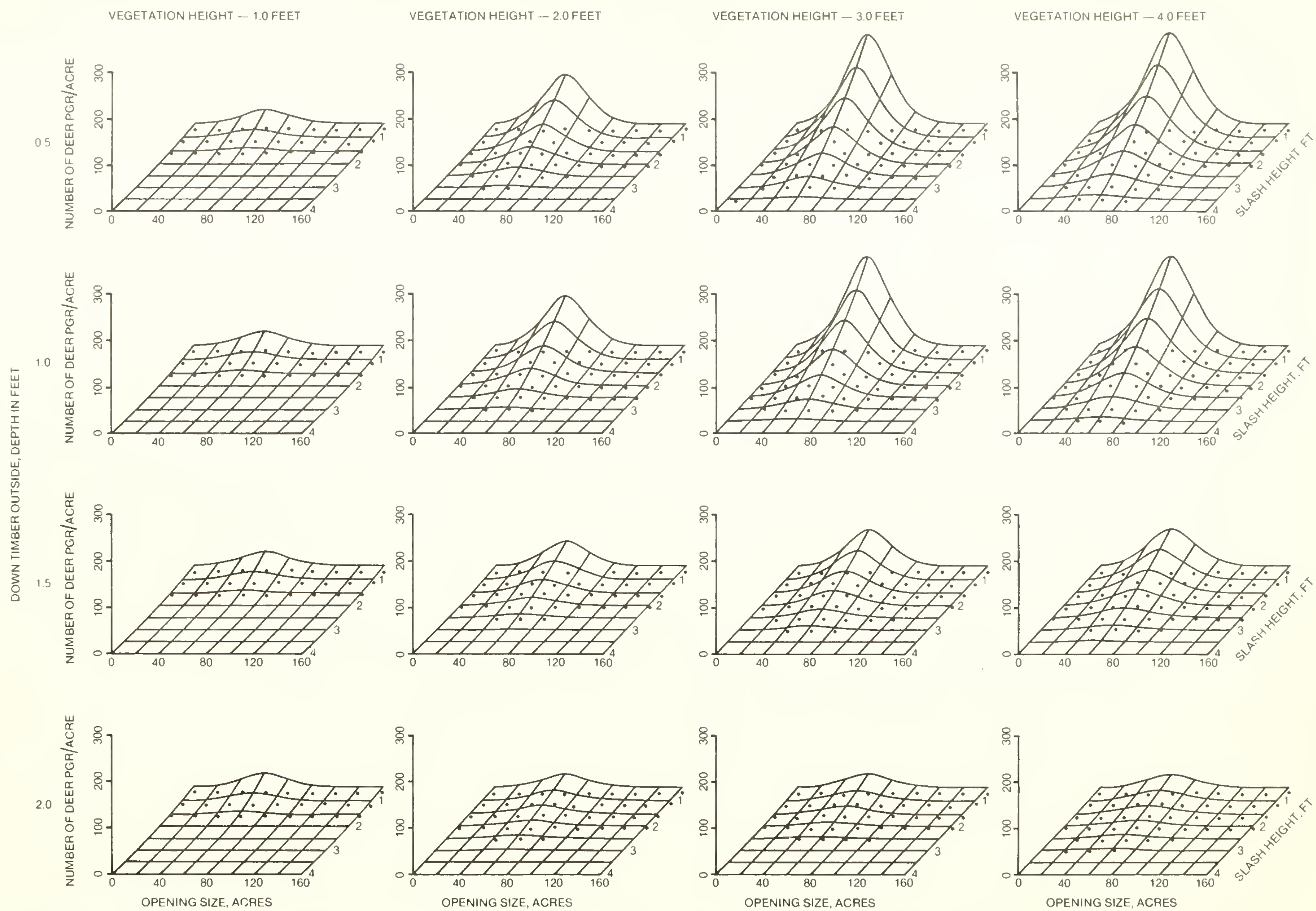

Figure 2.--Intensity of deer use of clearcut forest openings in western Montana, PGR = pellet groups per acre.

PGR = f1 (VI, SI, SO, Acres)

IF SI ≤ PO

$$\text{PGR} = \left\{ \frac{Y_p}{(\text{PO} - 0.6)^{1.55}} \left| \text{PO} - \text{SI} \right|^{1.55} \right\} (0.9721)(50$$

where

$$Y_p = Y_pS \left\{ \frac{ e^{-\left| \frac{\frac{\text{Acres} + 200}{260} - 1}{(X_I/X_p) - 1} \right|^{1.75}} - e^{-\left\{ \frac{1}{(X_I/X_p) - 1} \right\}^{1.75}} }{ 1 - e^{-\left\{ \frac{1}{(X_I/X_p) - 1} \right\}^{1.75}} } \right\} + 0.23$$

$$Y_pS = 0.57 + 3.23 \left\{ e^{-\left| \frac{\frac{VI}{8} - 1}{0.76} \right|^{20}} \right\} \left\{ e^{-\left| \frac{\frac{3 - SO}{3} - 1}{0.492} \right|^{10}} \right\}$$

$$\text{PO} = 6.289\, e^{-\left| \frac{\frac{VI}{10} - 1}{0.999} \right|^{10.5}} - 2.289$$

$$X_I/X_p = 0.897 - 0.067\, e^{-\left| \frac{\frac{VI}{8} - 1}{0.404} \right|^{3.5}}$$

IF SI > PO

~~DI~~ PGR = 0

Limits

$0 \le SI \le 4, \quad 0 \le SO \le 3$
$0 \le VI \le 8, \quad 0 \le \text{Acres} \le 300$

$R^2_{lin} = .21, \; R^2_{X_T} \doteq .71$

Graphic development of the model described by this function apparently resulted in great sensitivity to the interaction information contained in the data. But, since the degrees of freedom thereby sacrificed were unknown, conventional statistical parameters were not estimable. Some indication as to the goodness-of-fit of the functional form to the data set from which it was largely derived is provided by the proportion of the total sum of squares explained by the model $R^2 = 0.71$ here. Contrast this with the R^2 of 0.21 achieved with a minimum-effort additive regression model wherein linear effects of the same four independent variables have been fitted to the data by least squares. It would appear, at least, that sharp focus on interaction formulation was justified.

The complexity of the foregoing function may seem unwarranted but it must be recognized that mathematical constraints are necessary to the description of relationships involving such unique forms and strong interactions as are pictured in figure 2. Familiarity with the descriptor development techniques used makes it possible to interpret the form and magnitude of parameter effects from the function itself, although the net functional effect is generally more important to the user and is much more easily understood in the computer-produced graphic display (fig. 2). This has already been determined to be an excellent medium for communicating analytical results to users, land managers in this case. Also, e^{-K} has been found quite simple to manipulate on a desk-top computer.

Although new data were not available to evaluate the advanced hypothesis statistically, the model elicited intuitive confidence to the extent that it was adopted as an interim management tool.

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KEYWORDS: regression, model, transformation, bell shaped, sigmoidal, multidimensional, curvilinear interaction, response surface.

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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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PRESERVATION OF DEAD LODGEPOLE PINE POSTS AND POLES

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Ogden, Utah 84401

CONTENTS

INTRODUCTION

The northern Rocky Mountain area has a tremendous number of dead lodgepole pine nus *contorta* var. *latifolia* Dougl.) trees that have accumulated in the region's ests. Most of these trees were killed by the mountain pine beetle (*Dendroctonus* *derosae* Hopk.) during the past 25 years and, because of environmental conditions, arge proportion of the dead trees are still sound. A recent report (Lyon 19[illegible]) icated that trees larger than 8 inches (20.3 cm) in diameter will stand indefinitely.

Because of their size, straightness, minimum taper, and ease of preservation, en lodgepole pine trees have been preferred in the northern Rocky Mountains for ceposts, railings, corral poles, and utility poles. Tegethoff and others (1977) e determined that about 38 percent of the dead lodgepole pine trees in southeastern ho satisfy the specifications for power poles.

Use of dead trees for posts and poles has several distinct advantages: (1) the er percent moisture content of the dead trees eliminates or reduces the relatively g air-seasoning time required for green wood products; (2) the lower moisture cont also eliminates the necessity of acquiring and maintaining a large inventory, and uces hauling costs to and from the treating plant; (3) the preservative penetrates coats the wood surrounding various openings, thereby reducing the amount of reated wood exposed to fungous attack; and (4) removal of these trees from the est extends the timber supply, improves esthetics, and reduces fire hazard.

The objective of this investigation was to obtain information on the processing preservation of posts and poles made from dead trees. Three studies, two of ts and one of poles, were made at separate commercial treating operations where ferent treating methods and schedules were used. The studies are discussed arately.

PRESERVATIVE TREATMENT OF FENCEPOSTS BY THE COLD SOAK OR STEEPING METHOD

Procedure

Seventy-five lodgepole pine fenceposts were cut from stems that had been piled burning or from trees that had been felled in a precommercial thinning 4 years lier. Most posts from the thinned trees had retained their bark, but many obtained m the slash piles were without bark. The posts were taken from a single area in tern Montana.

In the field, posts were cut approximately 6.8 feet (2.1 m) long. In the laboratory, -inch (2.5 cm) disk was cut from each end of each post, and the posts were trimmed the desired length, 6.5 feet (2.0 m). The disks, identified as to post, were used the preparation of moisture content and specific gravity specimens. A strip, roximately 1 inch (2.5 cm) wide and containing the pith, was cut from the center tion of each disk. The strip was then sawed through the pith and specimens of sapd and heartwood were cut from each strip's half. The specimens obtained from one f were used for specific gravity determinations, and those from the second half moisture content determinations. Specific gravity was based on green volume and ndry weight. The ovendry method was used to determine moisture content.

Posts were separated into two groups, large and small, according to end diametei Thirty-six of the posts were classified as small and 38 were classified as large. Diameters of each post were measured before and after debarking. The diameters of tl small posts ranged from 2.6 to 3.4 inches (6.6 to 8.6 cm) at the small end and from 3.1 to 4.3 inches (7.9 to 10.9 cm) at the large end. The corresponding diameters foi the large posts ranged from 3.9 to 5.2 inches (9.9 to 13.2 cm) and from 4.4 to 5.7 inches (11.2 to 14.5 cm).

At completion of laboratory testing, the posts were taken to a commercial treati plant where each post was debarked, capped, and pointed prior to treatment. At this time, two large posts were discarded, leaving 36 of each size post to be treated. Also, 13 air-seasoned posts from green trees were combined with the study posts for control purposes. The posts were then placed upright in a series of tanks filled to depth of 30 inches (76.2 cm) with a 5 percent solution of pentachlorophenol in a ligh crude oil. Additional preservative was added during the 6-hour treatment to maintair the required depth. Three large posts, three small posts, and one control post, all selected at random, were removed from the tanks at 30-minute intervals. Two control posts were removed with the last group after 6 hours of steeping. The posts were the returned to the laboratory for examination.

A standard-size increment borer was used to extract a core from the approximate midpoint of the treated portion of each post. This boring was reserved for chemical analysis to determine the quantity of preservative absorbed. In addition, a disk was cut from near the midpoint of the treated area. The average sapwood depth and the average depth of penetration were determined from four measurements of each variable made on each disk. A chemical-indicating solution painted on the disk surface deline ated the heartwood/sapwood boundary.

The borings were evaluated at a commercial testing laboratory. The three boring from the large or small posts treated for a specific length of time were combined for analytical purposes; so 24 determinations were made of the borings from the dead tree posts. The borings from the control posts, too, were combined as follows: (1) posts treated 0.5, 1.0, and 1.5 hours; (2) posts treated 2.0, 2.5, and 3.0 hours; (3) posts treated 3.5, 4.0, and 4.5 hours; (4) posts treated 5.0 and 5.5 hours; and (5) borings from the two posts treated 6.0 hours.

Results and Discussion

The percent moisture content and specific gravity data for the small and large posts before treatment are summarized in tables 1 and 2. For the small lodgepole pin posts the average moisture content of the heartwood was 15.8 percent and the range wa from 14.2 to 18.1 percent. The average moisture content of the sapwood was 14.6 percent and the range from 12.3 to 18.3 percent. The average specific gravities of the heartwood and sapwood were similar 0.432 and 0.421, respectively (table 1). These results indicate that the posts were sufficiently dry for preservative treatmen and that no decay was present. The average specific gravity for lodgepole pine is 0.38 (U.S. Department of Agriculture 1974).

For the posts largest in diameter (table 2), the average moisture content of the heartwood was 23.0 percent and the range was from 18.8 to 27.5 percent. The moisture content of the sapwood averaged 19.8 percent and ranged from 16.5 to 23.8 percent. The average specific gravity of the heartwood was 0.430 and for the sapwood 0.419. The percent moisture contents were slightly higher than those normally attained for air-seasoned posts prior to treatment and were higher than the moisture contents of the small posts. The specific gravity values were practically the same as those for the small diameter posts.

Table 1.--*Summary*[1] *of average percent moisture content and specific gravity of test specimens taken from small lodgepole pine posts cut from dead trees before preservative treatment*

Length of treatment	Average moisture content		Average specific gravity	
	Heartwood	Sapwood	Heartwood	Sapwood
Hours	- - - - *Percent* - - - -			
0.5	18.1	14.3	0.439	0.40[illegible]
1.0	15.9	14.4	.436	.419
1.5	15.9	14.3	.459	.465
2.0	14.2	12.3	.459	.458
2.5	14.3	12.7	.412	.415
3.0	14.4	13.2	.423	.426
3.5	16.5	16.7	.438	.419
4.0	16.3	17.3	.425	.403
4.5	16.1	18.3	.438	.424
5.0	16.2	14.0	.425	.391
5.5	15.1	13.9	.391	.429
6.0	16.5	14.0	.439	.370
Average	15.8	14.6	0.432	0.421

[1]Each value is the average of six determinations.

Table 2.--*Summary*[1] *of average percent moisture content and specific gravity of test specimens taken from large lodgepole pine posts cut from dead trees before preservative treatment*

Length of treatment	Average moisture content		Average specific gravity	
	Heartwood	Sapwood	Heartwood	Sapwood
Hours	- - - - *Percent* - - - -			
0.5	23.7	20.3	0.444	0.416
1.0	21.9	19.4	.443	.472
1.5	21.0	17.9	.402	.387
2.0	26.4	21.1	.410	.461
2.5	18.8	17.5	.443	.402
3.0	23.8	21.7	.412	.396
3.5	20.5	17.4	.424	.402
4.0	24.9	23.8	.433	.424
4.5	27.5	22.1	.451	.413
5.0	23.3	18.5	.431	.400
5.5	20.4	16.5	.441	.415
6.0	23.5	21.8	.432	.405
Average	23.0	19.8	0.430	0.419

[1]Each value is the average of six determinations.

A slight difficulty was noted in the peeling of bark from the dead tree posts. These posts often were stopped in the debarker, and if the stoppages were not correct immediately an excessive amount of wood was removed. Also, the surface of the debark dead tree posts was rougher than the surface of posts from green trees. Roughness wa probably due to the lower moisture content at the time of debarking. Green tree post are usually debarked within a week or so after arrival in the yard and before air seasoning. A few of the treated posts are shown in figure 1.

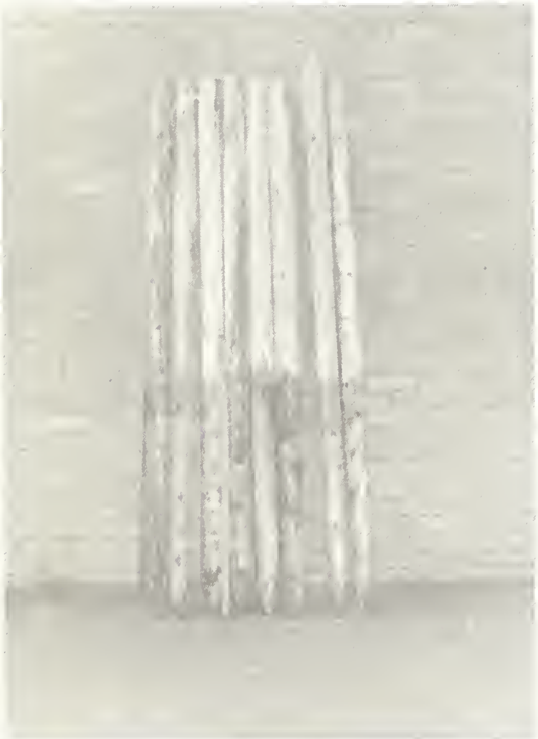

Figure 1.--A few of the lodgepole pine posts treated by the steeping method.

The disks taken from near the midpoint of the treated area were used to determin age, sapwood depth, and depth of preservative penetration. The average age of the small posts was 53 years and of the large posts, 67 years. The average sapwood depth was 0.47 inch (1.2 cm) and the average penetration, 0.46 inch (1.2 cm). These data indicate that the trees were relatively slow growing and that practically all the sapwood was penetrated by the preservative.

The borings were analyzed for preservative retention in accordance with American Wood Preservers' Association (AWPA) method A-5 (1969). The retention level specified for general-use fenceposts is 0.30 lb per ft^3 (4.81 kg/m^3), but the results of our analysis indicated that none of the treatments gave this minimum retention. The range of retentions was from 0.00 to 0.28 lb per ft^3 (0.00 to 4.49 kg/m^3)(tables 3 and 4). There was no consistent relation between the length of treating time, the depth of preservative penetration, and the pounds per cubic foot preservative retention. Neither was there a consistent difference between the large and small posts. The results from the control posts were also inconsistent. The average retention for these posts was 0.035 lb per ft^3 (0.56 kg/m^3) and the range was from 0.02 to 0.05 lb per ft^3 (0.32 to 0.80 kg/m^3).

The usual treating cycle for green tree posts is 24 hours. Obviously, our study-treating times were much too short to obtain adequate retention. Additional work needs to be done to determine the optimum treating cycle for dead tree posts by the steeping method.

Table 3.--*Summary of results taken from small fenceposts cut from dead lodgepole pine trees treated by the steeping method*

Post numbers	Length of treatment	Average sapwood depth		Average depth of penetration		Average retention	
	Hours	*Inches*	*cm*	*Inches*	*cm*	*Lb/ft³*	*kg/m³*
8,31,32	0.5	0.46	1.17	0.37	0.94	0.05	0.80
9,16,28	1.0	.48	1.22	.49	1.21	.14	2.24
17,36,37	1.5	.39	.99	.33	.84	.00	.00
23,30,40	2.0	.36	.91	.35	.90	.06	.96
14,22,24	2.5	.69	1.75	.58	1.47	.10	1.60
10,35,39	3.0	.49	1.24	.51	1.30	.12	1.92
7,11,20	3.5	.55	1.40	.58	1.47	.28	4.49
25,26,34	4.0	.51	1.30	.55	1.40	.05	.80
5,15,21	4.5	.62	1.57	.54	1.37	.18	2.88
6,13,19	5.0	.53	1.35	.64	1.63	.10	1.60
1,27,43	5.5	.45	1.14	.33	.84	.27	4.32
2,33,42	6.0	.42	1.07	.37	.94	.01	.16
Average		0.50	1.27	0.47	1.19	0.11	1.76

Table 4.--*Summary of results taken from large fenceposts cut from dead lodgepole pine trees treated by the steeping method*

Post numbers	Length of treatment	Average sapwood depth		Average depth of penetration		Average retention	
	Hours	*Inches*	*cm*	*Inches*	*cm*	*Lb/ft³*	*kg/m³*
31,33,39	0.5	0.49	1.24	0.34	0.86	0.21	3.36
1,4,24	1.0	.43	1.09	.33	.84	.12	1.92
11,28,37	1.5	.43	1.09	.48	1.22	.13	2.08
2,17,25	2.0	.39	.99	.36	.91	.06	.96
15,18,34	2.5	.36	.91	.35	.89	.08	1.28
9,22,38	3.0	.58	1.47	.65	1.65	.18	2.88
10,13,36	3.5	.58	1.47	.47	1.19	.27	4.32
8,20,35	4.0	.32	.81	.34	.86	.07	1.12
21,30,32	4.5	.46	1.17	.55	1.40	.08	1.28
5, 6,16	5.0	.49	1.24	.57	1.45	.14	2.24
7,19,23	5.5	.39	.99	.43	1.09	.10	1.60
3,12,26,27,29	6.0	.40	1.02	.46	1.17	.08	1.28
Average		0.44	1.12	0.44	1.12	0.13	2.08

PRESSURE TREATMENT OF DEAD LODGEPOLE PINE FENCEPOSTS

Procedure

Thirty-nine posts from dead lodgepole pine trees were taken from a single nationa forest in western Montana for use in this study. The same general procedure was followed in preparing the posts for treatment as in the preceding study. Disks were cut from both ends of each post and heartwood and sapwood specimens were cut from the disks for determination of specific gravity and percent moisture content. The posts were also cut to a uniform length, 6.5 ft (2.0 m).

The posts were next carried to a commercial wood-treating plant and all but five of the posts were debarked. The posts were then weighed to the nearest 0.5 lb (0.23 kg). The post number, weight, and end diameter were marked on metal tags and fastened to the respective post. Trams were used to transport the posts into the treating cylinder and the study posts were loaded on the last tram to enter the cylinder (fig. 2).

Figure 2.--Lodgepole pine study posts being loaded on last charge tram car prior to treatment by the pressure method.

After the cylinder is loaded and sealed, the usual treating procedure is to draw and maintain an initial vacuum of about 27 inches of mercury (9.83 kPa) for 30 minutes. At the completion of this interval, without releasing the vacuum, the cylinder is filled with the preservative solution and a pressure of 100 lb per inch^2 (689.48 kPa) is applied for 3 hours. The cylinder is then drained, the tram cars removed, and the posts unloaded and bulk piled until sold.

The preservative used is an unheated water solution, 1.50 to 1.75 percent of fluorchrome arsenate phenol, type B (Osmosalts). Sodium fluoride, sodium arsenate, sodium dichromate, and dinitrophenol are the principal preservative compounds.

The normal procedure was followed in treating the study posts except that the pressure period was reduced to 15, 30, or 45 minutes. After the pressure had been applied for 15 minutes, the cylinder was drained and opened, and 11 posts, including one with bark, were removed. After a second 15-minute pressure period another group of 12 posts, including one with bark, were removed; and after a third 15-minute pressure period, the remaining 15 posts, including three with bark, were removed. Upon removal, the posts were immediately reweighed to the nearest 0.5 lb (0.23 kg) and the end diameter was remeasured.

In the laboratory, a disk was cut from the approximate center of each post, and the age, sapwood depth, and preservative penetration were noted. The disks were then individually placed in polyethylene bags and shipped to the preservative manufacturer for chemical analysis. Increment borings, too, were taken from the post and sent for analysis.

Results and Discussion

Percent moisture content of the specimens taken prior to treatment ranged from 9.1 to 24.6 percent and moisture content averaged 13.2 percent. The specific gravity of the specimens ranged from 0.294 to 0.493 and averaged 0.378--about the same as the published value of 0.38 (U.S. Department of Agriculture 1974). The percent moisture content and specific gravity data are summarized by treatment in table 5.

Table 5.--*Before treatment summary of average percent moisture content and specific gravity of test specimens taken from fenceposts cut from dead lodgepole pine trees and treated with preservatives by three different pressure treating schedules*

Treating schedule	Number of posts	Average moisture content		Average specific gravity	
		Heartwood	Sapwood	Heartwood	Sapwood
		- - - - *Percent* - - - -			
30 min vacuum and 15 min pressure, 100 psi	11	13.3	12.1	0.377	0.371
30 min vacuum and 30 min pressure, 100 psi	12	12.3	11.6	.404	.368
30 min vacuum and 45 min pressure, 100 psi	16	14.1	15.8	.391	.363
Overall average		13.3	13.5	0.391	0.362

Again, debarking the dead tree posts demanded special attention to prevent excessive wood loss. Deep checks on the post surface caused the floating rosser head to stop the post and gouge the surface. Also, as before, the post surface was somewhat rougher than that of newly peeled green posts. A few of the study posts were of such low quality and appearance that under ordinary circumstances they would have been discarded.

The ages of the posts varied from 17 to 55 years. The sapwood depth ranged from 0.38 inch to 2.00 inches (1.0 to 5.1 cm). Preservative penetration measurements were made on the borings using Chrome Azurol S as a copper detecting reagent (AWPA Method A-3, 1969) and a mixture of O-anisidine hydrochloride and sodium nitrate as a pine heartwood indicator (AWPA M-2, 1969). The borings all showed 100 percent penetration of the sapwood. The post-treatment data are summarized in table 6.

Table 6.--*Summary of results obtained from fenceposts cut from dead lodgepole pine trees and treated with preservatives by three different pressure testing schedules*

Treating schedule	Number of posts	Average depth of sapwood		Average depth of penetration		Average preservative retention	
		Inches	*cm*	*Inches*	*cm*	*Lb/ft*^{3}	*kg/m*^{3}
30 min vacuum and 15 min pressure, 100 psi	11	0.85	2.16	0.84	2.13	0.517	8.28
30 min vacuum and 30 min pressure, 100 psi	12	.89	2.26	.89	2.26	.576	9.23
30 min vacuum and 45 min pressure, 100 psi	16	.88	2.24	.86	2.18	.701	11.23
Average		0.87	2.21	0.86	2.18	0.611	9.79

Preservative retention assays were performed on samples cut from the disks for each of the three treated groups. Individual samples were combined for each group and the group sample was assayed for copper, chromium, and arsenic by AWPA Method A-9 (X-ray emission spectroscopy). All samples exceeded the minimum retention of 0.4 lb per ft^3 (6.41 kg/m^3) of copper, chrome, and arsenic as required by AWPA C-5 for lodgepole pine fenceposts.

PRESERVATIVE TREATMENT OF POLES MADE FROM DEAD LODGEPOLE PINE TREES

Procedure

Thirty logs from dead lodgepole pine trees were selected in a sawmill storage yard for use in this investigation. The logs, 20, 25, or 30 ft long (6.1, 7.6, or 9.1 m) were suitable for poles in classes 5, 6, or 7. Ten of the poles were 20 ft long (6.1 m), 18 were 25 ft long (7.6 m), and 2 were 30 ft long (9.1 m). After selection, the poles were delivered to a commercial pole treating plant for processing and treatment.

Although the poles had very little bark, they were machine-peeled, numbered, and stored until time for treatment. During storage, the circumference at the top, butt, and groundline of each pole was measured and recorded and, in addition, a 1- or 2-inch (2.5- or 5.1-cm) thick disk was cut from both ends of the poles (fig. 3). These disks, numbered as to pole of origin, were used in the preparation of percent moisture content and specific gravity test specimens in the same manner described earlier for the fencepost disks.

Figure 3.--A few poles spread for examination and end sampling prior to treatment by the hot and cold bath method.

The poles were then randomly separated into two groups, based on length, and the oles in each group were randomly assigned a specific treatment. The six treating chedules and the number of poles from each group treated by the different schedules ere as follows:

Time	Poles used
Hours	
1. Six-hour hot bath followed by 12-hour cold bath.	5
2. Four-hour hot bath followed by 6-hour cold bath.	5
3. Two-hour hot bath followed by 6-hour cold bath.	5
4. Nine-hour cold soak.	2
5. Six-hour cold soak.	2
6. Four-hour cold soak.	2

CONCLUSIONS

The results of the three preservative treatment investigations indicate that som care should be exercised in selecting posts and poles from dead trees. The frequent occurrence of long, deep checks and wormholes results in lower quality and a higher cull factor in the dead tree products. In addition, greater care is required in processing the dead tree posts and poles. Posts exhibited a tendency to get stopped i the debarker and to be stripped of an excessive amount of wood, especially as the debarker head was passing over a deep or irregular check on the surface. This proble was not encountered in debarking the poles.

The debarked posts and poles were somewhat rougher on the surface than newly peeled green tree posts and poles. This undoubtedly was due to the lower percent moisture content of the dead tree products. More frequent maintenance of the debarkin head may aid in alleviating this problem.

The steeping method of preservative treatment gave inconsistent preservative retentions for the treating times used. None of the 85 posts treated by this method met the retention specification of 0.30 lb per ft^3 (4.81 kg/m^3). The retentions of th study posts ranged from 0.00 to 0.28 lb per ft^3 (0.00 to 4.49 kg/m^3). Although the greatest steeping time used was 6 hours, more time than that is needed. There are indications that the time required to treat dead tree posts would be less than the 24 hours needed to treat green tree posts.

Pressure treatment of dead lodgepole pine posts gave directly opposite results. All study posts, including those with bark met the preservative retention specificatic of 0.40 lb per ft^3 (6.41 kg/m^3). A treating cycle of 30 minutes vacuum and 15 minutes of pressure at 100 lb per $inch^2$ (689.48 kPa), the minimum treating time used, was more than adequate to obtain the necessary retention. The pressure treating time can thus be reduced to about one-twelfth the time needed to treat green posts.

Of the two treating methods used with poles from dead lodgepole pine trees, the results indicate that the hot and cold bath is the better method. All the poles treated by this method exceeded the specification requirements for preservative penetration and retention, 0.75 inch (1.9 cm) or 85 percent of the sapwood and 1 lb (0.45 kg) of dry pentachlorophenol in the outer 0.5 inch (1.3 cm), respectively. None of the poles treated by the cold soak method met the preservative retention requiremen and only the poles soaked for 9 and 6 hours met the preservative penetration requireme

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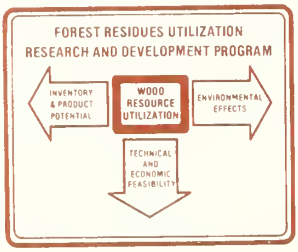

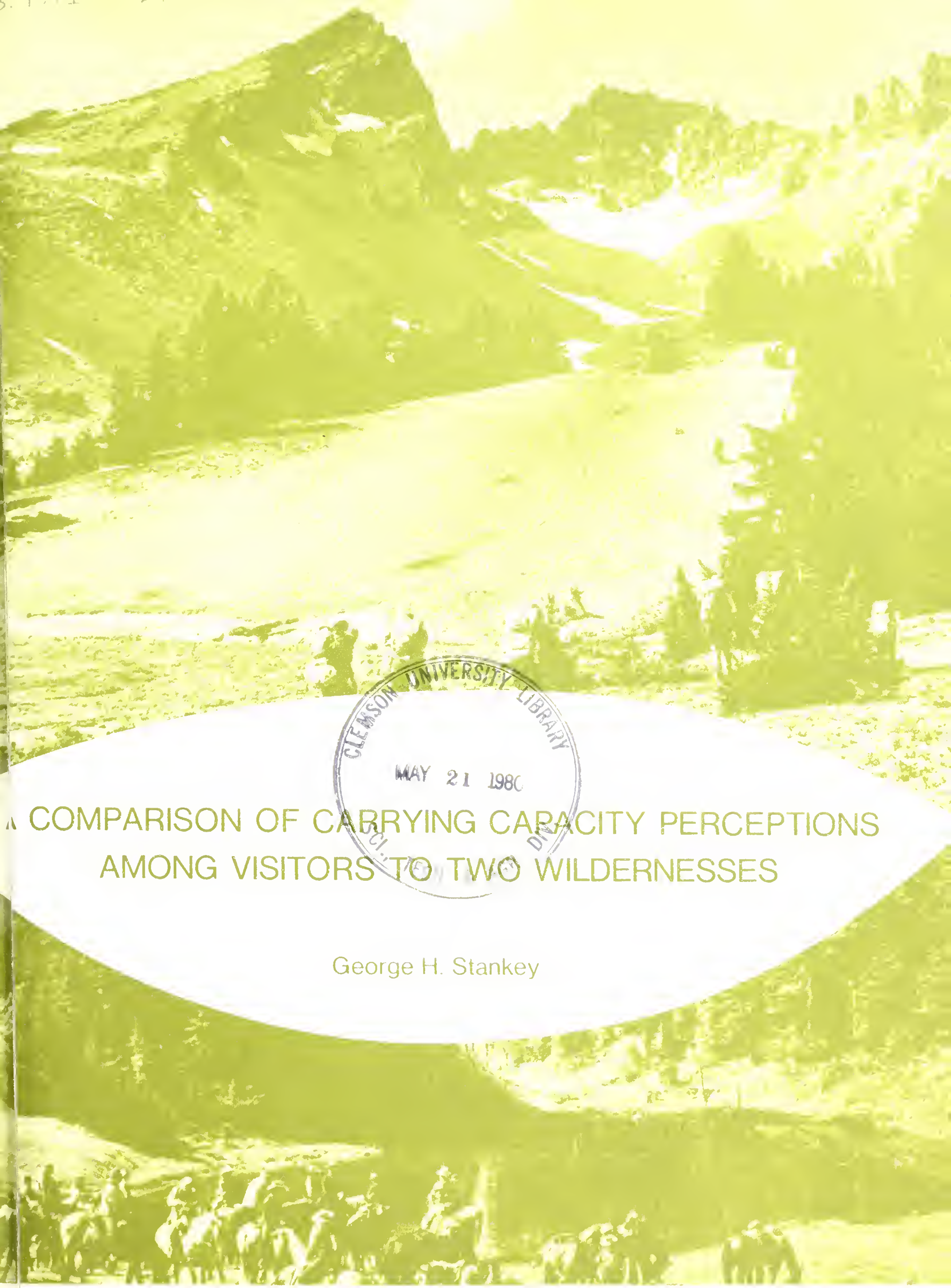

A COMPARISON OF CARRYING CAPACITY PERCEPTIONS AMONG VISITORS TO TWO WILDERNESSES

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RESEARCH SUMMARY

Visitors to two wildernesses - the heavily-used Desolation Wilderness in California and the lightly-used Spanish Peaks Primitive Area in Montana - were surveyed. Research objectives were to determine whether use levels produced differences in how wilderness was defined, what constituted appropriate use, the threshold at which crowding occurred, and what management actions were acceptable.

In terms of socio-economic characteristics, vistors to the two areas were similar. Type and pattern of recreational use differed, however: there was virtually no stock use or outfitter use in the Desolation Wilderness while day use and large parties were significantly more common in the Spanish Peaks. Most vistors in both areas reported previous wilderness use, although Desolation Wilderness visitors had more experience in the particular area.

Higher use levels in the Desolation Wilderness did not produce any appreciable difference among respondents in terms of generalized concepts of appropriate and desirable use. This finding is similar to the findings of other studies. Visitors in both areas hold common perceptions about wilderness and its use.

Significant differences were revealed in an analysis of the preference for inter-party contacts and the consequences of not finding preferred conditions. For contacts with backpackers and with large parties (defined as 12 or more people), medium satisfaction levels were consistently higher at increasing levels of contact in the Desolation Wilderness than in the Spanish Peaks. No contact with other parties at campsites was especially important in both areas. In general, it appears that Desolation visitors, exposed to higher use levels, have become more tolerant of heavy use than their Spanish Peaks counterparts.

Nevertheless, while tolerant, it is evident Desolation Wilderness visitors perceive high use as contributing to impact on the area; they were twice as likely to report that area quality was worse than before and that the area was used beyond its capacity. Perhaps as a result of the perception, nearly half of the Desolation Wilderness visitors who reported the area as used beyond capacity changed either the length or route of their trip to avoid crowding.

When use exceeds capacity, visitors in both areas agree that restrictions should be imposed. But there were differences in the types of controls favored. Not only was there a greater acceptance of regulation in the Desolation Wilderness, there was also more acceptance of direct regulation of use and users. Desolation vistors were more supportive of party size regulation and the control of stock numbers.

The data support the need for managers to be flexible and sensitive in their imposition of visitor management programs. Although the type of experience sought by visitors in these two areas were similar, individual differences in use intensity suggest the necessity of adjusting programs to meet particular circumstances. However, it is important that management impose regulation only as is necessary and be careful not to enact excessively regimenting actions before they are needed.

CONTENTS

INTRODUCTION

Over the past two decades, many studies have investigated recreational carrying pacity. Although some authors believe the concept of carrying capacity has only mited application to recreation and wilderness management (Wagar 1974; Bury 1976; berlein 1977), there is general recognition that increasing use can produce environ- ntal and social changes inconsistent with management objectives. It is also generally cognized that carrying capacity cannot be set without defining values that are to be phasized in management (Heberlein and Shelby 1977). Research provides estimates of e probable consequences of alternative decisions, but it cannot define the "right" swer--how much recreational traffic is "too much."

Most students of recreation and wilderness management recognize that carrying pacity judgments derive from two factors: First, the physical-biological impacts sulting from use represent one "cost" that managers must evaluate in determining ether some level of use is "too much." In some areas, substantial impact might be lerated (at a site managed for off-road vehicle use), while at others only limited anges in the natural order would be acceptable (wilderness). In any case, the *gnitude* of the impact is a relatively objective dimension amenable to precise measure. e *importance* associated with these impacts, on the other hand, will vary according to e relative values held by managers, visitors, and the general public.

Second, the impact of use on the experiences derived from different opportunities e of concern in carrying capacity judgments. High-density conditions might be appro- iate for certain opportunities (city parks, group campgrounds), while in other cases, w-density levels would be required (wilderness). Again, the magnitude of the social pacts is subject to relatively objective measures (how many interparty contacts occur some use level), but the importance of these impacts in affecting the visitor's perience will differ among various recreation opportunities and between visitors and nagers.

In an earlier investigation of attitudes about wilderness carrying capacity (Stankey 73), similar perceptions were discovered among four areas even though there was a -fold difference in use between the lightest and most heavily used areas. Neverthe- ss, there is concern that attitudes as to what constitutes excessive use ("crowding") ll gradually shift to more lenient definitions as visitors encounter heavier use and velop a tolerance to it. As these perceptions shift, people who still seek low-density portunities will be gradually displaced by those with greater tolerance to higher use tankey 1973; Shelby and Nielsen 1976; Heberlein 1977).

It is difficult to determine whether definitions of acceptable levels of use are adually changing. Most previous studies have been one-time, cross-sectional investi- tions; they have not been followed up to examine changes.

As noted above, an earlier study of four wildernesses having different physical aracteristics and use patterns, indicated no important differences in attitudes about pacity. In the study reported here, two areas similar in size and topography were osen. Visitors to these two areas--the Desolation Wilderness in California and the anish Peaks Primitive Area in Montana--were surveyed with an identical questionnaire.

Several issues were investigated: (1) preferences for meeting other groups; (2) pected impact on satisfaction associated with varying hypothetical contact levels; (3) pact of actual use levels on the area's capacities; (4) impact of encounters on spondent travel behavior; and (5) preferences for management techniques.

STUDY AREA DESCRIPTIONS

Table 1 compares the two areas' use and acreage as well as selected indices of dispersion potential and density. Annual visitation in the Desolation Wilderness wa approximately 18 times greater than the Spanish Peaks. Although the California area greater potential for dispersion of use (about 2-1/2 times as many access points and 3 times as much trail mileage per 1,000 acres [405 ha]), the two density measures still suggest a much greater intensity of use there.

Table 1.--*Comparison of use in the Desolation Wilderness and Spanish Peaks Primitive Area*

Area	Size	Entry points/ 1,000 acres	Trail miles/ 1,000 acres	Visitor days	Visitor days/acre	Visitors/ trail mile
	Acres					
Spanish Peaks (1970)	50,616	0.14	0.51	16,900	0.3	348.5
Desolation Wilderness (1972)	63,475	.35	1.56	305,700	4.9	3,084.5

STUDY METHODS

Sampling Procedures

Visitors to the Spanish Peaks Primitive Area were sampled from the third week i June 1970 and through late November. In the Desolation Wilderness, sampling covered entire year of 1972, although the bulk of use occurred during the same time period a in the Spanish Peaks.

Compiling a list of wilderness visitors adequate for sampling is difficult (Luc and Oltman 1971). In this study, two methods were used, which with the 2-year inter between studies, complicates data comparison. This problem will be discussed in sub quent sections.

In the Spanish Peaks, names were obtained by using special registration signs a personal field sampling at selected trail heads. The sign advised visitors that a research study was under way and requested that each person 16 years or older provid their names and addresses on a card. The sign was used at trail heads in the area where hiker use predominated (previous research indicated visitors using horses were less likely to register). On trails where horse use was significant, a field worker was present on sample days to contact all entering and exiting parties.

A list of names and addresses was prepared, using no more than one member of a particular group. A systematic interval sample of 452 individuals was drawn.

Four follow-up mailings were made to increase the response rate. Of the 431 deliverable questionnaires, 409 usable ones were returned, a 95 percent response rat Responses from individuals contacted in person were weighted so they might be combined with those obtained from the special registration sign (trails covered in pers were sampled on only some days; trails where the special sign was posted were, of course, covered every day), yielding an adjusted number of 515.

In the Desolation Wilderness, names were randomly sampled from a list of persons
ceiving wilderness permits during the 1972 season. A total of 350 names were sampled,
it 11 questionnaries were returned by the Post Office; 286 usable responses were
otained from the remaining 339 for a response rate of 84 percent. Thus, our sampling
iverse was composed of individuals who obtained a permit for their groups. Because
ie sample is based on groups rather than individuals (as in the Spanish Peaks), data
or the two areas are not fully comparable. For some types of data, such as socio-
onomic characteristics, substantial variations might be expected between persons
efined as the "party leader" and the other group members. However, for other data,
ich as attitudes about wilderness, less variation apparently exists.

For example, Jubenville (1971) found no significant differences between party
eaders and other party members on a series of attitude statements about wilderness.
ie study reported here focuses primarily on visitor attitudes.

The sum consequence of these differences--time of study, individual versus group
impling frame--mean that it is difficult to accurately assess observed differences
etween the two areas. Are they a function of real differences (for example, use
evels) or are they some complex function of differences in time or survey method?

VISITOR PROFILES

Three different types of descriptive data for users were collected: who they were,
w they used the wilderness, and their outdoor recreation experiences.

Socioeconomic Profile

A brief socioeconomic profile of users was developed, based on questions regarding
e, education, sex, and student status. Additionally, visitors were questioned regard-
g their membership in any conservation or outdoor recreation organizations. These
ta are presented in table 2.

Table 2.--[illegible]

Area	[illegible]
Desolation	[illegible]
Spanish Peaks	[illegible]

Area	[illegible]
Desolation	[illegible]
Spanish Peaks	[illegible]

Area	[illegible]
Desolation	[illegible]
Spanish Peaks	[illegible]

[illegible]

How names were collected affects interpretations of resulting data, particularly for descriptive information. For example, self-selected party leaders, such as we ar dealing with in the Desolation Wilderness, probably have important differences from other party members--namely, they could be more experienced, older, and so on.

Despite these problems, the data in table 2 are more striking for similarities than for differences. In both areas, educational attainment is high, with nearly hal of all visitors reporting a college degree or postgraduate work. This is consistent with previous studies of wilderness users throughout the country (Outdoor Recreation Resources Review Commission 1962; Hendee and others 1968; Echelberger and Moeller 197 The age distribution of visitors to the two areas is also similar, with slightly over one-third 25 years or younger, 40 percent between 26 and 40, and nearly one-fourth over 40 years of age. In the Spanish Peaks, only those persons 16 years or older wer asked to register; in the Desolation Wilderness, the party leader registration obtain from the mandatory permit probably also resulted in an upward bias in the age profile Nevertheless, the overall age profile is similar.

The distribution of females and males is reliable only for the Spanish Peaks, where *all* visitors were asked to register and names from this list were randomly chos Again, the party leader bias in the Desolation sampling list almost certainly over-estimates males. In the Spanish Peaks, males outnumber females two to one; at the ti of this study, wilderness recreation appears still to be predominantly a male activit but this situation is probably in flux and rapidly changing.

Finally, we found that a substantial number of visitors in both areas were still students, but they are clearly a minority (approximately one-third).

Thus, our socioeconomic profile of visitors to the Desolation and Spanish Peaks suggests that both areas draw a similar clientele. This is as we suspected; wilderne visitors in previous studies have been typically found to be highly educated, drawn f a wide age range, male, and nonstudent (Outdoor Recreation Resources Review Commissio 1962; Hendee and others 1968; Stankey 1971, 1973; Echelberger and Moeller 1977).

Characteristics of Recreation Use

While user characteristics in the two areas were quite similar, the recreation u characteristics differed in several instances. Table 3 summarizes data for five use-related variables: method of travel, length of stay, party size, use of outfitters, a recreational activities.

Wilderness Activities

Both wildernesses were mainly used by backpackers. Virtually all use in the Desolation Wilderness was by backpackers while about one-fourth of the Spanish Peaks visitors used horses. Thus, the potential for conflict between travel methods was clearly present in one area and almost absent in the other.

Table 3.--*Characteristics of visitor use in the Desolation Wilderness and Spanish Peaks Primitive Area*

Area	Method of travel: Hiker	Horseback	Hiker with stock	N	Length of stay (number of nights): 0	1	2	3	4-5	6-7	8-10	11 & over	N
	- - - Percent - - -				- - - Percent - - -								
Desolation	99	0	1	285	22	21	21	16	12	6	2	1	283
Spanish Peaks	74	26	0	508	63	6	14	11	3	1	0	0	513

Area	Traveling with outfitter: No	Fully outfitted	Spot pack	N	Activities: Fish	Hunt	Photography	Nature study	Mountain climb	Swim	N
	- - - Percent - - -				- - - Percent - - -						
Desolation	99	1	0	286	47	2	64	49	7	49	286
Spanish Peaks	91	4	5	508	45	27	67	39	6	13	514

Area	Party size: 1	2	3	4	5-6	7-9	10 and over	N
	- - - Percent - - -							
Desolation	12	37	17	19	7	3	5	284
Spanish Peaks	5	23	16	19	15	11	11	499

Length of stay in the two areas varied significantly, with nearly two-thirds of the Spanish Peaks visitors reporting day use only. About one-fifth of the Desolation Wilderness visitors were day users; however, this figure probably underestimates actua day use because of the lower compliance among day users in obtaining a mandatory wilde ness permit (Lucas and Oltman 1971). Correcting for noncompliance, Lucas (review draf Forestry Sciences Laboratory, Missoula, Mont.) has estimated day use in the Desolation Wilderness to be about 40 percent, still significantly less than the Spanish Peaks. Trips of more than 3 days are more common in the Desolation Wilderness than in the Spanish Peaks.

Average party size in the two areas was significantly different. Two-thirds of the groups in the Desolation Wilderness had 3 or fewer people in them, while 57 percen had 4 or more in the Spanish Peaks.

Outfitter use was nonexistent in the Desolation Wilderness and accounted for less than 10 percent of the Spanish Peaks use. As in most wildernesses, visitors usually travel on their own.

Finally, most visitors reported participating in a variety of recreational activi ties. Fishing is a common activity, as is photography and nature study. Swimming is quite popular in the Desolation Wilderness. Hunting was reported by about one-fourth of the Spanish Peaks visitors, but by only 2 percent of the Desolation Wilderness respondents.

Outdoor Recreation and Wilderness Experience

Our final descriptive information concerned previous outdoor recreation and wilde ness experiences of the visitors (table 4). Visitors to both areas had similar childh camping experiences. Although the majority had auto-camped with their parents, most h not camped, hiked, or canoed remote areas. However, most had been introduced to wilde ness camping prior to our survey; only about 10 percent of the Desolation Wilderness visitors and 25 percent of the Spanish Peaks visitors were on their first wilderness t

Moreover, most were young when their first wilderness trip occurred; nearly one-half had made their first trip before the age of 15. Only about one-fifth of the visitors reported their first visit after the age of 26. However, this does not necessarily mean that age represents a constraint on use. It more likely reflects the fact that tastes are shaped early in life and that these patterns, once establishe are generally stable over time. Nevertheless, new entry does continue to occur past t age of 30.

Most visitors reported more than one visit per year as typical. These wilderness visitors may also be considered consistent users, with 8 out of 10 in both areas indic ing at least one wilderness visit each year. This is further supported by looking at the number of wilderness trips reported in the past 12 months. Overall, about half reported visiting a wilderness from 2 to 5 times in the previous year. About twice as many Spanish Peaks visitors as Desolation Wilderness visitors reported no visit in the past 12 months. About two-thirds of the Desolation Wilderness users reported a previo visit to that area, whereas only about half of those in the Spanish Peaks had been there previously.

Area	Frequency of auto camping trips as a child: Never	Occasionally	Often	N	Frequency of hiking or canoe camping trips as a child: Never	Occasionally	Often	N
	- - - Percent - - -				- - - Percent - - -			
Desolation	44	38	18	272	62	28	10	267
Spanish Peaks	46	36	18	466	58	31	11	481

Area	Was this your first wilderness visit?: No	Yes	N	Age at time of first wilderness visit: 1-5	6-10	11-15	16-20	21-25	26-30	31-35	36 & over	N
	- - - Percent - - -			- - - Percent - - -								
Desolation	88	12	283	5	21	23	19	14	7	5	7	243
Spanish Peaks	77	23	511	7	22	17	24	12	8	5	5	395

Area	Frequency of wilderness trips: More than once a year	About once a year	Once every 2 years	Less than once every 2 years	N	Number of wilderness trips in past year: 0	1	2	3	4	5	6-10	11-20	21 & over	N
	- - - Percent - - -					- - - Percent - - -									
Desolation	61	19	10	9	249	10	23	23	14	8	8	11	4	0	273
Spanish Peaks	60	22	6	14	405	19	19	15	14	9	5	14	4	1	514

Area	Previous visit to the Desolation Wilderness (Spanish Peaks)?: No	Yes	N
	- - - Percent - - -		
Desolation	33	67	287
Spanish Peaks	49	51	484

EXPECTATION OF VISITOR CONTACT

Eight statements were developed to determine visitor attitudes about wilderness, particularly feelings about the level and type of social interaction that was appropr ate. We were especially interested in comparing attitudes of visitors to the Desolat Wilderness, where use levels are high, with attitudes of visitors to the Spanish Peak where use levels are light. Did high use breed tolerance or were attitudes independe of actual use?

Levels and Types of Contact

How many other parties do visitors expect to encounter in wilderness? Are these expectations shaped by actual use in the area?

More than three-fourths of the visitors in both areas agreed with the statement, "It is reasonable to expect that one should be able to visit a wilderness area and se few, if any, people."

There was no difference between the two areas in responses to the statement. Th data suggest relatively uniform expectations of what a wilderness ought to provide--a ideal that most subscribe to regardless of the actual use found in the specific areas they visit.

Two additional questions were asked about interparty contact:

"It's most enjoyable when you don't meet anyone in the wilderness."

Area	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
			Percent			
Desolation	3	14	18	31	34	279
Spanish Peaks	2	13	15	28	42	497

Chi-square = 4.28, 4 df, p <0.50

"You should see at least one group a day in the wilderness to get the most enjoyment out of your trip."

Area	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
			Percent			
Desolation	16	36	24	20	4	285
Spanish Peaks	22	39	17	19	3	496

Chi-square = 9.47, 4 df, p <0.10

Again, the pattern of response is striking for its similarity rather than its dif
ference. About 2 out of 3 visitors to both areas agree that it is most enjoyable not
o meet anyone; the strength of this attitude appears to diminish slightly in response
o the second item. Spanish Peaks visitors did show a tendency to select the more ex
reme response category ("strongly agree" in the first item, "strongly disagree" in the
econd).

Socialization at Campsites

Previous work (Stankey 1973) suggests that contacts at campsites are a particularly
rucial problem. Two items were asked to determine the relative importance of solitude
t the campsite. As can be seen, there was virtually no difference in response between
he two areas for either item:

"Meeting other people around the campfire at night should be part of any wilderness trip."

Area	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
	- - - - - - -	- - - - - -	- Percent -	- - - - -	- - - - - -	
Desolation	14	35	30	19	2	281
Spanish Peaks	17	31	33	16	4	496

Chi-square = 4.34, 4 df, $p < 0.50$

"When staying out overnight in the wilderness, it is most enjoyable not to be camped near anyone else."

Area	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
	- - - - - - -	- - - - - -	- Percent -	- - - - -	- - - - - -	
Desolation	0	6	13	40	40	284
Spanish Peaks	1	7	14	43	36	503

Chi-square = 1.89, 4 df, $p < 0.75$

It is clear that minimal intergroup contact at the campsite is important for visitors
in both areas. While about half of the respondents disagree that "meeting others around
the campfire" is part of the trip, about one-third are neutral on the matter, suggesting
that some temporary contact might not be inappropriate. However, respondents clearly
endorsed the notion that campsites ought to be located in relative isolation. (We will
return to this issue when we examine preferences for interparty contact.)

A third element of the normative question of intergroup contact relates to perceived
differences among user groups and the subsequent effects on social carrying capacity.
Earlier work by a number of investigators (Lucas 1964; Stankey 1973; Lee 1975) suggests
that the presence of dissimilar groups contributes to feelings of crowding and
dissatisfaction.

Responses to these items varied more than previous items. The first item concern whether people who backpack differed from those who travel on horseback. Visitors thought the two groups significantly different:

"There is a great deal of difference between the kind of people who like to backpack in the wilderness and those who prefer to travel by horseback in the wilderness."

Area	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
	Percent					
Desolation	2	15	24	34	24	284
Spanish Peaks	7	25	24	29	15	495

Chi-square = 26.47, 4 df, p <0.001

About 6 out of 10 Desolation Wilderness respondents thought that backpackers were different from those who use stock; only slightly more than 4 out of 10 agreed in the Spanish Peaks. Stock use is certainly more common in the Spanish Peaks than in the Desolation Wilderness; about one-quarter of the respondents in the Montana area were using stock, compared to only one party in the Desolation Wilderness sample. When method of travel was used as the independent variable, we found that Spanish Peaks hikers were about twice as likely to agree with the statement as were stock users. In this sense, the Spanish Peak hikers were more similar to their Desolation Wilderness counterparts than they were to their fellow Spanish Peaks visitors on horseback.

While there was a clear difference on this item between the two areas and between hikers and horse users, our second item concerning other kinds of parties revealed no difference between areas and only a small difference between hikers and horsemen in the Spanish Peaks:

"Seeing a large party (a dozen or more people from a club, etc.) reduces the feeling that you are out in the wilderness."

Area	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
	Percent					
Desolation	1	12	8	42	38	284
Spanish Peaks	1	11	11	38	39	502

Chi-square = 3.13, 4 df, p <0.50

Large groups tend to be perceived as inappropriate in wilderness (Outdoor Recreation Resources Review Commission 1962; Stankey 1973). The typical style of use in both areas reflected this perceived inappropriateness; only 11 percent in the Spanish Peaks and 5 percent in the Desolation were in groups larger than 10 persons. About two-thirds of the horsemen in the Spanish Peaks agreed compared to three-fourths of the overall sample.

The final normative element concerned the relative importance of perceived crowding as compared to finding litter. More than half the respondents disagreed with the item below, but another 25 percent did concur. There was no difference in response between the two areas:

"Seeing too many people in the wilderness is more disturbing than finding a littered campsite."

Area	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
	- - - - -	- - - - -	Percent	- - - - -	- - - - -	
Desolation	12	42	17	19	10	281
Spanish Peaks	16	42	15	19	8	500

Chi-square = 0.44, 4 df, $p < 0.97$

Although most visitors apparently find the presence of litter, especially at their campsite, more disturbing than crowding, a significant minority do not.

In summary, despite sharp differences in use levels and intensities, visitors to the two areas hold highly similar notions of appropriate and desirable use. Exposure to higher use in the Desolation Wilderness does not appear to influence generalized concepts of desirable social interaction, given their similarity to those held by Spanish Peaks visitors. Spanish Peaks' visitors are somewhat less likely to believe that hikers and stock users are different from one another, but this response is largely accounted for by individual method of travel; Spanish Peak hikers are quite similar in their beliefs on this issue to Desolation Wilderness visitors, almost all of whom were backpackers. Horse users in the Spanish Peaks generally see little difference between themselves and hikers.

PREFERENCES FOR VISITOR CONTACT

Studies of visitor preferences are familiar to most managers. But as Driver and Bassett (1977) have discussed, the concept of "preference" is complex, with several distinct meanings. In this discussion, preference refers to the relative importance that visitors attach to some situation or condition.

Measures of preference were obtained for several different situations. Preferred amounts and types of use were measured separately. However, because these elements are not independent (users contacted and how they react involves not only how many, but also what kinds), an effort was made to calculate how varying amounts of different types of use affected expressed preferences.

Level of Contact

Preferences for contact with other groups were examined in two settings: along trails and at campsites.

Two questions tested visitor preference for trail contacts: "meeting many other people on the trail" and "meeting no one all day." Responses to the two items were related, as can be seen below:

"Meeting many other people on the trail"

Area	Bother a lot	Bother some	Neutral	Enjoy some	Enjoy a lot	N
			Percent			
Desolation	22	40	20	16	2	284
Spanish Peaks	28	39	21	11	1	502

Chi-square = 8.22, 4 df, $p < 0.10$

"Meeting no one all day"

Area	Bother a lot	Bother some	Neutral	Enjoy some	Enjoy a lot	N
			Percent			
Desolation	0	8	23	22	46	283
Spanish Peaks	0	4	30	18	48	504

Chi-square = 10.06, 4 df, $p < 0.05$

About two-thirds of the respondents in both areas indicated a preference for minimal contact with others. Meeting many others along the trail was bothersome to most and enjoyable to only a few; conversely, meeting no one all day was something most enjoyed. However, about one-fourth of all responses to these two items fell into the "neutral" category, suggesting the existence of a significant minority who find the level of contact, at least along the trail, to be relatively unimportant.

Crowding at campsites might represent a critical constraint on wilderness carrying capacity. This was confirmed by the response to the following item:

"Camping at a place where several other parties are camped"

Area	Bother a lot	Bother some	Neutral	Enjoy some	Enjoy a lot	N
			Percent			
Desolation	38	47	11	4	0	283
Spanish Peaks	42	41	14	3	0	504

Chi-square = 5.68, 4 df, $p < 0.30$

More than 8 out of 10 respondents in both areas would be bothered by the presence of others near their campsite. None indicated they would enjoy such contact. A small percentage of users indicated a neutral response to the item. There seems to be a fairly strong preference for campsites that offer complete or partial isolation.

To follow up on the question of what level of campsite development was considered appropriate, we next asked respondents, "When you are camped in the wilderness, how many other parties would you prefer camped within sight or sound of your campsite?" Overall, two-thirds of the respondents preferred a campsite with no other camps within sight or sound. Desolation Wilderness visitors showed slight preference for two other camps nearby. Low-density camping is clearly preferred and there is little preference for more than two other camps.

"Number of other camper groups preferred within sight or sound"

Area	0	1	2	3	4 or more	N
			Percent			
Desolation	60	12	18	5	5	267
Spanish Peaks	69	12	11	3	5	508

Chi-square = 11.40, 4 df, p 0.05

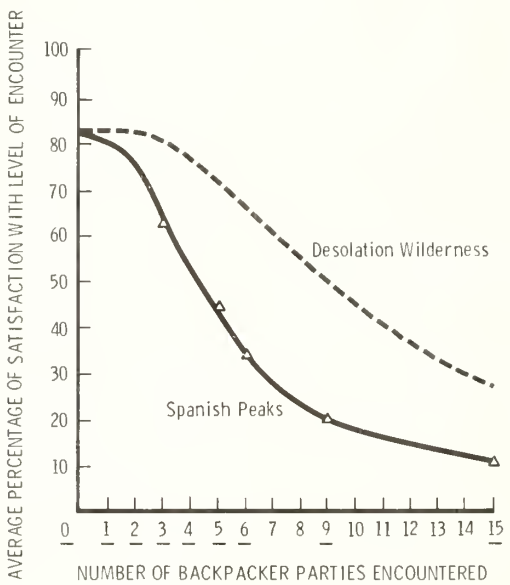
Amounts and Types of Contact

People who may not mind meeting two or three small backpacking parties may dislike meeting two or three similarly sized groups on horseback. Thus, it is difficult to dissociate preferences for amount of contact from preferences for types of contact. To deal with this problem, we asked a series of questions that probed how various amounts of different types of encounters affected visitor satisfaction with the level of interparty contact (as opposed to their satisfaction with the overall trip). The question required the respondent to judge a hypothetical situation; the question was to provide data for construction of a profile of the relationship between encounters and the hypothesized satisfaction with that encounter.

A number of investigators have found little or no relationship between actual use levels encountered and visitor reports of overall trip satisfaction (Lee 1975; Heberlein 1977; Neilsen and Shelby 1977). However, most also argue that it should not be inferred that crowding is not a problem or that people don't care about the level of use encountered. Thus, the most appropriate measure of satisfaction should be that associated with the level and mix of use encountered rather than the effects of interparty contacts on overall satisfaction. The purpose of the following data is to establish an index of what people prefer with regard to interparty contacts and the consequences of conditions that do not meet those preferences.

Four different encounters were described: (1) meeting average-sized backpacking parties (and no other kinds) on a 3-day trip; (2) meeting average-sized horseback parties on a 3-day trip; (3) meeting large parties (at least a dozen people) on the trail on a 3-day trip; and (4) camping within sight or sound of an average-sized backpacking party. Respondents were asked to consider various levels of encounters with these different groups (for example, no encounters at all in 3 days, etc.) and to state their level of satisfaction with that particular encounter level (see appendix for a discussion of some of the methodological problems with this technique). If a situation was perfectly satisfactory, they would indicate 100 percent; if totally unacceptable, 0 percent. Intermediate situations would be rated somewhere between 0 and 100. Although this required a major effort by respondents (more than 28 separate responses were needed) cooperation was excellent; more than 90 percent of the respondents fully completed the question.

Figures 1 to 4 show response to the questions. The curves are plotted on the basis of area averages. However, two intra-area tests for significance ($p < 0.05$) were also made. In both areas, the preferences of those visitors with less than 1 year's wilderness experience were tested against those with more than 1 year's experience. In the Spanish Peaks, attitude differences between hikers and horseback riders was tested (no such test was performed in the Desolation Wilderness because all visitors were hikers).



△ Statistically significant differences at the 0.05 level based on method of travel.

Underlined numbers represent contact levels for which data were collected.

Figure 1.--Reported satisfaction with backpacker contacts.

Figure 2.--Reported satisfaction with horseback party contacts.

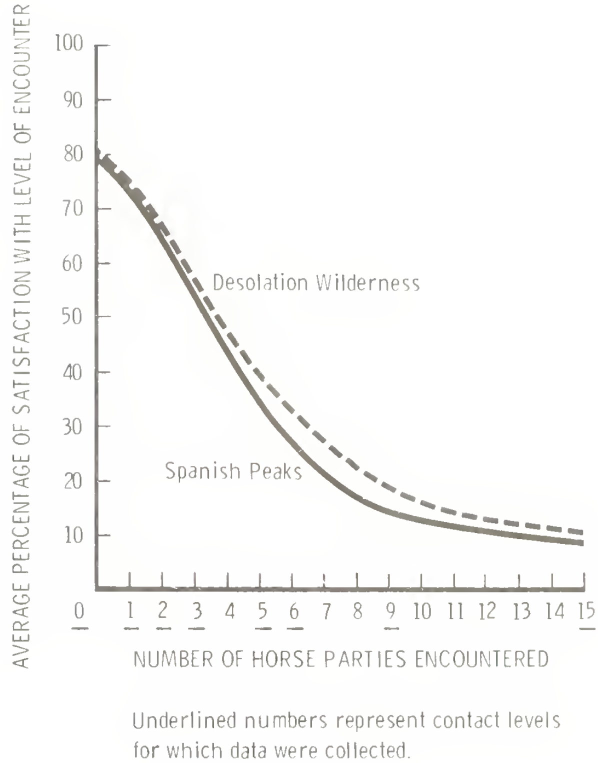
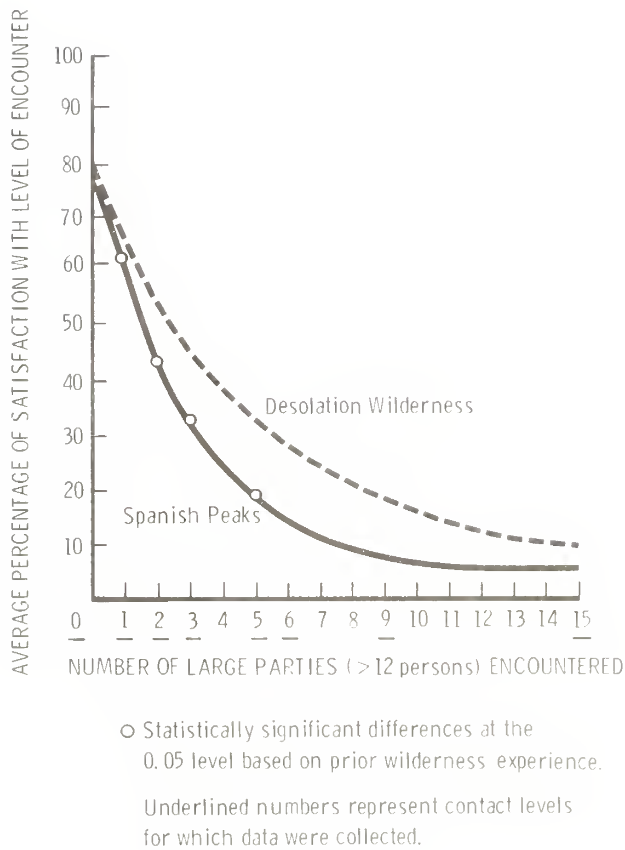


Figure 3.--Reported satisfaction with large party contacts.



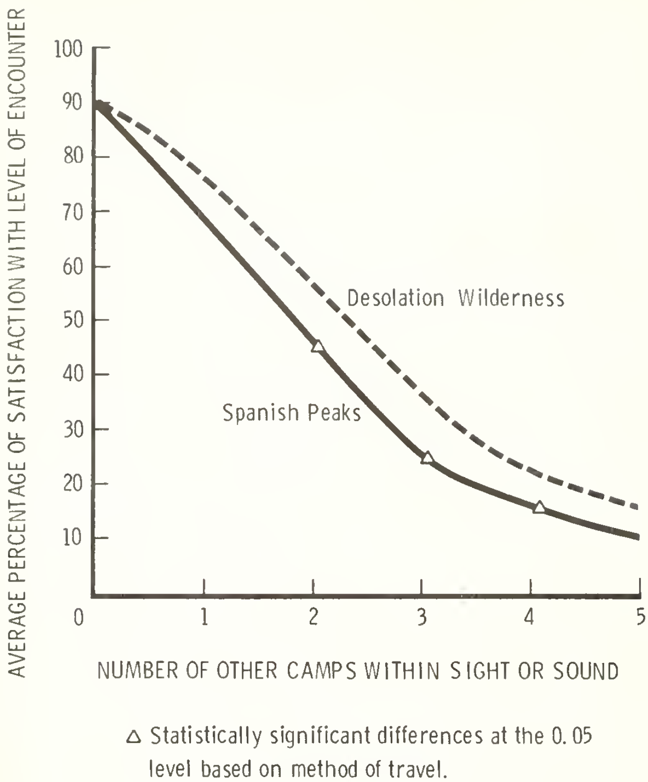


Figure 4.--Reported satisfaction with contacts at campsites.

In the Spanish Peaks, previous wilderness experience had little influence on preferred levels of contact, with the exception of encounters with large parties [defined as 12 or more people (fig. 3)]. Interestingly, more experienced users indicated a higher level of satisfaction with large parties than those less experienced. This may be related to the greater frequency of such parties in the area and the fact that repeat visitors are more accustomed to seeing them.

Tests for differences between hikers and horsemen in the Spanish Peaks also revealed little difference. One exception was the preference of contact with backpacking parties; hikers were more favorably inclined toward their fellow walkers than were horsemen (fig. 1).

In the Desolation Wilderness, no significant differences for preferred contact levels based upon previous experience were found.

A central interest has been the degree of similarity in preferred contact levels between the two study areas. At a general level, the image of wilderness and the wilderness experience seem closely shared, a finding previous reported (Outdoor Recreation Resources Review Commission 1962; Stankey 1973). But do the great differences in use intensity stimulate different notions of acceptable levels of interparty contact?

To answer this question, we examined the median levels of satisfaction reported in each area and tested for differences between the medians using a Kolmogorov-Smirnov test (Blalock 1972).[1] This interarea comparison allowed us to determine whether visitor attitudes were significantly different in two areas. Table 5 presents the results.

There is a statistically significant difference between the median values reported for backpacker contacts and encounters with large parties (defined as 12 or more persons). In the Desolation Wilderness, median satisfaction levels are consistently higher at increasing levels of contact than in the Spanish Peaks. In the Spanish Peaks, however, large parties appear more acceptable than in the Desolation Wilderness. Parties of a dozen or more people were about twice as common in the Spanish Peaks.

Table 5.--*A comparison of Desolation Wilderness and Spanish Peaks encounter tolerance levels*

Type of encounter	Number of encounters	Median level of satisfaction: Desolation Wilderness	Median level of satisfaction: Spanish Peaks	Level of significance
Backpacker	0	98	99	0.001
	1	95	90	
	3	90	70	
	6	70	25	
	9	50	10	
	15	19	0	
Horseback	1	90	90	NS
	3	60	50	
	6	21	10	
	9	1	0	
	15	0	0	
Large parties (<12 persons)	1	70	80	.001
	3	19	49	
	6	0	10	
	9	0	0	
	15	0	0	
Camping near other parties	0	100	100	NS
	1	89	80	
	2	61	49	
	3	30	11	
	5	1	0	

[1]Because of the highly skewed distribution of responses, the median values were selected as being more representative of central tendency than the mean (Blalock 1972). A Kolmogorov-Smirnov test was adapted to compare the cumulative frequency distributions of median satisfactions at different contact levels in the two areas. Because the cumulative distributions are based on median values rather than case observations, the actual sample sizes were used in computing the chi-square values rather than the sum of the distributions.

Horseback parties and encounters at campsites seem to evoke similar responses in the two areas. Although the level of satisfaction declines more rapidly in the Spanish Peaks for both types of encounters, the difference in the overall distributions is not statistically significant.

The similarity of attitude toward use of horses is especially interesting, given the virtual absence of horses in the Desolation Wilderness.

Although no difference in satisfaction is reported for no contact while traveling or while camped for the two areas, no contact at campsites is more desirable than no contacts on the trail. This concurs with earlier findings (Stankey 1973) indicating the importance of protecting campsite solitude and the possiblity that campsite capacity might be the critical factor in prescribing visitor capacity.

Differences in reported satisfaction from the two areas diverge rapidly with subsequent encounters. For example, with three trail encounters with backpackers, there is a 20 percent difference between the two areas; with six trail encounters, the spread rises to 45 percent.

In summary, table 5 reveals a high level of reported satisfaction with no contact conditions on the trail and at the campsite, and a relatively steady decline in satisfaction as contacts increase. However, Desolation Wilderness visitors exposed to substantially higher use levels have become more tolerant of conditions. Whether or not these norms will continue to demonstrate flexibility to accommodate greater use cannot be determined from these data. The data do suggest, though, that exposure does breed tolerance; thus reliance on some measure of satisfaction as an indicator of whether or not conditions are becoming unacceptable may not be warranted.

PERCEPTIONS OF ACTUAL CONDITIONS

The previous two sections have dealt with how visitors defined and perceived capacity in a hypothetical situation. We next consider how they perceived actual conditions and if, and in what ways, these conditions affected the trip.

Judgments about what constitutes "appropriate" or "acceptable" are, of course, dependent on the expectations that visitors hold. Expectations, in turn, are a function of many factors, including past experience in wilderness. Most visitors in both areas had previous wilderness experience: 77 percent in the Spanish Peaks and 88 percent in the Desolation Wilderness. A similar percentage in both areas visited a wilderness at least once a year.

Changes in Area Quality

We asked respondents who had previously visited the areas to indicate whether conditions were improving, getting worse, or unchanged. Although the majority of respondents in both areas felt that conditions were unchanged, visitors to the Desolation Wilderness were nearly twice as likely to describe conditions as worse than before:

"How does the quality of the area compare with the way it was?"

Area	Same	Better	Worse	N
	- - - - - - - -	Percent	- - - - - - - - - -	
Desolation Wilderness	54	4	43	18[illegible]
Spanish Peaks	70	6	24	258

Chi-square = 15.87, 2 df, $p < 0.001$

Specific complaints were the same in both areas--the increasing level of use and the growing presence of litter. Accurate, long-term records are not available for either area; thus, it is difficult to assess accurately how visitor perceptions relate to actual increases in use. Whether the perceived decline in quality is a function of measureable changes or of selective perception (remembering the good things that once were, forgetting the bad) is also not clear. Nevertheless, a substantial percentage of the Desolation Wilderness visitors reported that conditions were worse than before. In neither area do we find much support for the idea that conditions are improving.

The Relationship Between Use and Capacity

Returning to a consideration of all the sampled visitors, we next asked whether the respective areas were overused. No effort was made to define capacity or to specify whether social or ecological measurements (or both) should be used to define it.

Desolation visitors were more likely to define the California area as overused.

"Is the Spanish Peaks (Desolation) used beyond its capacity?"

Area	No	In a few places	In most places	N
	- - - - - - - -	Percent	- - - - - - - - - -	
Desolation	32	54	13	281
Spanish Peaks	72	25	3	185

Chi-square = 17.82, 2 df, $p < 0.001$

Two-thirds of the Desolation Wilderness visitors thought the area overused. In the Spanish Peaks, about 3 out of 4 felt the area was not used beyond capacity; most of those who thought it was overused thought the problems were localized (at one particular lake).

We next asked two questions of those who thought the areas were used beyond capacity--did excessive use bother them and did it influence their trip (their route or their length of stay)?

As expected, those who felt the area was used beyond capacity also indicated the overuse bothered them, as shown in the following tabulation:

"Did overuse bother you?"

Area	No	A little	Some	A lot	N
	Percent				
Desolation	0	12	49	39	187
Spanish Peaks	1	23	38	39	132

Chi-square = 8.55, 3 df, $p < 0.05$

Although visitors to both areas were bothered by overuse, Desolation Wilderness visitors responded more strongly to it. Perhaps a more significant measure of response is found in the data describing the behavioral reaction to overuse:

"Did overuse cause you to change the length of trip, route of trip, or both?"

Area	No	Length	Route	Both	N
	Percent				
Desolation	56	6	24	14	187
Spanish Peaks	75	3	9	13	132

Chi-square = 15.31, 3 df, $p < 0.01$

Whereas 3 out of 4 Spanish Peaks visitors did not find overuse sufficiently distressing to alter their trip, nearly half of the Desolation Wilderness visitors did. One out of four altered the route (easy to do in the open, gentle terrain). Length-of-stay and route-of-travel were altered by about the same percentage of visitors in both areas.

Thus, while previous responses from the two areas have been markedly similar, actual conditions do produce different perceptions of changes in area quality, level of crowding, and how crowding affects visitor behavior. The more heavily used Desolation Wilderness is perceived as crowded more commonly than the Spanish Peaks and visitors make more effort to avoid or offset these overcrowded conditions.

The situation in the Desolation Wilderness might be called a "predisplacement" condition. That is, the use conditions may be approaching the point at which one group, originally attracted by relatively low use, increasingly discovers this condition more difficult to find. At the same time, the nature of the existing opportunity is increasingly attractive to a new clientele drawn by the greater opportunity for social interaction. Thus, the potential for a "turnover" in the kinds of people found in the area must be recognized, one that could lead to a new series of attitudes and behavior, which wilderness managers might find difficult to accommodate in wilderness.

MANAGEMENT PREFERENCES

The final set of data concerns visitor preferences for management actions that could hold use within carrying capacity. Our interest centered on the acceptability of management actions, ranging from no control to tight restrictions on specific kinds of use.

A number of studies of wilderness users have highlighted the spontaneity and freedom of the experience as primary elements that attract people (Outdoor Recreation Resources Review Commission 1962; Hendee and others 1968; Stankey 1973). Freedom from increasing regulation may prompt many people to visit wilderness. At the same time, we have seen in both areas a substantial expression of concern about increasing use. In the Desolation Wilderness, 2 out of 3 respondents told us the area was used "beyond capacity"; more than 1 out of 4 felt the same about the Spanish Peaks. Thus, many visitors seeking freedom and spontaneity discover that the unregulated traffic is destroying the values sought.

We set out to discover how visitors felt about allowing use to continue unabated, thus preserving maximum individual freedom. Three statements were posed as follows:

"It would be better to be able to go to the wilderness whenever you want to, even if it was being used beyond capacity, than to have any kind of regulations on use."

Area	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
			Percent			
Desolation	46	37	9	4	4	283
Spanish Peaks	30	44	8	13	5	499

Chi-square = 31.60, 4 df, p <0.001

Visitors to both areas substantially disagreed with the statement. Unrestricted entry, when capacity has been exceeded, is clearly not acceptable. Desolation visitors are more inclined to disagree with the statement than Spanish Peaks users, which is not surprising considering the lighter traffic in the latter area.

We then asked to what extent visitors agreed or disagreed with the following statements:

"There should be restrictions on how many people can be in a wilderness at any given time."

Area	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
			Percent			
Desolation	1	7	6	51	35	282
Spanish Peaks	9	16	20	43	12	492

Chi-square = 101.00, 4 df, p <0.001

"If a wilderness becomes overcrowded, restrictions on the number of people allowed to visit it should be enforced."

Area	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
			Percent			
Desolation	2	4	3	41	51	283
Spanish Peaks	5	7	12	46	30	498

Chi-square = 45.61, 4 df, $p < 0.001$

About half of the Spanish Peaks visitors agreed with the first statement; in the Desolation Wilderness, nearly 9 out of 10 agreed. However, in the second item, which at first appears to merely restate the first, the differences in attitudes between the two areas, while still statistically significant, are much less sharp. The difference is linked to the fact that the first statement proposes use restrictions without considering carrying capacity. In the Spanish Peaks, where use levels are low and most visitors (72 percent) feel the area's capacity has not been exceeded, use restriction does not have overwhelming support (although more than half do agree with it). On the other hand, nearly 90 percent of the Desolation Wilderness visitors agree with the statement, an outcome that can probably be attributed to considering the item in the context of the situation in the Desolation.

When we look at the data for the second item, we find a sharp increase in the percentage of Spanish Peaks users supporting use controls. By specifying that use restrictions ought to be imposed only at such time the area becomes overcrowded, we have added an important new condition with which most Spanish Peaks visitors can concur. Apparently, Desolation Wilderness visitors distinguished very little between the two items, considering both in the context of the conditions in the area.

Specific Control Measures

Lime (1975) has described a continuum of management actions that range from subtle (such as providing people with better information) to authoritarian (such as rationing). In general, these actions can be grouped according to whether they directly influence the behavior of the visitor or indirectly influence behavior by persuasion, etc. Generally, indirect measures seem preferable to direct measures (Stankey and Baden 1977) and are favored by most wilderness users (Stankey 1973).

Visitors to the two areas were presented a list of possible management actions and asked if use of a wilderness was heavy and controls on use were being considered, to what extent they would favor or oppose each action. Table 6 presents the results in terms of the percentage of respondents favoring each technique.

The pattern of response is not clear and simple. In the Desolation Wilderness a majority of visitors favored a first-come, first-served permit system, a mail reservation system, a test of wilderness skills and knowledge, and blocking off access roads back from the wilderness boundary. In the Spanish Peaks, only a reduction in the number of trails and signs received as much as 50 percent support. Thus, there is greater acceptance for visitor regulation in the Desolation Wilderness than in the Spanish Peaks, as well as more acceptance of direct control.

Table 6.--Visitor support toward selected use-control measures

Policy	Percentage favoring		Level of significance
	Spanish Peaks[1]	Desolation Wilderness[2]	
	- - - - - - Percent - - - - -		
Require test of wilderness skills and knowledge (asked only in Desolation)	--	57	--
Reduce number of trails and signs	50	43	0.1
Block access roads back from wilderness boundary	45	53	.01
Issue permits on first-come, first-served basis	41	57	.001
Issue permits through mail reservation system	29	59	.001
Charge entrance fee	25	30	.02
Assign visitors to campsites	23	17	.02
Issue permits on a lottery basis	18	11	.05

[1]Sample size approximately 500.
[2]Sample size approximately 280.

A mandatory permit system is in effect in all California wildernesses, and although these permits were not used to regulate use in the Desolation Wilderness visitors are accustomed to obtaining one. As can be seen in table 6, there is substantial support for having to obtain a permit either on a first-come, first-served or mail reservation basis--techniques currently used to distribute the mandatory permits.

The lottery is the least-favored system in both areas. It has less support than either a fee or assigning visitors to specific campsites, measures that are frequently cited as being particularly inappropriate in wilderness (Stankey and Baden 1977).

Some favor requiring visitors to demonstrate knowledge and skill as a prerequisite to visiting wilderness (Hardin 1969). The idea is not new; Wagar (1940) suggested the idea of the "certified outdoorsman" back in the early forties. The idea is that by reducing the level of impact of each individual user, more onerous control measures, such as permits or fees, can be avoided or at least postponed.

Data on this type of control were obtained only for the Desolation Wilderness. Support was high, with only about one-fourth opposed to it. People have very little experience with this type of method for allocating outdoor recreation. The "Hunter Safety" program that requires a youth to pass a test of hunting knowledge and gun safety is perhaps the closest thing. However, the response does suggest such a technique might have promise for allocating entry to wilderness.

The overall pattern of response for the two areas is not strikingly dissimilar, but different techniques receive more support in one area than in the other. In general, there is less support for direct control in the Spanish Peaks (probably because visitors do not see a need for such action yet); preferences for indirect measures are mixed. Certain measures are clearly more preferable than others; the data strongly suggest that some standardized national program for controlling visitor entry if rationing becomes necessary would be inappropriate, at least from the visitors' viewpoint.

Party Size Restrictions

Limitations on party size are a common management action in many wildernesses. Large parties have been cited as the cause of a disproportionate amount of resource damage, as well as a major source of dissatisfaction for other users (Lime 1972; Stankey 1973). Thus, restrictions on party size may be a relatively easy way to eliminate several problems.

Support for a party size restriction differed between the two areas. As can be seen below, just half of the Spanish Peaks visitors supported restricting party size; in the Desolation Wilderness about 8 out of 10 did:

"Should there be a limit to the size of parties visiting a wilderness?"

Area	No	Yes	No opinion	N
	Percent			
Desolation	13	81	6	279
Spanish Peaks	38	51	11	512

Chi-square = 68.86, 2 df, p <0.001

Average party size in the two areas (4.8 in the Spanish Peaks, 3.4 in the Desolation Wilderness) was well within the limits commonly imposed on party size in most wildernesses (approximately 12-15). Nevertheless, there are sharp differences between the two areas in terms of the acceptability of large groups.

Among those who answered "yes" to the need for party size limits, we asked for estimates as to what those limits ought to be, both for visitors and for recreational stock. While there are sharp differences in the number of stock that ought to be allowed, there is substantial consensus regarding the permitted number of people:

Maximum number of stock

Area	0	1-2	3-4	5-7	8-10	>11	N
	Percent						
Desolation	37	20	21	15	6	1	265
Spanish Peaks	10	10	22	19	20	19	251

Chi-square = 376.6, 5 df, p <0.001

Maximum number of people

Area	1-2	3-4	5-7	8-10	>11	N
	- - -	- - -	Percent	- - -	- - -	
Desolation	0	9	33	38	20	218
Spanish Peaks	0	9	31	36	24	355

Chi-square = 2.34, 4 df, $p < 0.80$

More than one-third of those visiting wilderness preferred no stock and three-fourths preferred a restriction of no more than four animals. Overall about 40 percent of the Spanish Peaks respondents supported a limit of four animals; however, about half the hikers endorsed this limit as opposed to only 10 percent of the horsemen. Given the make-up of our sample populations in the two study areas (no stock users in the Desolation, about 25 percent in the Spanish Peaks), the support for stock restrictions is not surprising.

Response to a party-size restriction is remarkably similar. Nearly 8 out of 10 respondents in both areas supported a limit of no more than 10 persons per party. However, these data were derived from those users who supported the general idea of a party-size restriction (about 50 percent in the Spanish Peaks, 80 percent in the Desolation Wilderness) and who were in small parties themselves. Nevertheless, among those who do support such restrictions, there is little difference in the judgments as to optimum party size.

SUMMARY AND CONCLUSIONS

One of the major purposes of this study was to obtain a better understanding of how changing use conditions altered visitor preferences for social interaction and management actions. Did increasing use bring an increased tolerance of, or even desire for, contact with others? Were there significant differences between areas of differing use levels with regard to visitors' perceptions of acceptable management control actions?

The most appropriate study design for answering such questions would be to follow the behavior of specific individuals and groups over time (LaPage and Ragain 1971). The study reported here looked at two areas at about the same time and considered how different use levels affected the perception of crowding. Our understanding of how people adjust to and accommodate increasing use would have been deeper with a well-designed long-term study.

Nevertheless, we believe the lack of data on effects of increasing use levels on tolerances for high density, perceptions of appropriate behavior, and preferences for alternative management actions makes this analysis worth while. The Desolation Wilderness possibly represents a future scenario for the Spanish Peaks Primitive Area. In addition, of course, the data should provide some insight as to the effects of increased use levels on visitor perception of crowding and other changes.

In terms of socioeconomic characteristics and experience, visitors to the Spanish Peaks and Desolation Wilderness revealed little difference, either among themselves or compared with other wilderness users around the country. For example, the high educational attainment of most visitors again reminds us that perhaps one of our most significant management tools is the ability of most visitors to use information about what or what not to do, where and when to go, how to behave, and so on.

Recreational uses in the two areas did show similarities, but there were also some key differences. Perhaps the most significant were the virtual absence of stock use in the Desolation Wilderness and the preponderance of day use in the Spanish Peaks.

When we turn to the major objective of this study, two central conclusions emerge. First, visitors to both areas share a highly similar image of wilderness; their notions as to what a wilderness ought to be show little variation. (This is in keeping with past studies.) ORRRC Study Report 3 (1962) noted there seemed to be a "generic" appeal about wilderness that transcended individual area differences. In another study, Stankey (1973) found a similar pattern across four areas of widely differing use intensities, types of use, and physical characteristics. More recently, Echelburger and Moeller (1977) reported a high level of similarity in terms of characteristics, expectation, and satisfactions between visitors to the Cranberry Backcountry in West Virginia and visitors to western wilderness.

Secondly, acceptable frequency of interparty contact differs in the two areas, with visitors to the more intensively used area more tolerant. What are the implications of this: does it suggest that crowding need not concern us? Will people simply adjust to increasing densities with no appreciable loss in the quality of their experience?

A more appropriate interpretation of these data is to recognize that interparty contact--"solitude"--is only one dimension of the complex phenomenon we call the "wilderness experience." While it is probably an important element to many, and perhaps the major value to at least some, it is coupled with many other values related to esthetic experiences, exercise, challenge, socialization, and so forth. As opportunities for solitude decline, a variety of coping strategies probably will come into play. Some of these strategies relate to increasing the odds of finding the desired level of solitude, such as changing the route of travel (traveling cross-country) or by changing the time of visitation (avoiding weekends). In the Desolation Wilderness such actions were about twice as common as in the Spanish Peaks, a logical response considering that visitors reported the Desolation Wilderness was used beyond its capacity nearly 2-1/2 times as commonly as did Spanish Peaks visitors.

Visitors may adopt other strategies. For example, they may simply resign themselves to the situation and alter the relative importance they assign to solitude, making some other dimension(s) more important. Simply put, visiting the wilderness with more people than might be preferred is better than not going at all.

This may be true, however, only if access to wilderness is unrestricted. Some visitors may prefer a management program that limits their visits, but that insures lower density levels. Also, the presence of people in high-use conditions does not necessarily mean these use levels are preferred or desired. As Driver and Bassett (1977) have noted, "One can be recreating in a non-preferred area and be satisfied, but have a strong preference for an alternative area if conditions were such that the alternative were a real choice."

We need also to recognize that use intensities will always vary among units of the National Wilderness Preservation System. For example, if visitors-days-per-acre is used as a crude index of use intensity, in 1975 use varied from 0.01 to 7.6 visitor days/acre among National Forest wildernesses. That some areas are heavily used should not constitute a precedent for allowing all others eventually to support similar use levels. This probably would not happen anyway, given the diversity of physical characteristics, proximity to population centers, and access. Nevertheless, reducing opportunities for solitude would diminish an important part of the wilderness experience. Perhaps most seriously, it would truncate the range of experiences sought by wilderness visitors.

The data in this study support the need to maintain flexibility and continuity in visitor management. The need for visitor management is clearly recognized by most visitors; the criterion of acceptability seems linked to the perceived need for that specific type of action.

Managers should institute controls only after careful analysis of problems. Management overreaction could result in a visitor backlash to programs that might be needed later on.

The principle of "minimum regimentation" should guide management actions. Judiciously applying only the minimum level of regulation needed to accomplish an objective will almost certainly gain visitor support.

Visitors in our survey may be subject to the concept of recreational "invasion and succession" (Clark and others 1971). As new clientele enter an area (with different demands for facilities, access, level of social interaction, and so forth), their more tolerant standards can eventually lead to conditions that cause the original clientele to leave and be succeeded by the new group. Thus, it is possible that some of those most sensitive to crowding have, in fact, been displaced in the Desolation Wilderness. However, it seems more likely that most visitors have accommodated to changing use conditions by changing their norms.

The similarity-dissimilarity in the findings of this study has at least two important management implications. First, while individual wildernesses have obvious unique qualities about them, it is important that managers recognize that the general experiences sought by visitors probably vary little across space and, perhaps, time. Thus, it does not necessarily require a completely comprehensive profile of visitor data to manage wilderness.

The data presented here do not justify standardization of wilderness management procedures. Problems vary in their relative importance, their stage of development, and their most appropriate solution. What is appropriate or what will work best varies not only among areas, but within individual areas. For example, measures undertaken to manage horse use would be obviously different in the Spanish Peaks than those in the Desolation Wilderness. The data also suggest, however, that within the Spanish Peaks a variety of horse-use management actions would be appropriate. Thus, management diversity is called for, not only on an interarea basis, but intra-area as well. Such an approach will require an improved program of public information to alert visitors to these differences and, perhaps most importantly, to the reasons for them. Given the interest, commitment, and education of most wilderness supporters, this task should not be viewed as unreasonable or unattainable.

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APPENDIX:
THE EFFECTS OF ORDER ON THE STATISTICAL RELIABILITY OF SATISFACTION ESTIMATES[1]

Respondents were asked to estimate the satisfaction they would receive from various use levels. Because of the much greater use levels present in the Desolation Wilderness, a slightly different set of categories were used. For example, contact with small backpacking groups were presented in the following order in the two areas:

Encounters with:	Desolation	Spanish Peaks
No other groups	1	1
One other group	2	2
Two other groups	omitted	3
Three other groups	3	4
Five other groups	omitted	5
Six other groups	4	6
Nine other groups	5	7
Fifteen other groups	6	8
Thirty other groups	7	omitted
Sixty other groups	8	omitted

The differences in order raise the following question: Are responses (percentage of satisfaction assigned to an item) affected by the item's location in the array? For example, does the fact that "three other backpacking parties" was item 3 in the Desolation Wilderness, but item 4 in the Spanish Peaks, affect the manner in which respondents answered?

The problem stems from how a person would respond to an item array. Would he first assign values at the ends, and then fill in the middle items? Would he proceed from beginning to end? If reliability problems exist (i.e., that the measure is valid but inaccurate), then the structure of the array could influence how a person assigns values in order to produce a "consistent" distribution. However, if no such reliability problems were present, then responses to each item should be independent of order.

To test whether differences between the Desolation and Spanish Peaks samples are due to real differences in response to encounter levels or to item order, tests for difference between samples were used by comparing items (1) by their actual assigned value in encounter levels and (2) by the order of presentation regardless of actual value.

To reject the possibility of effect of order, the following hypothesis was tested:

> If order exerts "some" influence on the distribution of responses (relative effect in comparison to value not determined), then the two sample distributions will not differ when items are matched by order presented (regardless of item value).

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[1]The author is indebted to Randel F. Washburne for collaboration in preparing this appendix.

This "hypothesis" only suggests presence of an effect by indicating that samples do not differ significantly from their "order-mates." Confirming it does not deny the existence of a difference between samples due to actual response to item encounter value; nor do the data allow comparing effects of value and order in explaining variation between samples. It seems appropriate only to conclude that some effect of order does exist.

To test the hypothesis, cumulative distributions of satisfaction values in each type of encounter were compared between samples for (1) actual value and (2) order value. The former was done to insure that this technique produces similarly significant results to the item-by-item t-tests and to compare to the order tests. For actual value, only those items present in *both* samples were matched; all items presented to respondents were present in the order test (though item composition varied between samples). Campsite encounters are not included because the encounters were the same.

A modified Kolmogorov-Smirnov test of significance was used to compare each cumulative distribution, using the satisfaction values in the cumulative distribution and the sample sizes for the N's.[2] The test divides the cumulative value for each item by the cumulative total (F_S or F_D) and then subtracts each F from its counterpart. The largest of these is the greatest point of deviance of the two distributions (D). Significance is computed by:

$$\text{Chi-square} = 4D^2 \frac{N_D N_S}{N_D + N_S}$$

A chi-square table is then used to determine significance, using two degrees of freedom.

Results

A. BACKPACKERS

(1) By actual value:

Category value	Spanish Peaks $\bar{x}$ (sat. score)	Cum.	F	Desolation Wilderness $\bar{x}$	Cum.	F	$F_S - X_D$
0	82	82	0.285	80	80	0.209	0.076
1	80	162	.563	82	162	.423	.140
3	62	224	.777	80	242	.632	.145=D
6	33	257	.892	64	306	.799	.093
9	20	277	.962	49	355	.927	.035
15	11	288	1.00	28	383	1.00	--

$\chi^2 = 12.87$ significance = 0.01

[2]The test usually uses the sum of the cumulative distribution as N, since these usually represent cases or observations. Here it seems appropriate to use sample size, since the distribution is based on *scores* rather than cases.

(2) By order:

Order position	Spanish Peaks $\bar{x}$	Cum.	F	Desolation Wilderness $\bar{x}$	Cum.	F	F_S-F_D
1	82	82	0.202	80	80	0.199	0.003
2	80	162	.4	82	162	.403	-.003
3	73	235	.58	80	242	.603	-.023
4	62	297	.733	64	306	.763	-.03
5	44	341	.842	49	355	.885	-.043=D
6	33	374	.923	28	383	.955	-.032
7	20	394	.972	13	396	.987	-.015
8	11	405	1.00	5	401	1.00	--

χ^2 = 1.12 not significant

B. HORSE PARTIES

(1) By actual value:

Category value	Spanish Peaks $\bar{x}$	Cum.	F	Desolation Wilderness $\bar{x}$	Cum.	F	F_S-F_D
1	75	75	0.431	75	75	0.401	0.03
3	53	128	.736	54	129	.690	.046=D
6	25	153	.879	31	160	.856	.023
9	14	167	.960	18	178	.952	.008
15	7	174	1.00	9	187	1.00	--

χ^2 = 1.29 not significant

(2) By order:

Order position	Spanish Peaks $\bar{x}$	Cum.	F	Desolation Wilderness $\bar{x}$	Cum.	F	F_S-F_D
1	75	75	0.271	75	75	0.387	-0.116
2	67	142	.513	54	129	.668	-.155=D
3	53	195	.704	31	160	.829	-.125
4	36	231	.834	18	178	.922	-.088
5	25	256	.924	9	187	.967	-.043
6	14	270	.975	4	191	.990	-.015
7	7	277	1.00	2	193	1.00	--

χ^2 = 14.6 significance = 0.001

C. LARGE PARTIES

(1) By actual value:

Category value	Spanish Peaks $\bar{x}$	Spanish Peaks Cum.	Spanish Peaks F	Desolation Wilderness $\bar{x}$	Desolation Wilderness Cum.	Desolation Wilderness F	$F_S - F_D$
1	64	64	0.520	67	67	0.399	0.121=D
3	33	97	.789	46	113	.673	.116
6	14	111	.902	28	141	.839	.063
9	8	119	.967	18	159	.946	.021
15	4	123	1.00	9	168	1.00	--

$\chi^2 = 8.9$ significance = 0.02

(2) By order:

Order position	Spanish Peaks $\bar{x}$	Spanish Peaks Cum.	Spanish Peaks F	Desolation Wilderness $\bar{x}$	Desolation Wilderness Cum.	Desolation Wilderness F	$F_S - F_D$
1	64	64	0.342	67	67	0.385	-0.043
2	44	108	.576	46	113	.649	-.073=D
3	33	141	.754	28	141	.810	-.056
4	20	161	.861	18	159	.914	-.053
5	14	175	.936	9	168	.966	-.03
6	8	183	.979	4	172	.989	-.01
7	4	187	1.00	2	174	1.00	--

$\chi^2 = 3.24$ not significant

Conclusions

The hypothesis that order exerts "some" effect is sustained for backpacker and large party encounters, because the distributions matched on order were not different (though the actual value distributions did differ significantly). However, for horse party encounters, the order distributions were significantly different, although the actual value distributions were not.

The graphs (fig. 5) of backpacker encounters for both item order and item value provide some insights. The slopes of the lines for the order graph are generally quite similar (except between positions 5 and 6 where they cross), even though the intervals of values are quite different (e.g., at positions 5-6, value changes of 3 versus 15 occur).

Thus, the possible effects of order cannot be dismissed but neither are its effects clear and obvious. The potential for confusion, however, could be eliminated in the future by the use of identical categories and by their random ordering.

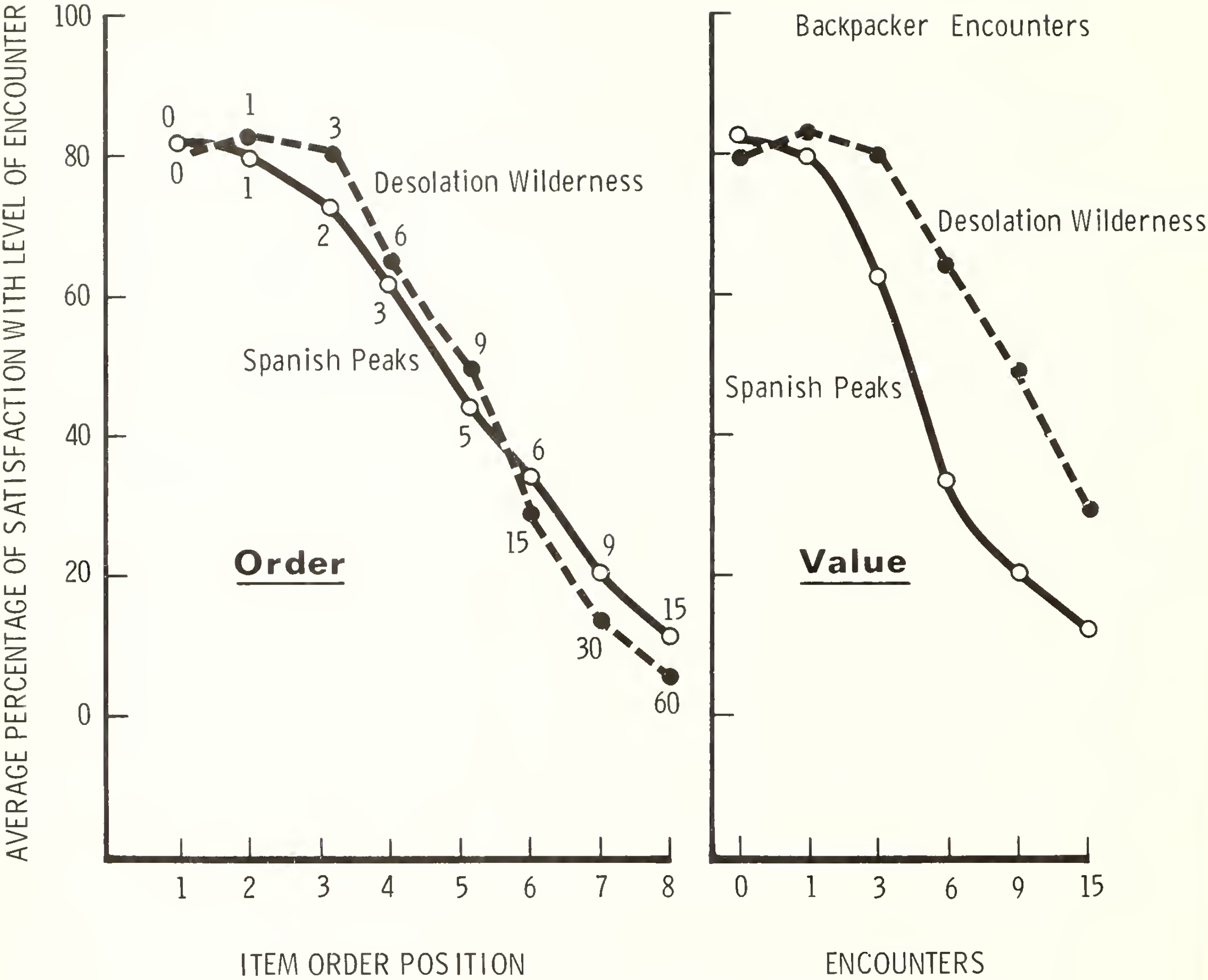

Figure 5.--Changes in satisfaction with backpacker encounters by item order and value.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1979-0-677-121/105

Stankey, George H.
1979. A comparison of carrying capacity perceptions among vistors to two wildernesses. USDA for. Serv. Res. Pap. INT-242, 34 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Reports on a study of visitor perceptions of carrying capacity in a lightly used and a heavily used wilderness. Although vistors to both areas had common images of wilderness in a general sense, those in the heavily used area were more tolerant of higher use. They were also more likely to define the area as overused and were more willing to accept use controls.

KEYWORDS: wilderness management, perception, carrying capacity.

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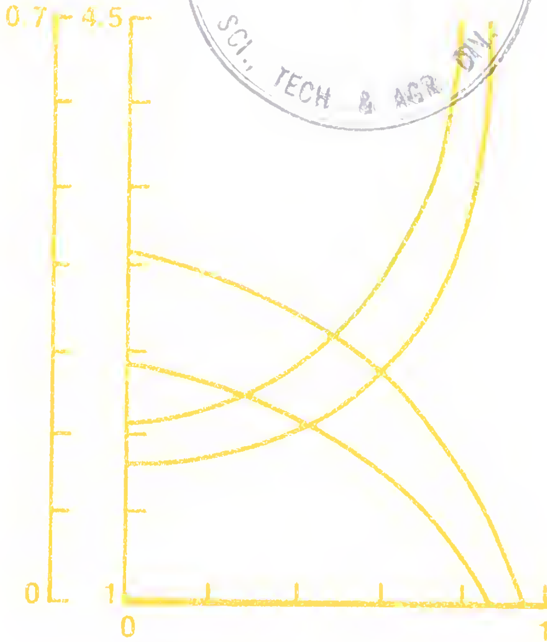
HERMOCHEMICAL PROPERTIES F FLAME GASES FROM NE WILDLAND FUELS

ank A. Albini



USDA Forest Service Research Paper INT-243
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE

[illegible]

THERMOCHEMICAL PROPERTIES OF FLAME GASES FROM FINE WILDLAND FUELS

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Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

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RESEARCH SUMMARY

This paper presents a theoretical model for the process by which is generated the gaseous fuel that burns in the free flame at the edge of a spreading wildland fire in fine fuels. The model is based upon a heat and mass balance for a hypothetical unit mass of solid fuel. As the fuel is heated, it is first desiccated, then pyroloyzed to release a fraction of its weight as combustible (and noncombustible) volatiles, with the remainder converted to char. The heat required to effect this process is supplied by partial combustion of either (1) the volatiles released or (2) equal fractions of volatile fuel and char, leading to two sets of equations. The equations predict the heat of combustion, the stoichiometric air/fuel mass ratio, the mass-averaged temperature, and the mass fraction of unburned fuel in the gas mixture, assuming that the partial combustion occurs at the rich limit (final temperature = 1100°C). Also given are equations for the fuel gas mass produced per unit mass lost by the fuelbed within the gas-generating zone.

Energy loss from the system is calculated as a fractional loss of radiant energy from the fuelbed. The radiant energy is assumed to be emitted from a tilted plane that represents the surface of contact between burning and unignited fuel. The fractional energy loss depends upon a single parameter of the fuelbed that is proportional to the fuel weight loading multiplied by the surface/volume ratio of the fuel particles. This functional dependence offers the possibility that a limiting value of fuel moisture content can be related to the geometrical properties of the fuelbed.

Several empirical relationships and approximations are introduced to simplify the equations and to reduce data requirements in using the model. It is argued that the speculative and approximate nature of the conceptual model do not warrant greater precision, so the simplifications, in themselves, do not weaken the theory.

Dependence of the fuel gas properties upon the fraction of fuel converted to char offers the possibility of calculating the synergistic interaction of fuel moisture content and the fire retardant effect of increasing the char fraction formed.

The interplay of intrinsic fuel properties, loading, particle size, and moisture content may permit testing of the theory by comparison with results from laboratory burns near the extinction limit of moisture content.

CONTENTS

INTRODUCTION

Fires spreading through wildland fuels can vary greatly in behavior, from smoldering in compact surface fuels to racing through shrub or tree crowns. The size and shape of the flames from such fires can be useful in describing the character of the fire. Flames are often photographed for research purposes, both in open burning (Adkins and Clements 1976; Anderson and others 1966; Brown 1972) and in laboratory fires (Rothermel and Anderson 1966; Thomas 1963). Relating flame structure to fuel properties and burning conditions has been the object of many research undertakings (Byram 1959; Thomas 1963; Steward 1964; Morton 1965; Nielsen and Tao 1965; Wohl and others 1949; Putnam and Speich 1963; Putnam 1965; Rothermel and Anderson 1966), because flame size is important in predicting or describing fire behavior and effects (Van Wagner 1967; Anderson 1969; Albini 1976).

The severity of a surface fire in terms of its resistance to control can be keyed to flame length (National Interagency Fire Training Center 1978), and flame height can be related to the height of lethal scorching of tree foliage (Van Wagner 1973). Flame height has also been related to the likelihood of crowning (Van Wagner 1977), and flame height, along with flame gas density and velocity, are needed to estimate the firebrand lofting capability of flames (Clements 1977; Tarifa and others 1965; Albini 1979). So the structure of the flame from a surface fire in wildland fuel provides much information about the fire in terms of its behavior and its possible effects. Thus a flame structure model may be used to predict behavior or effects of wildland fires, to interpret photographic data on wildland fires, and to analyze laboratory data.

Objectives

The flame from a spreading fire in wildland fuels can be classified technically as a free, turbulent, diffusion flame. The structure of such flames depends upon the properties of the gaseous fuel being burned, the size and shape of the gas-emitting area, the rate of flow of the gaseous fuel, and the flow field of the air into which the gaseous fuel is introduced. Most studies of the structure of flames begin with a series of assumptions, constraints, or measurements designed to specify the needed information in these four areas (Thomas and others 1961; Thomas 1963; Anderson and Rothermel 1965; Rothermel and Anderson 1966; Steward 1964; Fons and others 1960, 1962; Putnam 1965; Albini 1979; Becker and Liang 1978).

The principal use seen for the model presented here will be in analyzing and interpreting laboratory data. Direct measurements on flames, other than visual or photographic, are very difficult to obtain and often are subject to significant error or variation. Highly sophisticated diagnostic techniques now exist (Chigier and Strokin 1974; Lederman 1977) but are usually not applicable to spreading fires, especially if they are wind driven. More often, the experimenter is forced to record fuel weight as a function of time and rely on photography to capture flame structure information (Thomas 1963; Rothermel and Anderson 1966; Harmathy 1978A). When gaseous fuel is metered to a burner, there is no difficulty in describing thermochemical properties of the fuel since they are under the control of the experimenter. But in a spreading fire, processes at work within the flame-producing region at the edge of the fire determine the thermochemical properties of the gases that feed the free flame. In order to interpret or analyze experimental data, then, it is necessary to infer these properties from prefire measurements of solid fuel parameters and the weight loss history recorded during the fire.

For example, consider a line fire propagating in surface fuels. The sketch shown in figure 1 illustrates how one might idealize the flow of gaseous fuel as issuing from a slot of width equal to the depth of the burning zone. The weighing platform indicated in the figure could provide a measurement of the rate of weight loss of the solid fuel. If one could calculate from the weight data the rate of emission and the properties of the gaseous fuel as it passed through the conceptual orifice, one would have available all the elements necessary to satisfy the data needs of a model for flame structure (assuming the wind field to be known).

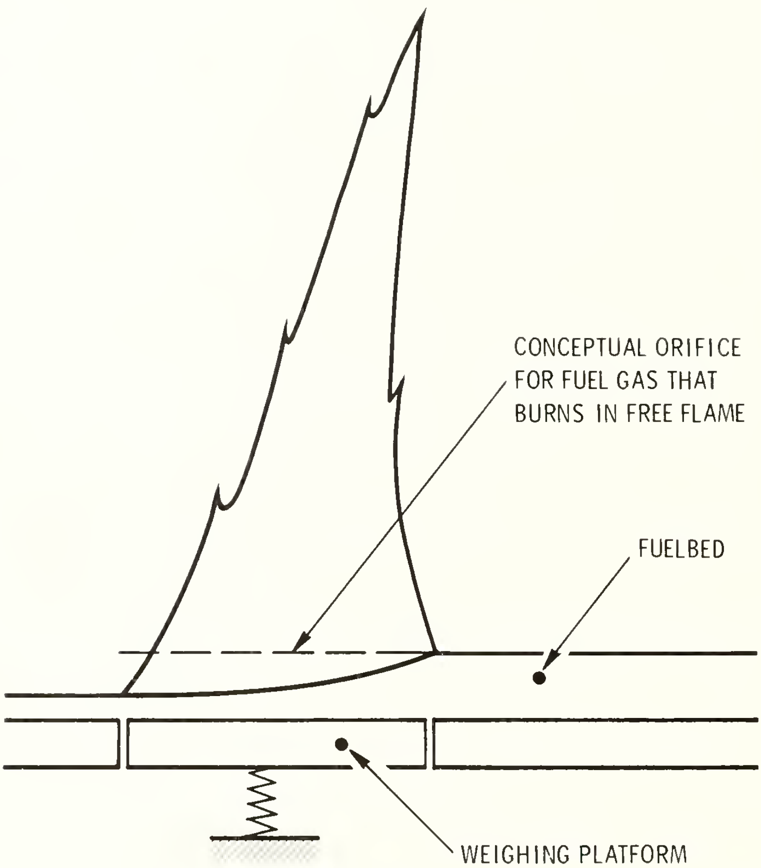

Figure 1.--Schematic diagram of a spreading fire, showing a fuelbed weight loss measuring scheme and the conceptual orifice for the flow of gaseous fuel that burns to form the free flame.

Scope

The purpose of this paper is to present a means of calculating the thermochemical properties of the fuel gases generated in the burning of fine forest fuels, using fundamental data that can be derived by laboratory procedures. These fundamental data are characteristics of the fuel material and can be catalogued for reference.

Attention is restricted here to fine fuels arranged in a uniform, continuous layer. The effect of fuel moisture content is included explicitly, the influences of fuelbed depth, compactness, and fuel particle size are explored parametrically. An effect of flame retardant salt additive is illustrated through the artifice of changing the fraction of the whole dry fuel converted to char during pyrolysis.

The model developed here is based on a highly simplified idealization of the processes taking place in the vicinity of the leading edge of a spreading fire. The idealized process is described verbally in the following section, with the detailed mathematical formulations spelled out in the appendixes. Empirical relationships and simplifying assumptions are discussed in the third section, and results are given in the fourth. The final section summarizes observations on the sensitivities of the model and proposes applications.

THE PROCESS OF COMBUSTIBLE-GAS GENERATION

The process by which combustible gas is generated near the front of a spreading fire can be described in terms of the history of a fuel particle as it passes through the zone under consideration. It is not possible to delimit this zone in specific geometrical terms, since the process described is only an abstraction and not an exact picture of all that transpires in a real fire. But by tracing the "experience" of a hypothetical particle of fuel we can reconstruct a physical process that approximates a real fire and so develop a model for it.

As the flame front approaches the fuel particle, the particle is heated and its temperature begins to rise. The heat is transported predominantly in the form of radiation (Thomas 1967; Anderson 1969; Telisin 1974; Fons 1946; Emmons 1965; Hottel and others 1965; Thomas and Law 1965; Williams 1977). The temperature of the fuel particle rises slowly at first, but increases very rapidly as the leading edge of the fire approaches to within 10 cm or less (Rothermel and Anderson 1966; Frandsen 1973). For sufficiently fine particles, the temperature on the inside of the particle will be very nearly equal to the temperature on its outer surface and the particle can be called "thermally thin" (Gebhart 1961; Frandsen 1973). In this paper attention will be restricted to fuelbeds composed only of such thermally thin particles. Typical wildland fuels that satisfy this condition are grass and the foliage of shrubs and trees. In wildland vegetation associations that contain larger fuel particles, fire spread still tends to be dominated by the fine, thermally thin, components (Rothermel 1972).

When the temperature of the hypothetical particle reaches about 100°C, the moisture held by the particle will begin rapidly to boil away. The amount of energy that must be absorbed by the particle during this phase of heating may be quite large because of the high latent heat of vaporization of water. The desiccated particle continues to absorb heat and its temperature continues to rise as it approaches the edge of the flaming zone.

As the temperature of the particle reaches about 200°C, some material begins to exude from the particle as gas (Shafizadeh and others 1977). The gas consists partly of volatilized constituent waxes, oils, resins, etc., and partly of the products of decomposition--pyrolysis--of the particle fibre. The rate of mass loss increases with increasing temperature until a maximum is achieved (in some cases, two maxima are exhibited), usually between 300° and 400°C (Muhlenkamp and others 1977). Gas production continues at a decreasing rate until particle temperature reaches 450-500°C, at which point the only thing remaining of the original particle is a solid carbonaceous char. The energy necessary to heat a unit mass of dry solid fuel to 500°C has been measured in the laboratory for a wide variety of forest fuel types (Muhlenkamp and others 1977).

In a wildland fire situation, between the temperature at which the particle begins to exude gases and the temperature at which it is reduced totally to char, it will have become immersed in flame. The attachment of a flame to a solid particle occurs when the rate of combustible gas generation by the particle is sufficient to maintain a flame. This usually happens at a temperature between 300°C and 380°C (Fons 1950; Martin 1964; Simms 1960, 1961, 1963). Recent findings (Mutch 1964; Stockstad 1975, 1976) indicate that the temperature for flame attachment, or piloted ignition, is approximately 325°C.

So at or about 325°C the hypothetical particle will have entered the zone of flaming combustion at the edge of the fire. And when it has reached about 500°C it will have contributed all its combustible volatilizable material to the flow of gas that burns as a free flame above the fuelbed. (Some of the char formed in this process may also have been burned by the time the particle consists solely of char--more on this possibility follows.) The intent of the effort here is to devise a means of calculating the bulk properties of this fuel gas, contributed by all the fuel particles in the vicinity of the edge of the fire as they undergo the process just described. The flames that are attached to the individual fuel particles most often cannot consume all of the combustible gas liberated by the heating of the particle because the rate of release is higher than the local rate of oxygen supply.[1] So some unburned combustible gas mixes with the products of the partial combustion occurring within the fuelbed--and the water vapor driven from the unignited particles--and issues from the fuelbed to burn in a free flame.

The heat of combustion available from this mixture, its temperature, and its stoichiometric mass ratio for combustion in air are the properties sought. To derive these quantities it is necessary to write down the heat and mass balances implicit in the process just described. These relationships will then provide a mathematical model allowing the prediction of the desired values from intrinsic properties of the fuel material and an estimate of the efficiency of the radiant heat transfer to the fuel ahead of the fire.

Structure of the Fuel Gas-Generating Zone

The volume of space in which the processes described take place can be defined in terms of an idealization of the processes. Rothermel and Anderson (1966) discuss these processes and their localization with respect to the edge of a fire. Berlad and others (1971) described fire spread in fine fuel arrays in terms of a

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[1]The rate of oxygen supply to this gas-producing zone is a rate-limiting factor implicit in the model developed here. The model presented here is independent of the rate at which the processes occur, but any of a host of factors impose rate limits. Later in the development of the model it is assumed that the combustion occurring in the fuelbed below the free flame takes place at the fuel rich limit, so is limited in rate by the availability of air. Gas sampling during large scale compartment fires indicates that this process is at play in stationary fire situations not unlike what is pictured here (Harmathy 1978B).

wave of fuel volatilization and combustion propagating along and into the fuelbed. Rothermel (1972) idealized the processes and introduced the concept of a "reaction zone" at the edge of a spreading fire. Rothermel's reaction zone is in rough coincidence with the physical volume envisioned here.

The forward boundary of the volume in question is taken to be the surface within the unignited fuelbed along which the temperature of the fuel particles begins to rise "significantly." This surface is presumed to lie parallel to the surface on which ignition or flame attachment occurs, a short distance away from it. This latter surface can be inclined at a large angle from the vertical for rapidly spreading fires but will be nearly vertical for fires spreading very slowly (Thomas 1967; Frandsen 1971; Rothermel 1971).

The lower boundary of the zone of gas generation will be considered to be the bottom of the fuelbed. For open fuel arrangements, such as grass or shrubs, this surface would be the ground or the top of the litter lying on the ground. For compact fuelbeds, such as forest litter, the lower boundary can be much more difficult to define, since in many cases only the loose upper portion of the layer will be involved in the flame gas production associated with the spreading fire. In this case it is necessary to define the lower boundary as the imaginary surface that separates the fuel into two portions. The upper portion is ignited during the time the flame-production zone (or Rothermel's reaction zone) passes over a point. The lower portion is the fuel that is ignited only after the passage of the zone, if at all. The only difficulty caused in the mathematical description of the process by this definition is in the lack of a clearly specified fuelbed depth. This problem is not severe in terms of the uncertainty it causes in the quantities calculated.

The upper surface of the gas fuel generation zone is simply the top of the fuelbed. This surface forms the imaginary orifice through which the fuel flows into the free flame.

The rearward surface of the zone, however, must be defined in terms not specifiable before the fact. The rearward edge of the zone from which combustible gas issues must be coincident with the surface upon which the fuel particles reach 500°C and so have been reduced to char. But since the fuel particles may not all be exactly the same size nor experience exactly the same history on passing through the flame-producing zone, this surface may exist at a variety of places at the same time. Mathematically one would say that the region is not simply connected. Physically this means that it must be considered that some fuel particles will have been partially or totally consumed (even the char) by the time that most of them have ceased to produce combustible gas. The release of heat from char combustion can be an important component of the heat budget for the flame-producing zone and the products of any char combustion must be included in the bulk fuel gas flow. So the rearward boundary of the zone can be taken to be the surface upon which "most" fuel particles have ceased to emit combustible gases, but ahead of which some fuel particles may have been completely consumed. This surface, in other words, is a mathematical artifice that may not have a geometrical counterpart in reality. The degree to which real situations conform to this conceptualization will be one of the limiting factors on the validity of the model.

Two limiting cases can be considered in which the rearward boundary is clearly definable, if not easily located in space. In the first case, it is postulated that there exists a rearward surface forward of which all fuel particles are emitting gas and none have yet been reduced to char but behind which all particles are pure char and none emit combustible gas. In the second case it is postulated that the rearward surface is also a boundary behind which all the fuel particles are reduced to char at 500°C, but in this case a fraction of the fuel ahead of the surface will have been completely consumed and the remainder will not as yet have been reduced to char. The fraction in question is determined by equating the heat required to accomplish the volatilization to the heat released by the burning of the whole fuel, as is described below.

Mass Balance

If the volume of space described above is considered to be fixed to a steadily advancing flame front, the mass flow of the idealized processes described above can be represented schematically by the sketch shown in figure 2. In this figure solid fuel, with its associated moisture, enters the process volume along with air. Enough air must be present to accomplish the combustion needed to satisfy the heat balances detailed below or the process will not be in steady state. The process is self-adjusting if a wind acts on the fire. A wind-driven fire will spread faster as the windspeed increases, thus raising the mass flow rate of fuel into the volume. In a backing fire, the process volume shrinks in response to increasing windspeed, and some char may be burned in the volume shown. So windspeed affects the mass flow rates, but not the balance. Some air may pass through the process volume without interacting with the fuel or entering into any combustion process. This air is ignored in the mass balance and heat balance formulations. If the quantity of noninteracting air becomes a large fraction of the air needed for combustion, its neglect in the heat balance probably will lead to significant error, since it should carry away some heat even if it does not react in the process zone.

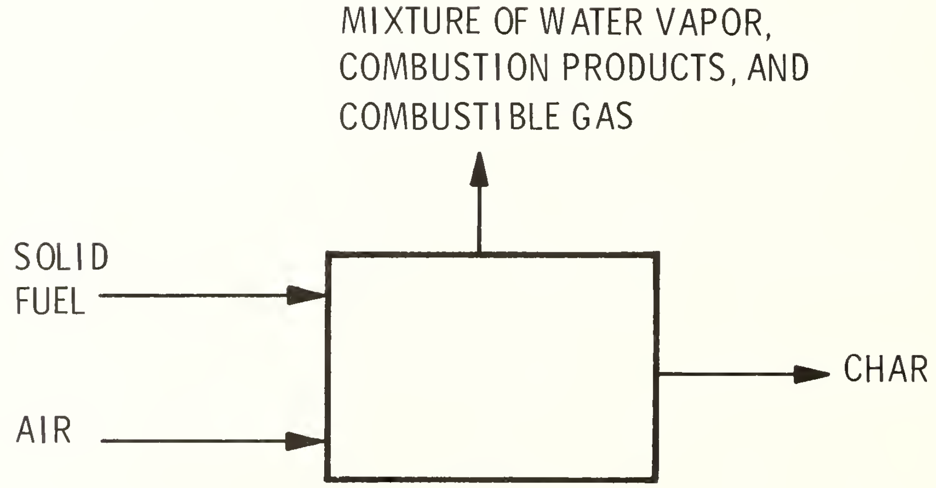

Figure 2.--Schematic mass flow diagram of the process to be analyzed.

Out of this volume flows the hot combustible gas that will fuel the flame and the char remnants of the solid fuel that may later burn by glowing combustion. The combustible gas consists of the unburned pyrolyzate from the original solid fuel, the products of all combustion that takes place in the process volume, and the initial moisture of the solid fuel.

The fraction of the initial dry weight of solid fuel that is converted to char appears to be a characteristic of the type of fuel being burned and a very weak function, at most, of its rate of heating. Several investigators have established this fact for temperature rise rates up to 160°C/min (see, e.g., Leu 1975). Recent experiments by Susott (data on file at NFFL, Dec. 1978) have shown that this relationship is maintained when predried samples are suddenly immersed in a furnace at 500°C, establishing temperature rise rates of at least 3000°C/min. These later experiments more closely approximate conditions in a spreading fire (Rothermel and Anderson 1966; Rothermel 1972) than any previously done and so clearly yield data suitable for use in this model.

The mass of air that enters into reaction with either the volatile fuel or the char can be related to the mass of volatile or char reacted by the chemical balance required of the reaction. The ratio of the mass of oxygen (hence air) to the mass of fuel burned is the stoichiometric mass ratio, a constant fixed by the relative abundance of hydrogen and carbon in the fuel component. The stoichiometric mass ratio of the volatilized fuel is a property of the solid fuel from which it was produced,[2] and can be determined by experiment. Thus by using one or the other of the two special-case definitions of the rearward boundary of the process zone described above, the mass of air involved can be related to the mass of fuel consumed, either in the volatile phase only or *en toto*. The sum of the reacted fuel mass, the air needed to burn it, and the moisture makes up a diluting flow of noncombustible gas that is mixed with the combustible volatiles released. As the proportion of burned gas diluent increases, the heat of combustion of the mixture declines, along with its stoichiometric mass ratio. The proportions of these two components are determined by satisfying the heat balance described in the following section.

Heat Balance

By following a unit (dry) mass of fuel through the process zone, we can calculate the amount of heat that it must absorb in order to go from its initial state to its final state. This amount is simply the sum of the quantities of heat needed to:

1) Raise the temperature of the (wet) fuel from ambient to the boiling point of water (100°C).
2) Boil away the water held by the fuel at 100°C.
3) Raise the temperature of the solid dry fuel from 100° to 500°C, and in the process reduce it to char and volatile components.

This sum represents a quantity of heat that must be supplied to the fuel as it passes through the process volume. The requirement of steady state conditions dictates that this heat requirement be satisfied by the energy release from an

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[2]This fact has been established experimentally by R. A. Susott in an extensive series of tests using the oxygen coulometer at the Northern Forest Fire Laboratory. These data will be reported in forthcoming publications by Susott.

equal mass of fuel within or near the process volume. We posit, for this model, that this energy is supplied by combustion within the process volume.

Additional heat is required, though, as we can determine from a closer inspection of the process outlined above. The sources of additional heat demand included here are the following:

1) Only part of the radiant energy emitted from the burning region into the fuelbed ahead of the ignition surface is absorbed by fuel particles. That which passes through the fuelbed into the air above or the solid surface below is lost from the system. So the energy demand of a unit mass of fuel, as it goes from ambient temperature to ignition temperature ($\approx$325°C), must be increased to include this leakage of energy. The other boundaries of the burning region are the same as those of the process volume and are assumed to be in radiation balance. So no additional energy loss is attributed to those surfaces.

2) The hot gas issuing from the upper surface of the process volume will have a mass-averaged temperature in excess of 500°C, which temperature represents a rough lower limit for visible radiation from the gas. The energy needed to raise the steam, the volatilized solid fuel, and the reaction products to this average temperature must be supplied by the partial combustion occurring within the process volume. A means of establishing the mass-averaged temperature is spelled out in appendix I, based on a more detailed examination of the combustion occurring within this zone.

With these additional heat demands included we have a rather complete accounting of the debit side of the energy budget for a hypothetical unit mass of dry fuel. In order for the process described to continue in a steady state, this budget must be balanced by combustion of part of a unit mass of dry fuel.

The greater is the total of energy requirements the greater will be the fraction of fuel consumed to satisfy the needs of the process. As a result, less energy will be available in the form of unburned volatile fuel to feed the free flame. (Another way of looking at this is to realize that the combustion process must go farther toward completion within the fuelbed, leaving less to be burned above the bed.) For example, if the moisture content of the fuel is increased, more heat is needed to boil the water and heat the steam associated with a unit mass of dry fuel. So a greater fraction of the unit mass would have to be burned to provide this energy. Of course, as more fuel is burned, more air must be used, so an additional demand for heat is incurred to raise the products of combustion to the average temperature of the effluent gas. This compounding effect amplifies the influence of an incremental change in the basic heat requirement.

The effect of a change in fuel arrangement can also be inferred from the list above. If the fuel is deep and compact so that little radiation can pass through the bed and escape, the energy loss by escaped radiation will be small. But if the fuelbed is open and shallow, more radiant energy will be required to heat the fuel to ignition, since much would escape. An implication of this model then, is that a deep, compact fuelbed should be able to support a free flame at greater fuel moisture content than could a shallow, open bed of the same fuel particles.

An implicit assumption evident here is that the fuelbed is not so compact as to restrict the flow of air to the extent that flaming combustion cannot be maintained in the process volume. Some compact forest litter mats may exhibit such an oxygen starvation effect; these would then burn mainly by smoldering (unless aided by wind) with no free flame.

The energy to be supplied by combustion in the process volume will be generated by the burning of some of the volatilized fuel and perhaps some of the char. Two cases are considered here: In the first case it is assumed that only volatile fuels are burned to balance the heat budget. In the second case it is assumed that equal fractions of char and volatile fuel are burned. The first case is thought to be representative of rapidly spreading fires, in which the flame-producing zone passes quickly over a fuel particle, leaving it nearly whole, with glowing combustion to occur after the flame zone has passed. Some grass and shrub fires exhibit this character. The second case is thought to be more representative of slowly spreading fires, in which some fuel particles are totally consumed within the flame-producing zone. Fires in conifer litter sometimes show this trait. Hopefully these two special cases will serve to "bracket" the behavior of fires in many real situations.

SIMPLIFYING ASSUMPTIONS AND APPROXIMATIONS

A mathematical description of the processes described is readily produced in symbolic form (see appendixes), but a large number of parameters must be specified in order to calculate the desired quantities. To minimize this demand for data and to simplify the computations, some empirical relationships and approximations are introduced. Because the physical processes represented by the equations are themselves highly simplified approximations of reality, the use of approximate values in them does not weaken the model. In other words, any inaccuracies caused by the approximations should be overshadowed by the approximations that the equations themselves represent. As more experimental data are accumulated it may result that some properties treated as fuel-specific in this model can be replaced by constants, so further simplifications may be made. For the present, the following set of assumptions are used in the model and are introduced without discussion in the mathematical development:

The specific heat capacities (at constant pressure) of air, gaseous fuel, and combustion products are considered to be constant with temperature and equal to each other. This approximation is fairly accurate in the temperature range of interest in this problem (Weast 1967).

The specific heat capacity of steam (from fuel moisture only--not combustion products) is also taken to be constant and equal to twice the value for the other gases. This, too, is a fair approximation (Weast 1967).

The volatilized fuel gas emitted from the heated solid fuel is emitted at different rates as the temperature of the solid increases, as described in the previous section. For the purpose of estimating the additional heat required to raise the gas to a common temperature, the rate-versus-temperature curve is approximated by two straight lines. The ascending line (rate increasing with increasing temperature) rises from zero at 200°C to a maximum at 350°C; from the maximum a descending line reaches zero again at 450°C. By this crude approximation, a modest correction to the experimentally determined heat required to pyrolyze the solid fuel (Muhlenkamp and others 1977) can be calculated.

The stoichiometric air/fuel mass ratio for the volatile fuel gas and for char is assumed to be proportional to the heat of combustion (high heat value) of the fuel. This empirical rule has long been known to be rather accurate (Thornton 1917) and has recently been confirmed for a wide variety of fuels (Susott and others 1979). The ratio of the heat of combustion to the stoichiometric air/fuel mass ratio was found in the later work to be nearly constant at 3270 J/gm air. This value is used in the model presented here.

Conventional determination of the heat of combustion by bomb calorimetry provides what is called the high heat value of the fuel. For combustion processes in which the latent heat of vaporization of the water in the combustion products is not recovered, the heat of combustion must be reduced by this amount, to give what is called the low heat value of the fuel. The correction term is readily computed if one knows the relative abundance of hydrogen in the fuel. Elemental analysis of a variety of natural fuels (Susott and others 1975) has revealed that a hydrogen content of 6.3 percent of the ash-free whole fuel weight is quite representative, so this figure is used to derive the correction term for heat of combustion. The volatilized fuel contains about 7.2 percent hydrogen by weight (Susott and others 1975) and this figure is used also. The corrections are modest, and the high heat value is used only to obtain the stoichiometric mass ratio, so the model is not very sensitive to these fractions in any case.

The heat of combustion of whole fuel can be expressed as the sum of the heats of combustion of the volatile and char components. Since the heat of combustion of ash-free char from rapidly heated samples of various forest fuels has been found to be virtually constant at 31,200 J/gm (Susott and others 1975), the heat of combustion of the volatile component can be calculated from this relationship if the fraction of whole fuel converted to char is known, along with the ash fraction and the heat of combustion of whole fuel. These latter parameters are readily measured and tabulated while the heat of combustion of the volatile material is difficult to obtain experimentally. So even though no reduction in the number of input variables is achieved, the model is made easier to apply by using this relationship.

In formulating the heat balance described above, matter enters the process volume at ambient temperature and leaves it as char at 500°C or at a mass-average gas temperature to be determined. The latter temperature is found through an intermediate step. First, all the mass (solid fuel, volatiles, moisture, and air) is presumed to be heated to 500°C. Then the fraction of fuel that burns in the process volume is assumed to produce gaseous products with a final temperature of 1100°C. Along with this fraction an equal fraction of the moisture (as steam) is assumed to be heated to 1100°C, serving as a diluent of the reacting components. This two-temperature mixture contains all the sensible heat of the effluent gas, so a mass-averaged uniform temperature is readily calculated. The choice of 1100°C for the final temperature of the combustion products is based upon the empirical rule that both lean and rich limits of premixed flame propagation tend to occur at this final temperature for a wide variety of fuels and diluents (Gaydon and Wolfhard 1960).

The process of heat loss through radiation leakage was discussed above. This component of the energy balance is calculated in terms of the energy required to raise the temperature of a unit mass of fuel to the flame-attachment temperature of 325°C from ambient. To make this calculation, the interface between burning and unignited fuel is assumed to be a radiating plane panel tilted at a fixed angle to the horizontal. The fraction of the energy emitted through this plane that escapes the fuelbed is computed by treating the fuelbed as an absorbing layer with a constant extinction coefficient. The extinction coefficient is proportional to the product of the fuelbed packing ratio and the surface/volume ratio of the fuel particles (Anderson 1969; Thomas 1967; Rothermel 1971; Telisin 1974). The critical assumptions here are that the shape of the interface surface is planar, the fuelbed is homogeneous, and that the process volume radiation loss can be adequately characterized by that from a radiating surface. The sensitivity of the results (fraction of energy lost) to the tilt angle of the hypothetical plane surface indicates that the shape is not a critical factor in the loss process. The homogeneous composition of the fuelbed implies a restriction on model applicability. The use of a radiating surface to characterize loss from a volume is strictly valid only if the volume is opaque to radiation over the spectrum containing a large fraction of the radiant power. It is a good approximation for the sooty flames from natural fires if the integrated soot concentration through the flame exceeds about 1 gm/m² ([illegible]). That is, for a particulate concentration of 1 gm/m³, a flame 1 m deep would be virtually opaque. A fraction of a meter thickness would suffice to make natural fire flames virtually opaque, if the flame continually occupied all the volume considered. The phenomenon of intermittency (temporary local extinction, sometimes called "flickering" or "pulsating") lowers the time-averaged emissivity of the flame volume, weakening this approximation.

More serious sources of inaccuracy no doubt lie in neglecting radiation from the free flame to the unignited fuel (Anderson 1969) as an additional heat source and in neglecting radiation losses through other boundaries of the process volume. The first source of error is more important for rapidly spreading fires with large flames while the second source no doubt becomes important for fires nearing the condition of extinction. So, if there were no other uncertainties, the model should be expected to predict a heat of combustion of gaseous fuel that is too low for low fuel moisture and too high for high fuel moisture.

EXAMPLES OF MODEL RESULTS AND DISCUSSION

Using the equations assembled at the end of appendix I and the data displayed in table 1, some numerical examples were calculated. A computer program facilitated the effort, so both fuel moisture content and radiation loss fraction were varied parametrically. In addition, the char fraction formed by excelsior[3] was varied parametrically up to 0.60, to illustrate the influence of typical flame retardants on the combustible gas properties (Williams 1974; George and Blakely 1972). Results are given graphically in this section.

There is a uniform and consistent difference in the results between the two methods of computation described. When the heat budget is balanced using combustion of whole fuel (as opposed to volatile component only) the predicted properties of the combustible volatiles are those of a slightly more energetic fuel. The mass fraction of unburned fuel in the gas mixture is slightly higher, so the heat of combustion and the stoichiometric air/fuel mass ratio are higher. Also the mass-averaged temperature is slightly lower as is the ratio of gas produced to fuel load lost. Figures 3-7 illustrate these differences for the five fuel types considered, with plots of gaseous fuel properties versus solid fuel moisture content for a nominal value of radiation leakage fraction of 0.3 (see appendix II).

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[3]Excelsior is a commercial product available in bulk, widely used for packing around fragile items for shipment and as a stuffing for upholstery. It is made by shaving wood (typically aspen or poplar) into long, curled filaments of cross-sectional dimension in the range of 0.5 mm.

Table 1.--*Fuel properties data used for example calculations*

Fuel material	Heat of combustion (low heat value) J/gm	Heat required to raise temp. from 25°C To 325°C J/gm	To 500°C J/gm	Ash content fraction	Char formed fraction
Poplar excelsior	18,234	441	772	0.0046	0.1328
Ponderosa pine dead needles	21,548	603	1,017	.0405	.2717
Cellulose	15,992	440	954	.00075	.0418
Chamise foliage (green, freeze-dried)	20,686	600	767	.0045	.3036
Manzanita foliage (green, freeze-dried)	20,413	605	778	.0369	.3023
NOTES	(1)	(2)	(3)	(4)	(5)

NOTES

(1) Data on file at Northern Forest Fire Laboratory. High heat values corrected for assumed 6.3% H content; ash-free basis; 25°C ref. temp.

(2) Data taken from Muhlenkamp and others (1977); dry weight, ash included; 160°C/min heating rate.

(3) Data extrapolated from source (2), same basis.

(4) Data on file at Northern Forest Fire Laboratory. Dried sample immersed suddenly in 500°C furnace, N_2 atmosphere. Ash formed by introducing air to hot sample, temperature raised to 600°C at 20°C/min; ash weighed at 600°C; average of 3 samples.

(5) Data from source (4); char fraction determined at 30 s from time of immersion in furnace (stable weight achieved).

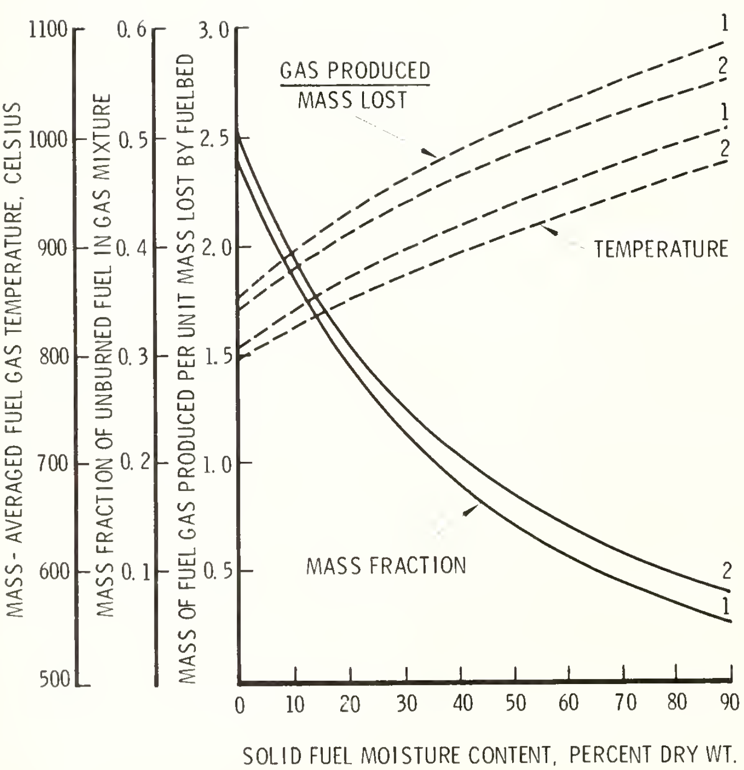


Figure 3.--Variation of gaseous fuel properties with moisture content of solid fuel. Curves labeled "1" are based upon balancing the heat budget by combustion of volatile fuel only; "2" signifies burning of whole fuel. Fuel in this figure is poplar excelsior (see properties shown in table 1). Radiation leakage fraction assumed to be 0.30. To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,320 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.47.

Figure 4.--Variation of gaseous fuel properties with moisture content of solid fuel. Curves labeled "1" are based upon balancing the heat budget by combustion of volatile fuel only; "2" signifies burning of whole fuel. Fuel in this figure is dead ponderosa pine needles (see properties shown in table 1). Radiation leakage fraction assumed to be 0.30. To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 18,490 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 6.14.

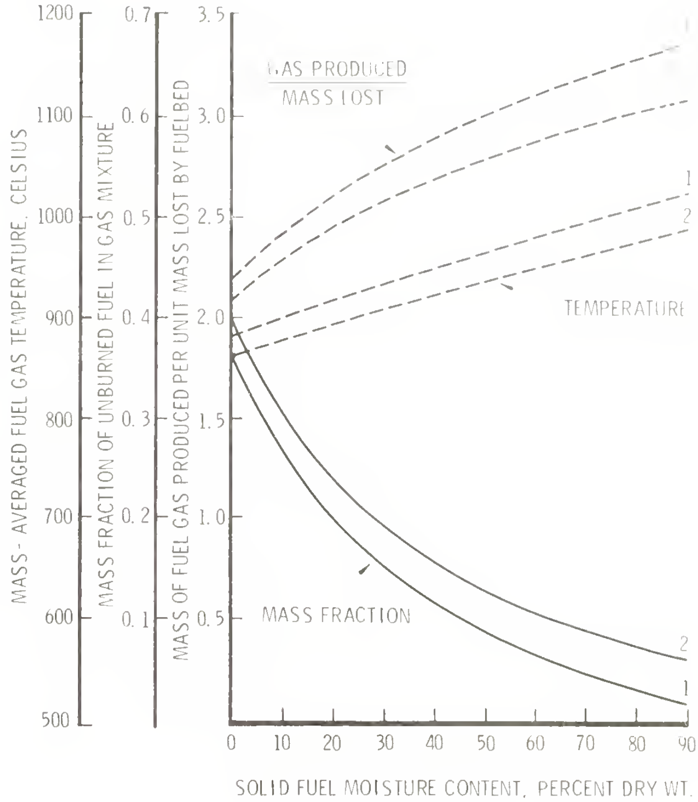
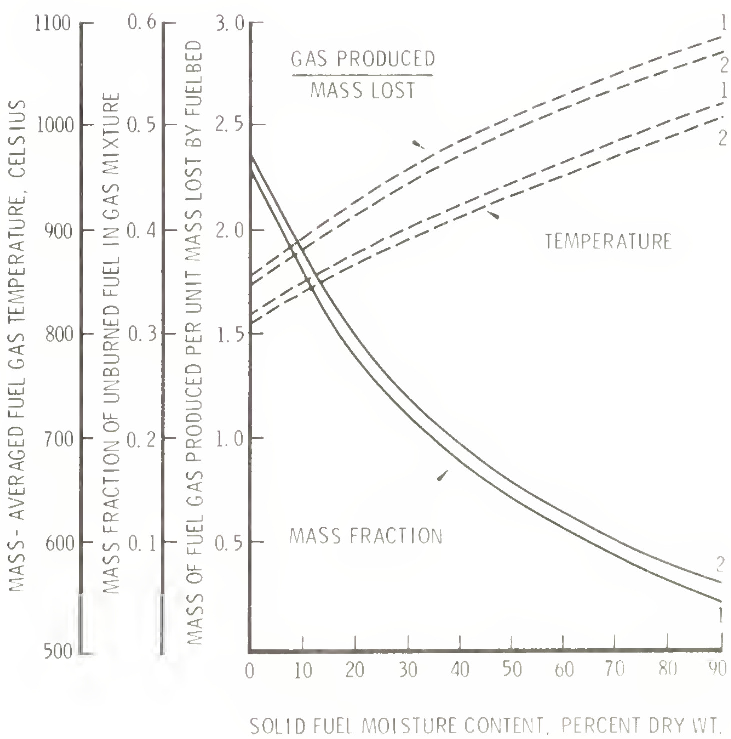


Figure 5.--Variation of gaseous fuel properties with moisture content of solid fuel. Curves labeled "1" are based upon balancing the heat budget by combustion of volatile fuel only; "2" signifies burning of whole fuel. Fuel in this figure is cellulose (see properties shown in table 1). Radiation leakage fraction assumed to be 0.30. To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 15,340 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.17.



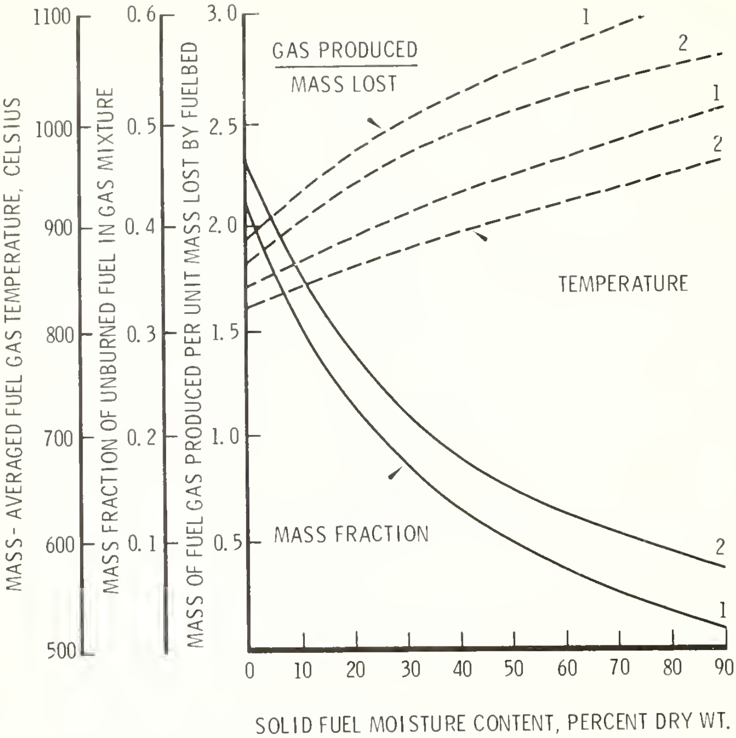


Figure 6.--Variation of gaseous fuel properties with moisture content of solid fuel. Curves labeled "1" are based upon balancing the heat budget by combustion of volatile fuel only; "2" signifies burning of whole fuel. Fuel in this figure is green chamise foliage (see properties shown in table 1). Radiation leakage fraction assumed to be 0.30. To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,770 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.61.

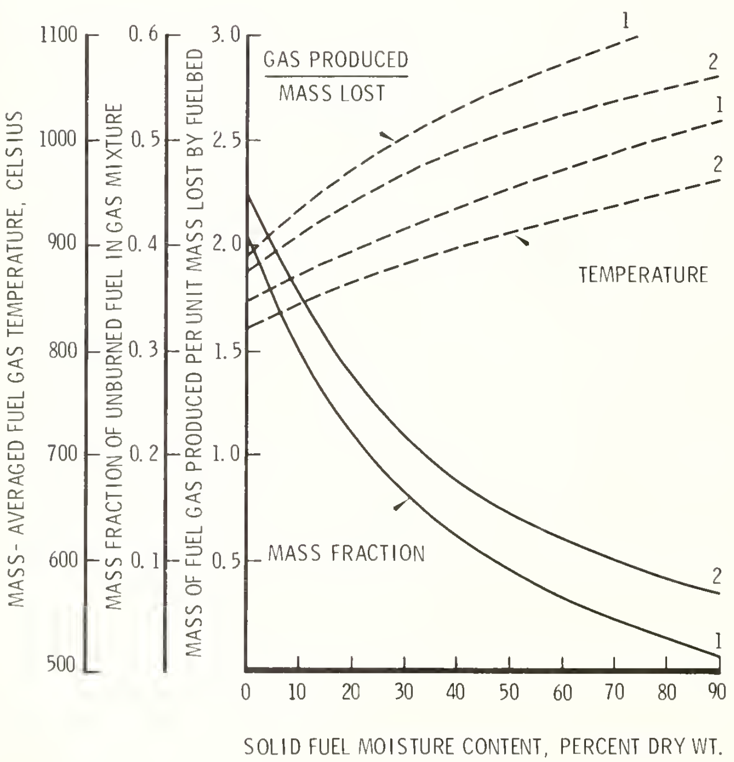


Figure 7.--Variation of gaseous fuel properties with moisture content of solid fuel. Curves labeled "1" are based upon balancing the heat budget by combustion of volatile fuel only; "2" signifies burning of whole fuel. Fuel in this figure is green manzanita foliage (see properties shown in table 1). Radiation leakage fraction assumed to be 0.30. To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,310 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.47.

This series of figures also serves to illustrate the influence of moisture content on the properties of the gaseous fuel generated by a spreading fire. Note that the temperature (mass-averaged basis) of the fuel gas increases as the moisture content rises. This seeming paradox can be readily understood if one realizes that more energy is demanded by the fuelbed to release the volatile fuel as the moisture increases. Hence the combustion process must go further toward its ultimate completion to satisfy this requirement, and less unburned fuel is available to feed the free flame standing above the fuelbed. That is, the top of the flame is getting closer and closer to the top of the fuelbed as the flame shrinks. Because we have modeled a process with no excess air, the more fuel consumed, the greater the temperature. The decline of the stoichiometric air/fuel mass ratio with increasing fuel moisture content tells this story.

The effect of fuelbed geometry, as reflected in the radiation leakage fraction, is illustrated in the series of figures 8 through 12. There are two versions of each figure; version A is based on volatile fuel combustion only and version B is based on whole fuel combustion. The general appearance of these figures illustrates that radiation leakage plays much the same role, and has a similar influence, as fuel moisture content. The similarity of the curves for such disparate fuels as those used here indicates that the use of surrogate fuels in research activities may not introduce substantial distortion when the results are interpreted to describe fire behavior in forest fuels.

Figures 13-15 illustrate the dramatic influence that the char fraction has on flaming combustion behavior of excelsior. Excelsior is often used to test fire retardant effectiveness (George and Blakely 1972) so was chosen to illustrate this effect here. Any of the other fuels would have exhibited approximately the same behavior. Since the fraction of fuel mass converted to char appears to be a function of the concentration of flame retardant (Browne and Tang 1962), the influence of retardant chemicals in reducing flaming combustion may be explainable by the process modeled here.

This series of figures shows that the greatest impact of an increase in the char fraction formed is on the heat of combustion of the fuel gas mixture. This occurs because the heat value of the nascent volatile fuel declines as well as does the mass fraction of unburned fuel in the mixture. The indication is, then, that as the level of retardant application increases, a rapid transition from flaming fire spread to smoldering should occur as a critical level of char fraction is achieved. If such a critical value exists, it would probably be a function of fuelbed geometry and moisture content.

The effect of fuel moisture on volatile fuel properties for elevated char fractions is shown in figures 16-18, which show unburned fuel mass fraction and gas production per unit load loss versus moisture content. In these figures, as in 3-12, the heat of combustion of the gas mixture is a constant multiple of the unburned fuel mass fraction. The multiplier is 15,070 J/gm for figure 16, declining to 12,760 for figure 17 and to 9,690 for figure 18. Assuming for illustrative purposes that a "critical" heat of combustion value is 3,000 J/gm (3KJ/gm), this value would be achieved at a moisture content of 36 or 47 percent (a mass fraction of 0.2 in either case, but the moisture level depends upon which process is assumed) for a char fraction of 0.2 (fig. 16). But if the char fraction were 0.3 (fig. 17), the mass fraction figure would have to be 3,000/12,760 or 0.235; this would be achieved at 18 or 33 percent fuel moisture. And if the char fraction were 0.4 (fig. 18), the required mass fraction would be 0.31, which would occur at 2 or 15 percent fuel moisture. So there appears to be a synergistic effect in the combination of fuel moisture content and flame retardant (i.e., char fraction formed) according to the model. This phenomenon has been noted for natural fuels (Rothermel and Hardy 1965) but the data do not permit quantitative comparisons with results predicted here.

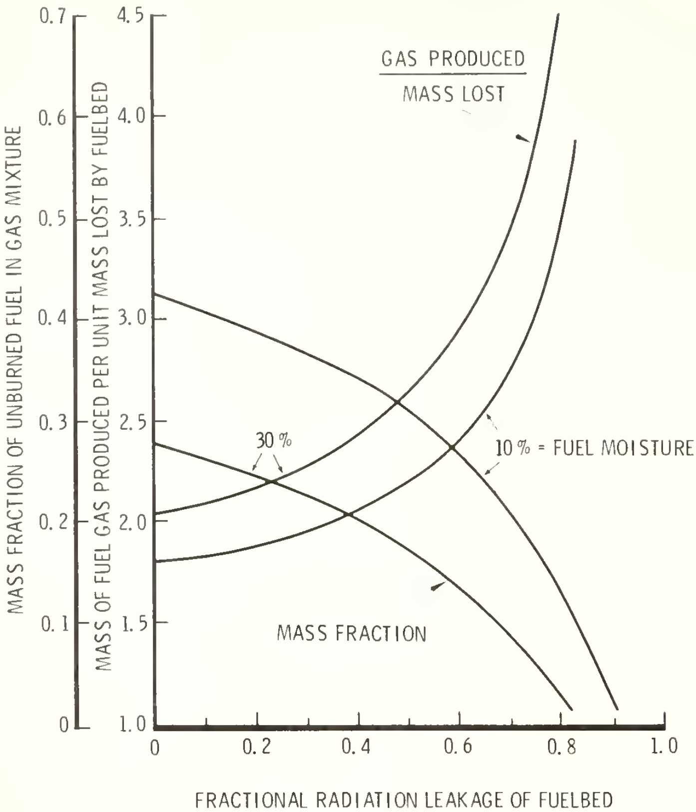


Figure 8A.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of volatile products only. Fuel in this figure is poplar excelsior (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,320 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction by 5.47.

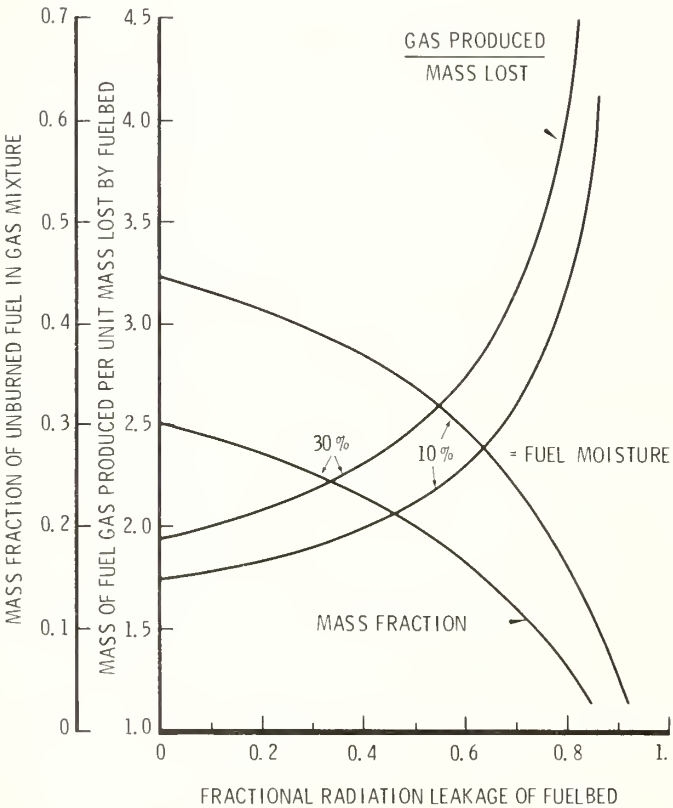


Figure 8B.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of whole fuel. Fuel in this figure is poplar excelsior (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,320 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.47.

Figure 9A.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of volatile products only. Fuel in this figure is dead ponderosa pine needles (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 18,490 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction by 6.14.

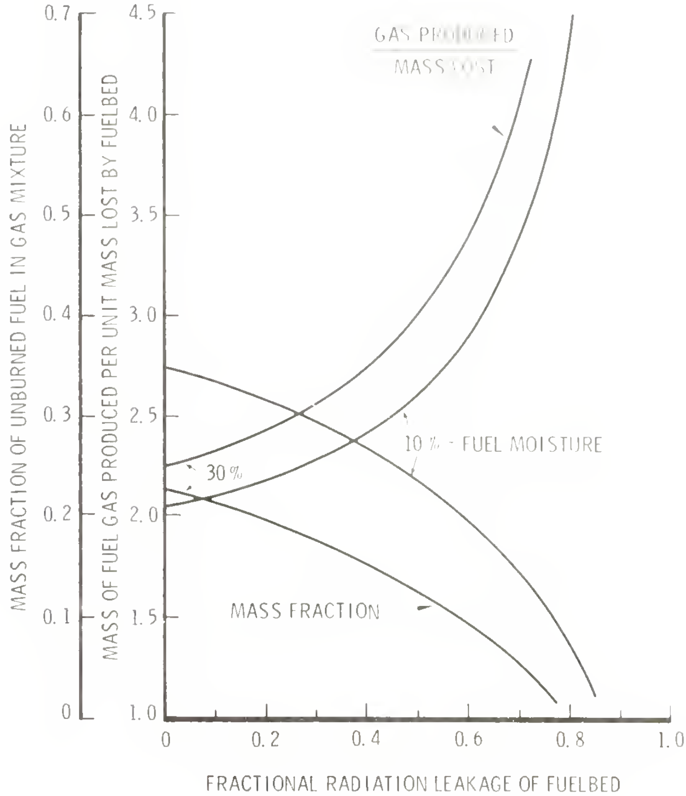
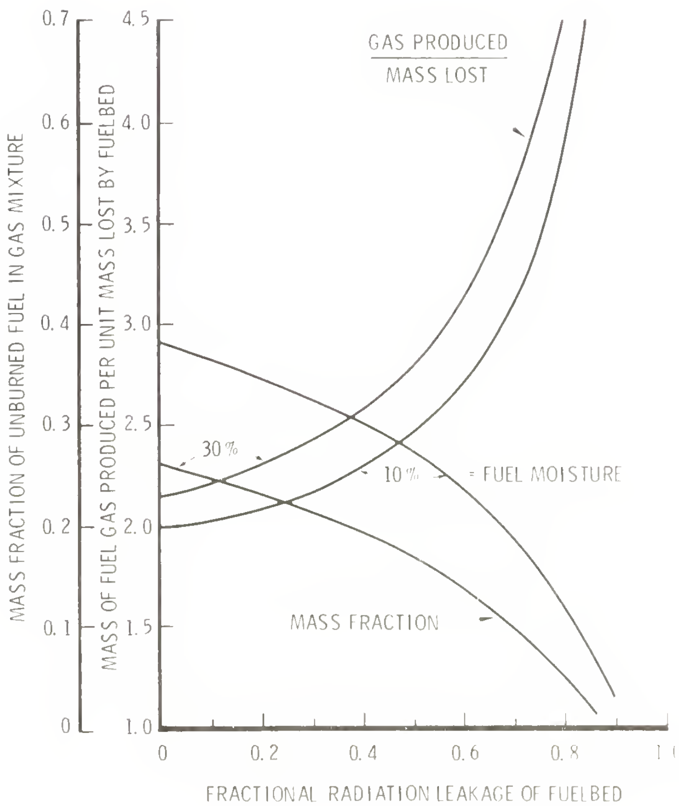


Figure 9B.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of whole fuel. Fuel in this figure is dead ponderosa pine needles (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 18,490 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 6.14.



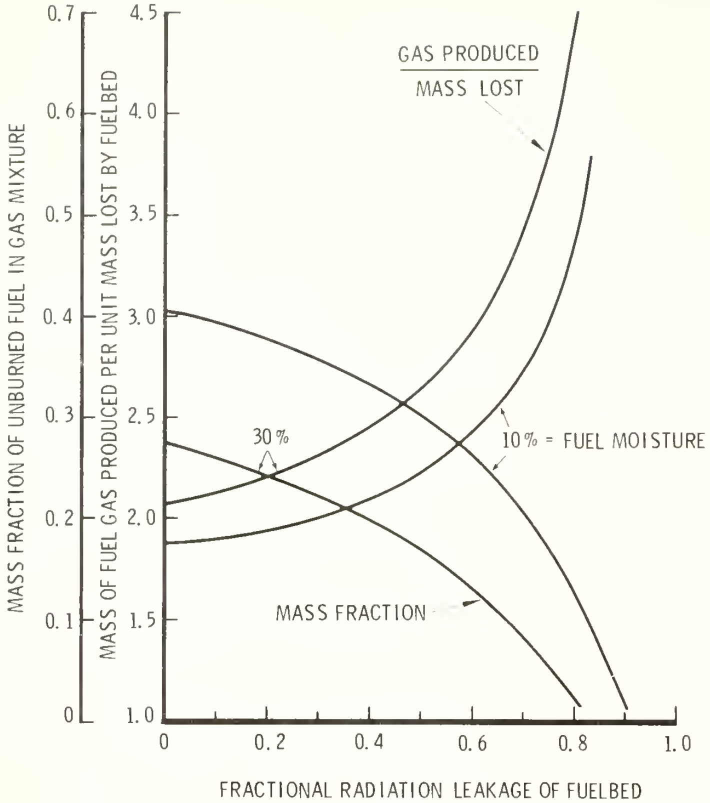


Figure 10A.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of volatile products only. Fuel in this figure is cellulose (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 15,340 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction by 5.17.

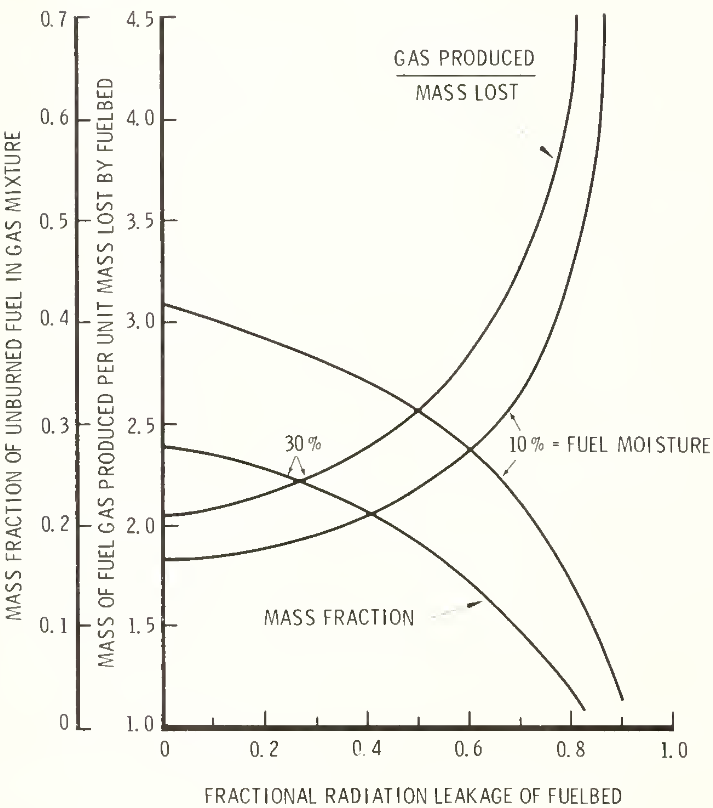


Figure 10B.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of whole fuel. Fuel in this figure is cellulose (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 15,340 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.17.

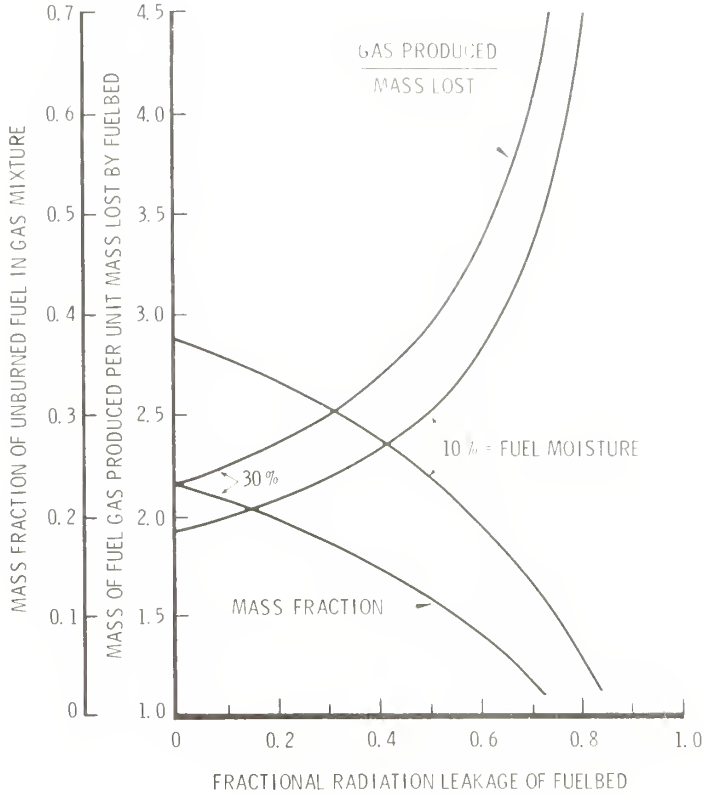


Figure 11A.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of volatile products only. Fuel in this figure is green chamise foliage (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,770 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction by 5.61.

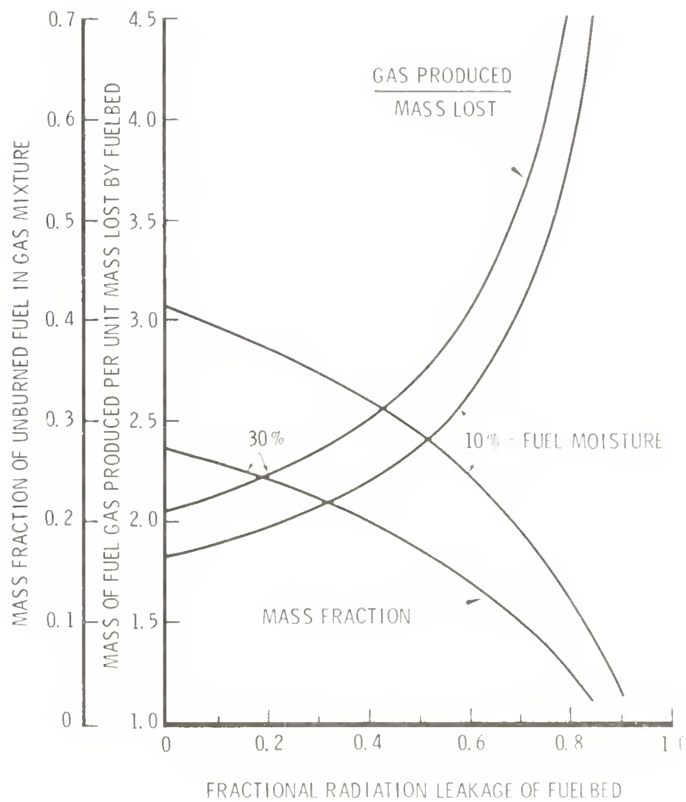


Figure 11B.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of whole fuel. Fuel in this figure is green chamise foliage (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,770 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.61.

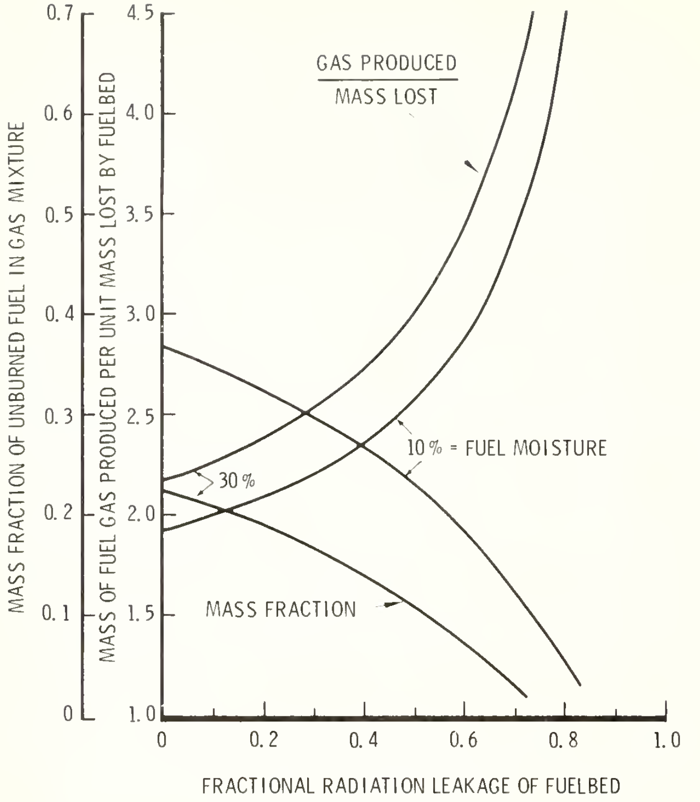


Figure 12A.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of volatile products only. Fuel in this figure is green manzanita foliage (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,310 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction by 5.47.

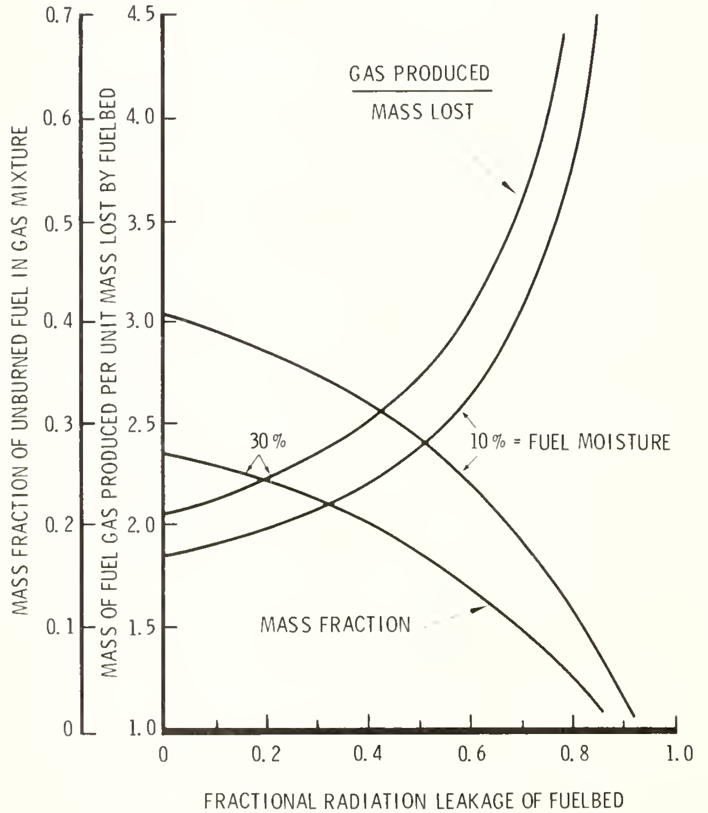


Figure 12B.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of whole fuel. Fuel in this figure is green manzanita foliage (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,310 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.47.

Figure 13.--Variation of fuel gas properties with the char fraction formed from the solid fuel. Curves marked "1" are derived from a heat balance based upon burning of released volatiles only; curves marked "2" are based upon burning of whole fuel. The fuel is poplar excelsior, a surrogate forest fuel that has been often used to test the effectiveness of flame retardant chemicals. The principal influence of such chemicals is to increase char formation. The fuel moisture content in this case is set at 6 percent, typical of retardant test conditions. The radiation leakage fraction here is 0.1.

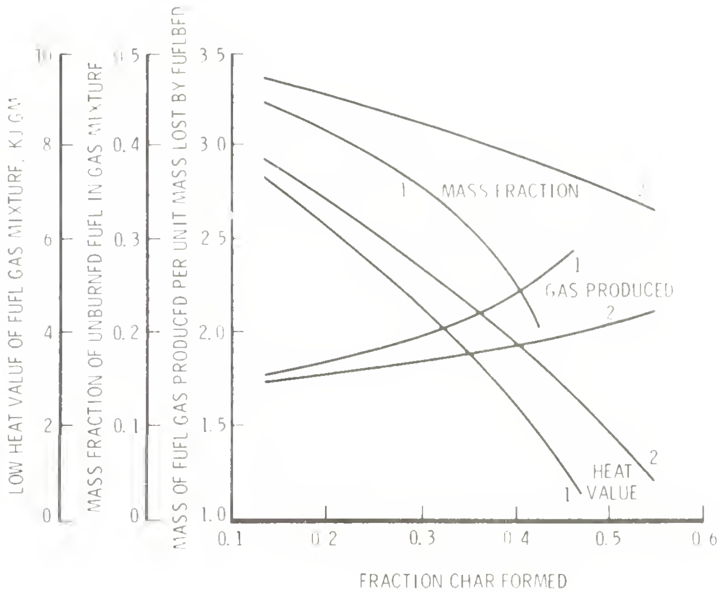
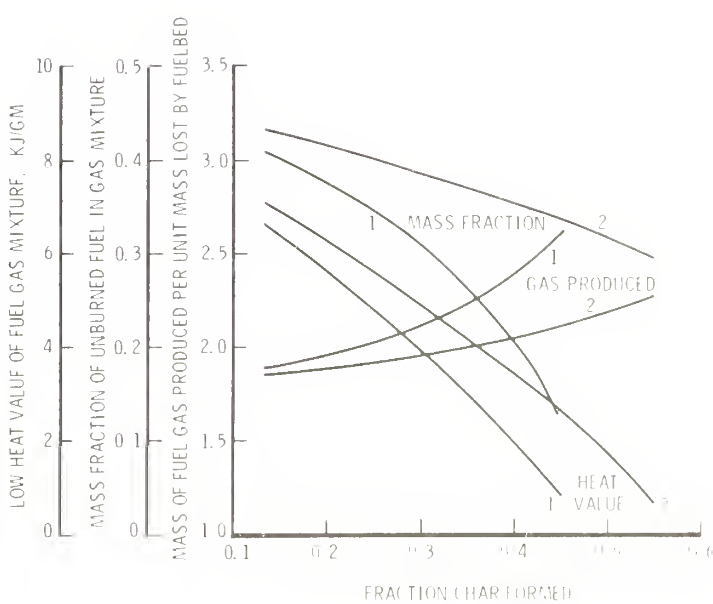


Figure 14.--Variation of fuel gas properties with the char fraction formed from the solid fuel. Curves marked "1" are derived from a heat balance based upon burning of released volatiles only; curves marked "2" are based upon burning of whole fuel. The fuel is poplar excelsior, a surrogate forest fuel that has been often used to test the effectiveness of flame retardant chemicals. The principal influence of such chemicals is to increase char formation. The fuel moisture content in this case is set at 6 percent, typical of retardant test conditions. The radiation leakage fraction here is 0.3.



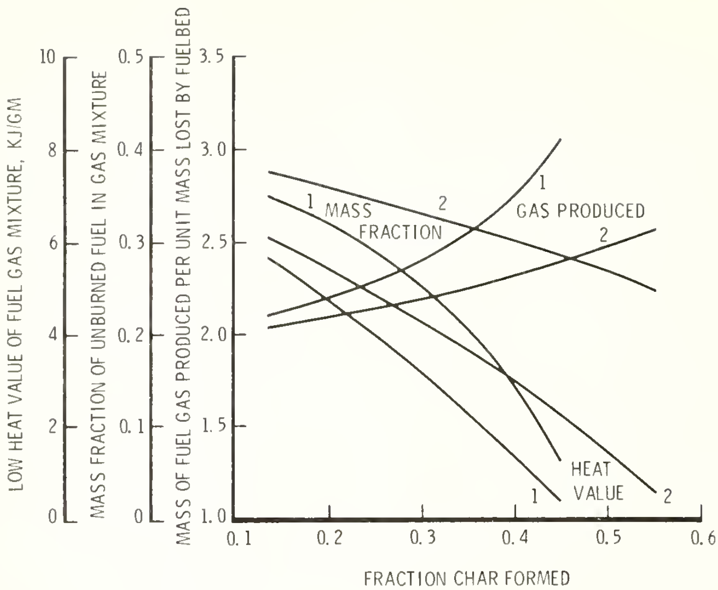


Figure 15.--Variation of fuel gas properties with the char fraction formed from the solid fuel. Curves marked "1" are derived from a heat balance based upon burning of released volatiles only; curves marked "2" are based upon burning of whole fuel. The fuel is poplar excelsior, a surrogate forest fuel that has been often used to test the effectiveness of flame retardant chemicals. The principal influence of such chemicals is to increase char formation. The fuel moisture content in this case is set at 6 percent, typical of retardant test conditions. The radiation leakage fraction here is 0.5.

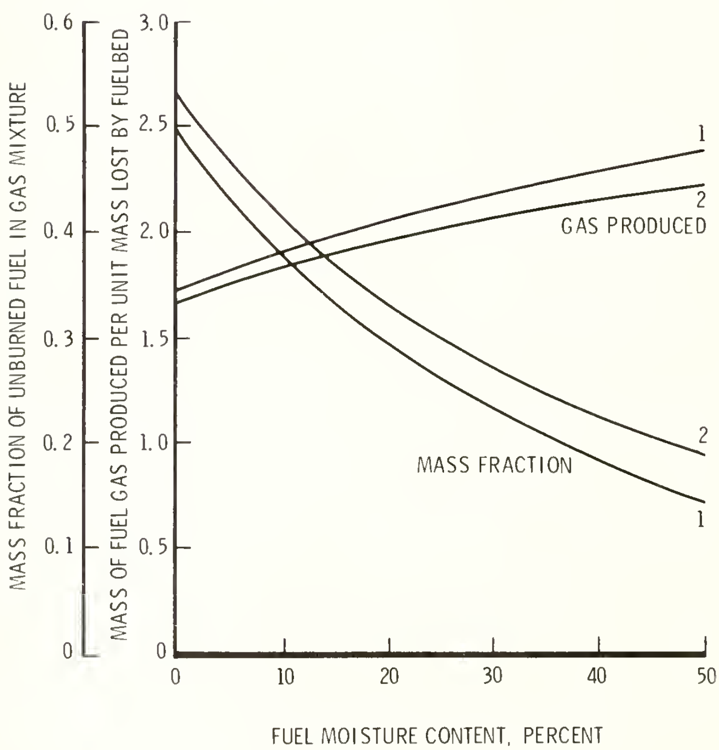
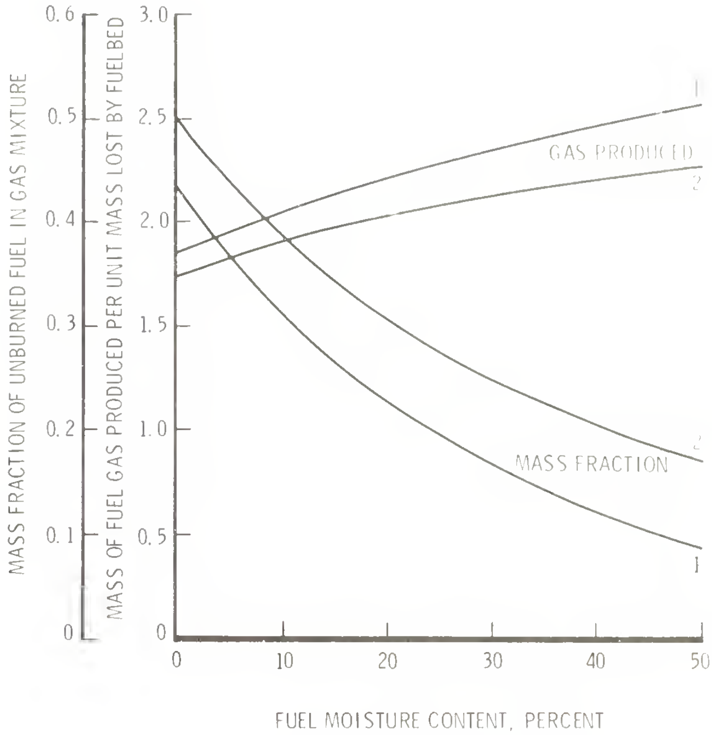


Figure 16.--Variation of fuel gas properties with moisture content for poplar excelsior treated with retardant to increase char fraction to 0.2. Radiation leakage fraction here assumed to be 0.1, typical of retardant test fuelbed geometry. To find the low heat value of the fuel gas mixture, multiply the mass fraction values by 15,070 J/gm. Similarly, the stoichiometric air/fuel mass ratio for the mixture is 5.09 times the mass fraction.

Figure 17.--Variation of fuel gas properties with moisture content for poplar excelsior treated with retardant to increase char fraction to 0.3. Radiation leakage fraction here assumed to be 0.1, typical of retardant test fuelbed geometry. To find the low heat value of the fuel gas mixture, multiply the mass fraction values by 12,760 J/gm. Similarly, the stoichiometric air/fuel mass ratio for the mixture is 4.38 times the mass fraction.



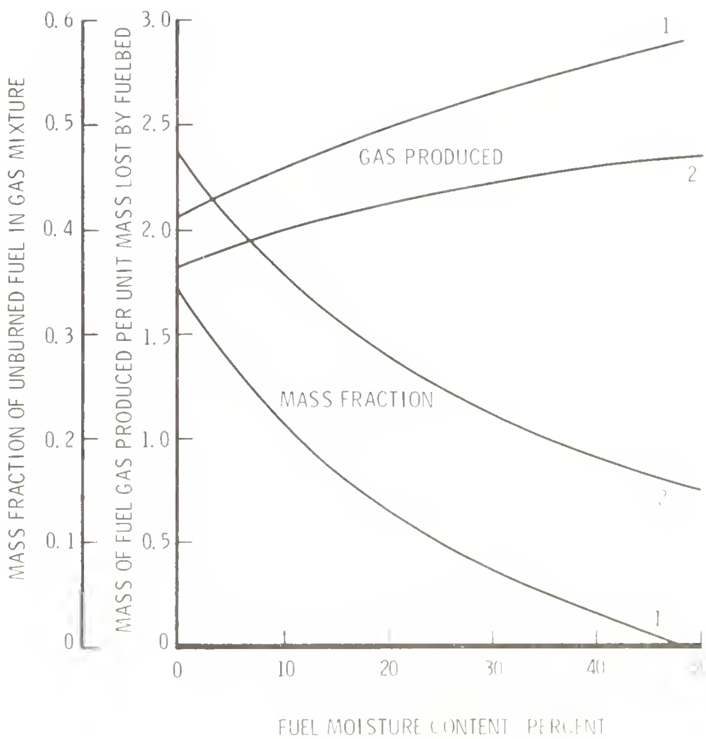


Figure 18.--Variation of fuel gas properties with moisture content for poplar excelsior treated with retardant to increase char fraction to 0.4. Radiation leakage fraction here assumed to be 0.1, typical of retardant test fuelbed geometry. To find the low heat value of the fuel gas mixture, multiply the mass fraction values by 9,690 J/gm. Similarly, the stoichiometric air/fuel mass ratio for the mixture is 3.45 times the mass fraction.

The model presented here is not a predictive tool in that a complete description of the fuel (in terms of the intrinsic properties of the fuel particle material, particle size, and fuelbed loading) does not permit the calculation of the thermochemical properties of the flame gases that would be generated if the fuel were burned. Not only does one have to specify the flame-fuel surface inclination angle (see appendix II to derive a radiation leakage fraction, but one also must choose which of the two model to use. At this stage of development no way is seen to predict either the interface angle or which model to use. But, as was discussed above, fires that are spreading rapidly should exhibit large flame-fuel interface angles and might be expected to admit of little char burning in the flame-generating zone at the head of the fire. And fires propagating near the limit of extinction are known to exhibit near vertical flame-fuel interface orientations and more complete fuel consumption in the flaming zone.

If these two principles are tentatively accepted, then one might expect a fuelbed burned under very low moisture content conditions to be described by the first model (only volatile fuel burning in the flame-producing zone) and to exhibit a large radiation leakage fraction. The same fuelbed, burned at a moisture content such that it would barely qualify for description by the models given here, might have a vertical flame-fuel interface (hence showing the smallest radiation leakage fraction possible for the fuelbed) and might be best described using the second model. For conditions between these extremes, neither model would apply adequately by itself and the radiation leakage fraction would have intermediate values. So a graph showing the heat of combustion of bulk fuel gas versus fuel moisture content might follow a curve such as that shown in figure 19, drawn for a fuelbed of dead ponderosa pine needles arranged in a loose mat (opacity factor $\simeq$2.5--see appendix II). The two solid curves show the behavior expected under the limiting conditions and the dashed line connecting the two is included only to illustrate that a smooth transition between the two is to be expected over some range of fuel moisture content. The shape of the composite curve, including the dashed line, is reminiscent of the "moisture damping" coefficient curves given by Rothermel (1972) based upon experimental measurements. Such similarity is encouraging but cannot be construed as supportive of this theoretical work.

Experimental confirmation or refutation of the theoretical developments presented here will be very difficult to obtain, since none of the predicted quantities are readily measured. It is tempting to speculate, however, that there exists a critical value of the heat of combustion or the stoichiometric air/fuel mass ratio of the fuel gas mixture below which the flaming combustion zone would collapse as a coherent structure. If so, perhaps the fuel intrinsic properties, moisture content, and fuelbed opacity parameter (hence radiation loss fraction--see appendix II) combinations that lead to this condition could be used to correlate and to predict the occurrence for other fuel/moisture/fuelbed opacity combinations. Controlled-condition laboratory fires near the extinction limit are both difficult and time consuming, but work in progress at present[4] may lead to sufficient data to test the concept.

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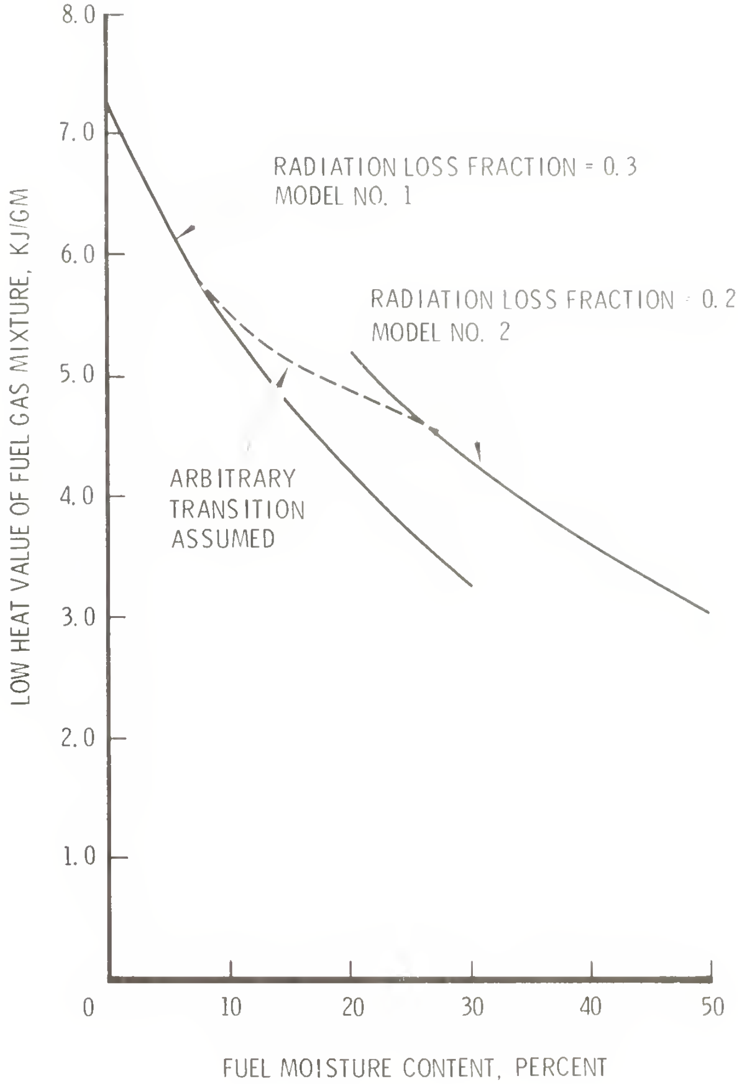
[4]Ralph Wilson, "Moisture damping of fires under variable fuel loading conditions." USDA For. Serv. Study Plan 2103-12; Intermt. For. and Range Exp. Stn., Northern For. Fire Lab., Missoula, MT, Line Project FS-INT-2103, Fire Fundamentals, 22 July 1977.

Figure 19.--Variation of heat of combustion of fuel gas mixture with fuel moisture content. Fuel is ponderosa pine needles arranged in a loose mat, so the radiation loss fraction lies between 0.2 and 0.3 for all values of fuel-fire interface angle between 10 and 90 degrees (see appendix 11). The two solid curves show the behavior expected in the extreme conditions; the dashed line indicates that a smooth transition between the two is to be expected over some range of moisture contents. Model 1 implies combustion of volatile fuels only in the flame-producing zone while model 2 implies combustion of whole fuel.



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APPENDIX I: HEAT AND MASS BALANCE MODEL

This appendix presents the mathematical formulation of the models described in the text, with some elaboration. Assumptions and approximations discussed in the text will not be reiterated here, but will be briefly indicated as they are introduced. First the "debit" side of the heat budget is developed for a unit mass of dry solid fuel. Then two alternative forms of the energy supply budget are derived, as outlined in the text. Symbols are defined as they are introduced, for the sake of clarity.

Heat Required by a Unit Mass of Fuel

The heat energy needed to raise the temperature of a unit mass of dry solid fuel from ambient to 500°C, reducing it to char and liberating the volatilizable component, is a measurable quantity that seems to be a property of the fuel material. Example values of this quantity are tabulated in the text. Let this quantity of heat be represented by H_D.

Before the fuel reaches the char state, it will have become involved in flaming combustion, as described in the text. In order to take account of the loss of energy by radiation leakage, it is necessary to estimate the amount of heat absorbed by the fuel before flame attachment. This amount of heat, H_i, can be expressed, approximately, as follows:

$$H_i \doteq M\left(Cp_W(T_B - T_A) + L\right) + H_i'$$

where

M = moisture content of fuel (fraction dry weight)

Cp_W = specific heat capacity of water = 4.18 J/gm/deg C

T_B = boiling temperature of water = 100°C

T_A = ambient temperature (assumed = 25°C)

L = latent heat of vaporization of water = 2260 J/gm

H_i' = heat required to raise the temperature of a unit mass of dry solid fuel to ignition temperature (a measured value--see tables in text)

so

$$H_i = H_i' + 2570M \quad \text{J/gm.}$$

Now if a fraction, F, of the energy radiated into the fuelbed ahead of the flame/fuel interface is lost (see appendix II), then the amount of heat required to raise a unit mass of fuel to ignition temperature is approximately H_I, where

$$H_I = H_i/(1 - F).$$

This is the energy output demanded from the process volume.

After the fuel has entered the flaming zone, the energy required to complete the char/volatilization process, H_p, is given by

$$H_p = H_D - H_i'.$$

This energy will liberate the volatiles at a temperature-dependent rate as described in the text. To raise the temperature of the volatiles to a uniform temperature T* (= 500°C) requires an additional increment of heat, H_R. Assuming the bilinear rate of evolution described in the text, this quantity can be derived as follows:

Let m(t) = the mass of gas evolved from a unit mass of solid fuel at time t after the gassification starts. Then

$$\frac{dm}{dt} = \left(\frac{dm}{dt}\right)_{max} \cdot \begin{cases} (T - T_1)/(T_2 - T_1), & T_1 \leq T \leq T_2 \\ (T_3 - T)/(T_3 - T_2), & T_2 \leq T \leq T_3 \end{cases}$$

where

$\left.\frac{dm}{dt}\right|_{max}$ = the maximum rate of gas evolution, which occurs at temperature $T = T_2$

T_1 = temperature at which gas liberation starts (~200°C)

T_2 = temperature at peak gas evolution rate (~350°C)

T_3 = temperature at which gas evolution is complete (~450°C).

The rate at which energy (E) would have to be supplied to the evolved gas to bring it instantly up to the reference temperature T* would be given by

$$\frac{dE}{dt} = \frac{dm}{dt} C_p (T^* - T)$$

where

C_p = specific heat capacity of volatiles.

Assuming that the temperature-versus-time curve for the fuel particle is adequately approximated by a straight line over the range $T_3 \leq T \leq T_1$,

$$dE = \left(\left(\frac{dm}{dt}\right)\Big/\left(\frac{dT}{dt}\right)\right) C_p (T^* - T)\, dT$$

where

$$\frac{dT}{dt} \doteq \text{constant}.$$

The total mass of gas evolved is given by Δm, where

$$\Delta m = \int_{T_1}^{T_3} \left(\left(\frac{dm}{dt}\right)\Big/\left(\frac{dT}{dt}\right)\right) dT$$

$$= \left(\left(\frac{dm}{dt}\right)_{max}\Big/\left(\frac{dT}{dt}\right)\right)\frac{1}{2}(T_3 - T_1)$$

so the energy demand per unit mass of evolved gas is

$$\int_{T_1}^{T_3} \frac{dE}{dT} dT / \Delta m = \frac{2C_p}{T_3 - T_1} \int_{T_1}^{T_3} (T^* - T) \left\{ \left(\frac{dm}{dt}\right) / \left(\frac{dm}{dt}\right)_{max} \right\} dT$$

and hence

$$H_R = (1 - \gamma) \frac{2C_p}{T_3 - T_1} \int_{T_1}^{T_3} (T^* - T) \frac{\left(\frac{dm}{dt}\right)}{\left(\frac{dm}{dt}\right)_{max}} dT.$$

Here γ is the fraction of dry fuel converted to char (so $1 - \gamma$ is the fraction converted to volatiles).

$$H_R = \frac{2(1-\gamma)C_p}{T_3 - T_1} \left\{ \int_{T_1}^{T_2} (T^* - T) \frac{T - T_1}{T_2 - T_1} dT + \int_{T_2}^{T_3} (T^* - T) \frac{T_3 - T}{T_3 - T_2} dT \right\}$$

$$H_R = \frac{(1-\gamma)C_p}{T_3 - T_1} \left\{ (T_2 - T_1) \left[(T^* - T_1) - \frac{2}{3}(T_2 - T_1) \right] + (T_3 - T_2) \left[(T^* - T_3) + \frac{2}{3}(T_3 - T_2) \right] \right\}$$

Inserting the numerical values

$$C_p = 1.05 \text{ J/gm/deg C}$$
$$T_1 = 200°C$$
$$T_2 = 350°C$$
$$T_3 = 450°C$$
$$T^* = 500°C$$

this becomes simply

$$H_R = 175(1 - \gamma) \quad \text{J/gm.}$$

The steam (water driven off before ignition temperature is reached) must also be heated to the reference temperature T^* since it forms part of the effluent gas from the process volume also. The heat required by this component is H_s, where

$$H_s = MC_{ps}(T^* - T_B)$$

and

C_{ps} = the mean specific heat capacity of water vapor in the temperature range 100°-1000°C (= 2.09 J/gm/deg C)

H_s = 836M J/gm.

The sum of the components listed above gives the heat, H_N, required to desiccate, heat, and decompose a unit mass of solid fuel and heat the char and gases (water and volatilized fuel) to the reference temperature T^*:

$$H_N = H_I + H_p + H_R + H_s.$$

Heat Available Through Partial Combustion

The net sensible heat demand H_N is to be met by the combustion of some of the fuel (either as gas or as whole fuel, gas plus char) within the process volume. In turn, the combustion product mass (air + consumed fuel) must be heated to the rich-limit combustion temperature, T_C, which process demands additional sensible heat. An equal fraction of the liberated moisture is assumed to be heated to T_C also.

Assume first that only volatile fuel is burned in the process volume. Let the fraction of the volatile fuel that is burned be X_1 and the heat of combustion (low heat value) of the volatile fuel be ΔH_V. Then if the stoichiometric air/fuel mass ratio of the volatile fuel is N_V, the net sensible heat released by this combustion, per unit mass of dry solid fuel is H_{A1}, where

$$H_{A1} = X_1(1-\gamma)\Big(\Delta H_V - C_p(T_C - T^*) - N_V C_p(T_C - T_A) - MC_{ps}(T_C - T^*)\Big).$$

Since we assume equal specific heat capacities for the volatile fuel, air, and combustion products, the heat of combustion of the volatiles need not be corrected for temperature.

Using the numerical values employed before, this reduces to

$$H_{A1} = X_1(1 - \gamma)(\Delta H_V - 630 - 1130N_V - 1255M) \quad \text{J/gm.}$$

Equating H_{A1} and H_N gives the equation for X_1, the fraction of the volatile fuel burned in the process volume. The mass-averaged temperature, T_{M1}, of the gaseous fuel mixture leaving the process volume is readily expressed in terms of X_1:

$$\Big(MC_{ps} + (1-\gamma)(1+X_1N_V)C_p\Big)(T_{M1} - T^*) = (1-\gamma)X_1\Big(MC_{ps} + (1+N_V)C_p\Big)(T_C - T^*).$$

This equation expresses a sensible heat balance in the gas phase. Solving for the mass-averaged temperature gives

$$T_{M1} = T^* + \frac{(T_C - T^*)(1 - \gamma)X_1\Big(MC_{ps} + (1 + N_V)C_p\Big)}{MC_{ps} + (1 - \gamma)(1 + X_1N_V)C_p}$$

or

$$T_{M1} = 500 + \frac{600(1 - \gamma)X_1(2M + 1 + N_V)}{2M + (1 - \gamma)(1 + X_1N_V)} \quad \text{deg C.}$$

The fraction of the mass of the exiting gas that consists of unburned volatile fuel vapor, Y_1, is also simply expressed in terms of X_1:

$$Y_1 = (1 - \gamma)(1 - X_1)/\Big(M + (1 - \gamma)(1 + X_1N_V)\Big).$$

The numerator is simply the fraction of the dry weight of a unit mass of fuel that leaves the volume unburned while the denominator is the mass of gas generated per unit (dry) mass of fuel processed. If the denominator is divided by the mass loss (as would be sensed by a weighing system under the fuelbed) per unit mass of dry fuel processed, we find the ratio of gaseous fuel mass evolved per unit mass loss by the fuelbed within the process volume, μ_1:

$$\mu_1 = \left(M + (1 - \gamma)(1 + X_1 N_V)\right)/(M + 1 - \gamma).$$

The heat of combustion ΔH_{F1} of the gas mixture leaving the control volume, treated as a diluted fuel, is simply the product of Y_1 and ΔH_V. Similarly, the stoichiometric air/fuel mass ratio N_{F1} for this mixture is Y_1 times N_V.

In the second case discussed in the text, whole fuel is consumed in the process volume (i.e., equal fractions of char and volatile components) rather than just some of the volatiles. The development of the equations proceeds along the same lines as just above. Let the fraction of the whole fuel that is burned be X_2, the low heat value of the (ash-free) whole fuel be ΔH_o, and the stoichiometric mass ratio of the (ash-free) whole fuel be N_o. The net sensible heat released by this partial combustion is H_{A2}, where

$$H_{A2} = X_2\Big((1-\varepsilon)\big(\Delta H_o - C_p(T_C - T^*) - N_o C_p(T_C - T_A)\big) - MC_{ps}(T_C - T^*)\Big)$$

$$H_{A2} = X_2\big((1 - \varepsilon)(\Delta H_o - 630 - 1130N_o) - 1255M\big) \quad \text{J/gm.}$$

The parameter ε in this equation is the fraction of whole fuel (dry) weight that is mineral ash. This fraction is not converted to volatile (it is included in γ) but neither is it burned when the char burns. Again, equating H_{A2} and H_N gives the equation for X_2, in terms of which the mass-averaged temperature, T_{M2}, of the mixture can be expressed:

$$T_{M2} = T^* + \frac{(T_C - T^*)X_2\big(MC_{ps} + (1 - \varepsilon)(1 + N_o)C_p\big)}{MC_{ps} + \Big(1 - \gamma + X_2\big(N_o(1 - \varepsilon) + \gamma - \varepsilon\big)\Big)C_p}$$

$$T_{M2} = 500 + \frac{600X_2\big(2M + (1 - \varepsilon)(1 + N_o)\big)}{2M + 1 - \gamma + X_2\big(N_o(1 - \varepsilon) + \gamma - \varepsilon\big)}.$$

The fraction of the exiting gas that consists of unburned volatile fuel vapor, Y_2, in this case, is given by:

$$Y_2 = (1 - \gamma)(1 - X_2)/\Big(M + 1 - \gamma + X_2\big(N_o(1 - \varepsilon) + \gamma - \varepsilon\big)\Big).$$

As before, the heat of combustion of the gas mixture, ΔH_{F2}, is $Y_2 \Delta H_V$ and the stoichiometric air/fuel mass ratio, N_{F2}, is $Y_2 N_V$.

The ratio of gaseous fuel mass produced to fuelbed mass lost in the process volume, μ_2, can be expressed in terms of X_2 also:

$$\mu_2 = \frac{M + 1 - \gamma + X_2(N_o(1 - \varepsilon) + \gamma - \varepsilon)}{M + 1 - \gamma + X_2(\gamma - \varepsilon)}.$$

In the expression for H_{A2} above, the heat of combustion of the whole fuel, ΔH_o, should be corrected for the difference in enthalpy changes between reactants and products due to the temperature shift between the posited reference temperature T* and the temperature at which the heat of combustion is measured (usually ~25°C). But this difference would be composed only of product of γ, the difference between the specific heat capacities of solid and gas phase reactants, and the temperature shift, plus the heat of reaction (including phase change) associated with the pyrolysis process. This "latent heat" term is known to be very small, but it is not clear whether the process is generally exothermic or endothermic (Roberts 1971). In any case the difference between the heat of reaction at the elevated reference temperature and the usual laboratory temperature of determination is small and will be neglected here.

Simplication and Summary of Equations

The number of input variables required to use the equations given above is quite large. Fortunately, additional simplifications are possible by using the approximations and empirical relationships discussed in the text.

The heat of combustion of the volatile component, ΔH_v, can be calculated from the equation for the whole fuel heat of combustion, ΔH_o, and the heat of combustion of the (ash-free) char, ΔH_C.

$$(1 - \varepsilon)\Delta H_o = (1 - \gamma)\Delta H_v + (\gamma - \varepsilon)\Delta H_C,$$

so

$$\Delta H_v = ((1 - \varepsilon)\Delta H_o - (\gamma - \varepsilon)\Delta H_C)/(1 - \gamma)$$

where all heats of combustion are low heat values and ΔH_C is taken to be constant at 31,200 J/gm.

The high heat value of the volatile fuel, $\Delta H_v'$, is calculated from ΔH_v and the estimate that these volatiles contain 7.2 percent hydrogen. Similarly, the whole fuel high heat value $\Delta H_o'$ is calculated assuming a 6.3 percent hydrogen fraction by weight.

$$\Delta H_v' = \Delta H_v + 1580 \quad \text{J/gm}$$

$$\Delta H_o' = \Delta H_o + 1380 \quad \text{J/gm}$$

These values are used to calculate the stoichiometric air/fuel mass ratios, using the figure 3270 J/gm air as an empirical constant (see discussion in text):

$$N_v = \Delta H_v'/3270$$

$$N_o = \Delta H_o'/3270.$$

Other constants used in the calculations leading to the figures presented in the text were introduced above as the need arose. The set of equations used is assembled here for ready reference, with numerical values inserted.

DATA REQUIRED

H_D = heat required to raise unit mass of dry fuel to 500°C, J/gm

H_i' = heat required to raise unit mass of dry fuel to 325°C, J/gm

γ = fraction of fuel (dry weight) converted to char, ash included

ε = fraction of fuel (dry weight) that is mineral ash

ΔH_o = low heat value of ash-free whole fuel (dry weight basis)

M = fuel moisture content, fraction of dry weight

F = fraction of heat radiated into fuelbed from process volume that is lost to the environment (calculated in appendix II)

EQUATION SUMMARY

$$H_i = H_i' + 2570M$$

$$H_I = H_i/(1 - F)$$

$$H_p = H_D - H_i'$$

$$H_R = 217(1 - \gamma)$$

$$H_s = 836M$$

$$H_N = H_I + H_p + H_R + H_s$$

$$\Delta H_v = ((1 - \varepsilon)\Delta H_o - (\gamma - \varepsilon)31{,}200)/(1 - \gamma)$$

$$\Delta H_v' = \Delta H_v + 1580$$

$$\Delta H_o' = \Delta H_o + 1380$$

$$N_v = \Delta H_v'/3270$$

$$N_o = \Delta H_o'/3270$$

$$X_1 = H_N/((1 - \gamma)(\Delta H_v - 630 - 1130N_v - 1255M))$$

$$T_{M1} = 500 + \frac{600(1 - \gamma)X_1(2M + 1 + N_v)}{2M + (1 - \gamma)(1 + X_1 N_v)}$$

$$Y_1 = (1 - \gamma)(1 - X_1)/(M + (1 - \gamma)(1 + X_1 N_v))$$

The first form represents loss to the lower boundary and the second represents loss to the upper boundary.

The net fractional energy loss is given by F, where

$$F = \int_{L=0}^{\delta/\sin\alpha} \int_{-\pi/2}^{\pi/2} \frac{\cos\theta}{2} \frac{\sin\alpha}{\delta} \exp(-kD)\, d\theta dL.$$

Carrying out the integral over L first, this becomes

$$F = \frac{1}{2k\delta} \left\{ \int_{-\pi/2}^{\alpha-\pi/2} \Big(\exp\big(k\delta/\cos(\alpha-\theta)\big) - 1\Big) \cos\theta \cos(\alpha-\theta)\, d\theta \right.$$

$$\left. + \int_{\alpha-\pi/2}^{\pi/2} \Big(1 - \exp\big(-k\delta/\cos(\theta-\alpha)\big)\Big) \cos\theta \cos(\theta-\alpha)\, d\theta \right\}.$$

Changing to the variable $x = \alpha - \theta - \pi/2$ in the first integral and $x = \alpha + \pi/2 - \theta$ in the second gives the form

$$2k\delta F = \int_0^{\alpha} \sin x \sin(\alpha-x)\big(1 - \exp(-k\delta/\sin x)\big)dx$$

$$+ \int_{\alpha}^{\pi} \sin x \sin(x-\alpha)\big(1 - \exp(-k\delta/\sin x)\big)dx.$$

Replacing $k\delta$ by C and differentiating the expression above twice with respect to the angle α gives

$$2C \frac{d^2F}{d\alpha^2} = 2 \sin\alpha \Big(1 - \exp(-C/\sin\alpha)\Big) - 2CF.$$

By this device it is possible to evaluate the integrals indirectly, by solving the differential equation numerically. The set of equations then is:

$$CF\big|_{\alpha=\pi/2} = \frac{1}{2}\left\{\int_0^{\pi/2} \sin x \cos x \,(1 - \exp(-C/\sin x))dx - \int_{\pi/2}^{\pi} \sin x \cos x \,(1 - \exp(-C/\sin x))dx\right\}$$

$$= \frac{1}{2}\left\{1 - \int_0^1 u \exp(-C/u)du + \int_1^0 v \exp(-C/v)dv\right\}$$

$$= \frac{1}{2}\left\{1 - 2C^2 \int_C^{\infty} (1/t^3)\exp(-t)dt\right\}$$

$$= \frac{1}{2}\left\{1 - (1 - C)\exp(-C) - C^2E_1(C)\right\}$$

where $E_1(C)$ is the exponential integral (Abramowitz and Stegun 1964)

$$E_1(C) \equiv \int_C^{\infty} \exp(-t)dt/t$$

$$\frac{d}{d\alpha}(CF)\big|_{\alpha=\pi/2} = 0$$

$$\frac{d^2}{d\alpha^2}(CF) = \sin \alpha(1 - \exp(-C/\sin \alpha)) - CF.$$

The differential equation was solved numerically using a standard Runge-Kutta integration program coded for the CDC-7600 computer at the Lawrence Berkeley Laboratories computer facility on the University of California, Berkeley, campus. A polynomial approximation for the exponential integral (Abramowitz and Stegun 1964) was used to establish the initial condition for various values of the parameter C. Figure II-1 is a plot showing the variation of the radiation loss fraction, F, as a function of the fuelbed opacity parameter, C, for two values of the tilt angle (α) of the flame interface surface.

The parameter C can be related to familiar fuelbed descriptors, since the extinction coefficient, k, is given by Anderson (1969)

$$k = \sigma\beta/4$$

where

σ = fuel particle surface area/volume ratio
β = fuelbed packing ratio, the fraction of fuelbed volume filled with solid fuel particles.

From this form we have

$$C = \sigma\beta\delta/4$$

which has values in the range from about 0.5 (e.g., for sparse grass) to perhaps 5.0 or more (e.g., for pine litter). This range of values gives rise to potential radiation leakage fractions of 0.1 to 0.7 (see fig. II-1) and greater variability is readily conceivable.

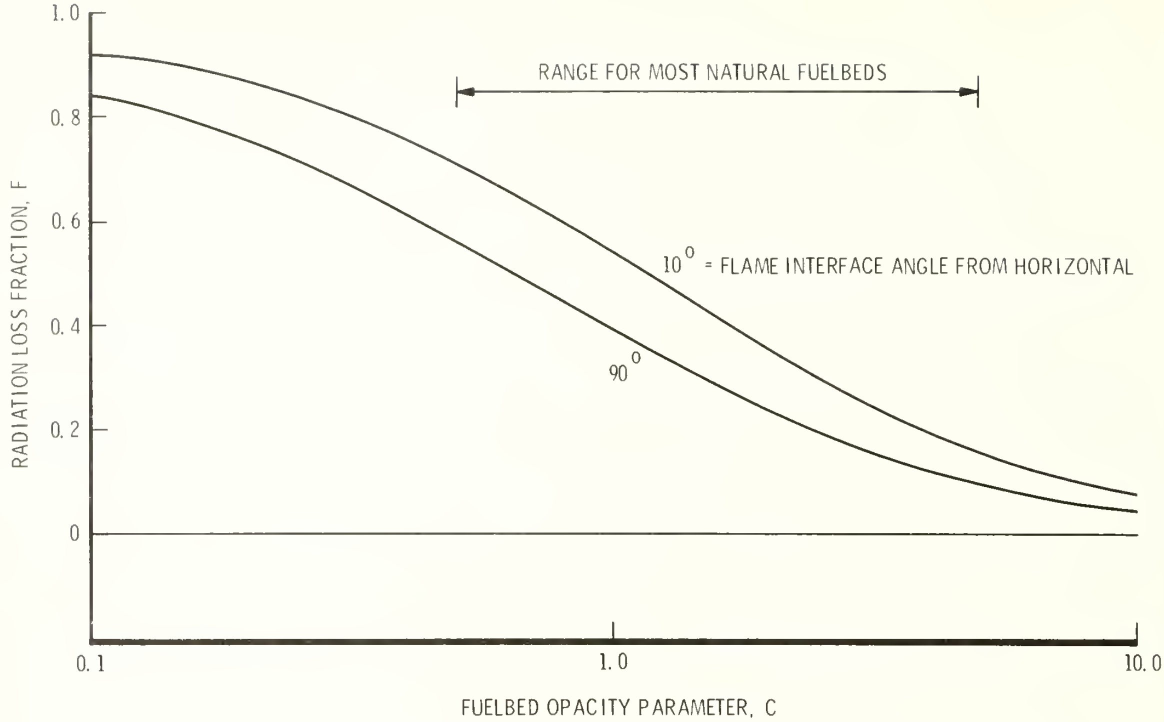

Figure II-1.--Variation of the radiation loss fraction, F, with fuelbed opacity parameter, C.

The dependence of the chemical properties of the gases fueling the free flame upon the geometrical properties of the fuelbed raises the possibility that the elusive "moisture of extinction" variable (Rothermel 1972; Albini 1976) may be predictable from such considerations.

The equation for C can be written also in terms of w, the weight loading (for single size class fuelbeds) and ρ, the density of the fuel particles. Since

$$\beta = w/\rho\delta$$

$$C = \sigma w/4\rho .$$

For fuelbeds with more than one size class, the value of C is to be found by summing the values for each of the individual components.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1979-0-677-121/113

Albini, Frank A.
1979. Thermochemical properties of flame gases from fine wildland fuels. USDA For. Serv. Res. Pap. INT-243, 42 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Describes a theoretical model for calculating thermochemical properties of the gaseous fuel that burns in the free flame at the edge of a spreading fire in fine forest fuels. Predicted properties are the heat of combustion, stoichiometric air/fuel mass ratio, mass-averaged temperature, and mass fraction of unburned fuel in the gas mixture emitted from the flame-producing zone. These variables depend upon readily determined intrinsic properties of the fuel, the fuel moisture content, fuel particle surface/volume ratio, particle mass density, and fuel loading. Numerical examples are given for several fuel types, exploring the sensitivity to moisture content, char fraction formed (an inherent property of the fuel that can be modified by fire retardants), and an energy-leakage fraction related to fuelbed opacity. All the equations are given in appendixes.

KEYWORDS: flame, heat of combustion, stoichiometry, fuel moisture content, char, volatiles, burning characteristics, combustion properties.

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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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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)

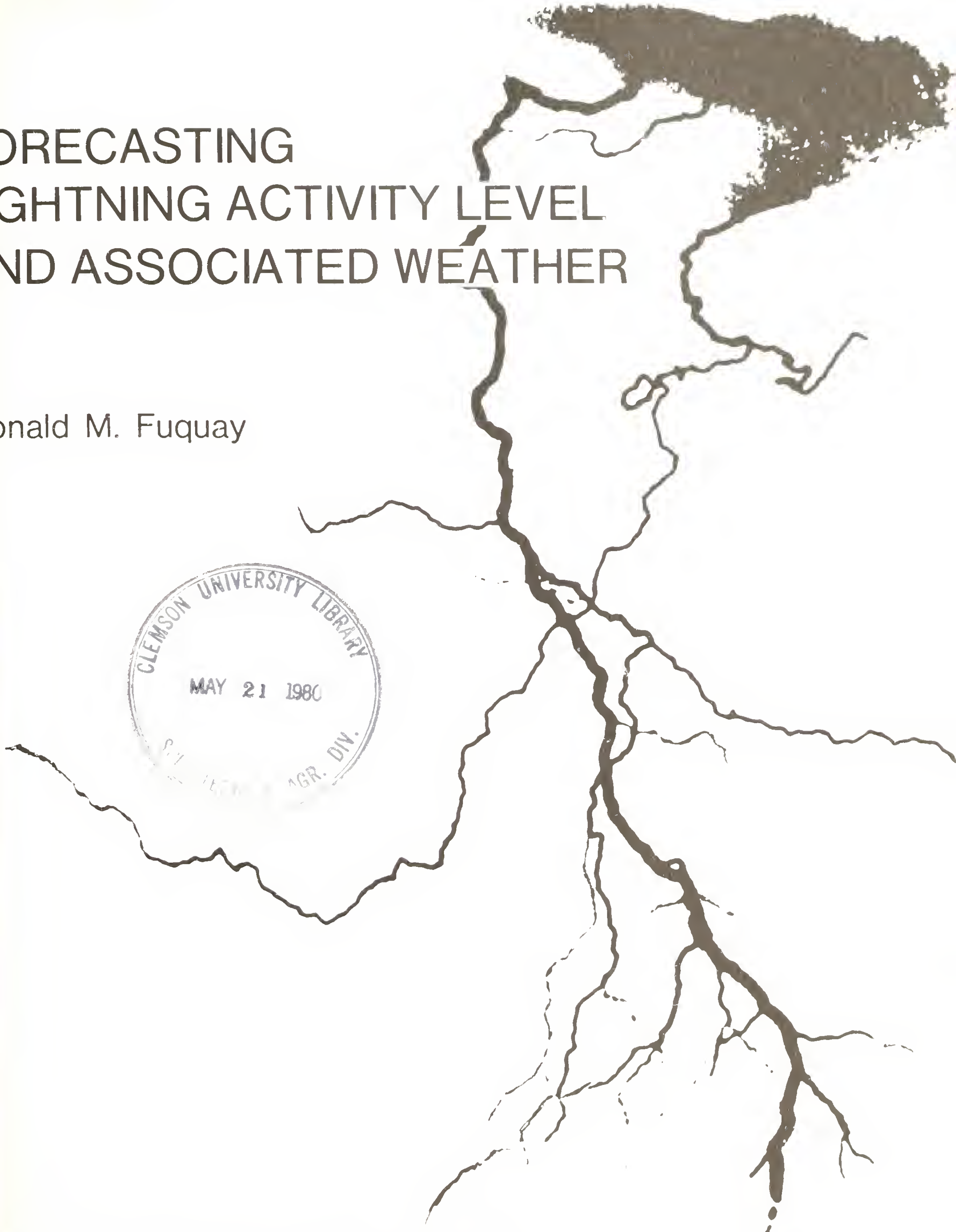
Moscow, Idaho (in cooperation with the University of Idaho)

Provo, Utah (in cooperation with Brigham Young University)

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

FORECASTING LIGHTNING ACTIVITY LEVEL AND ASSOCIATED WEATHER

Donald M. Fuquay



USDA Forest Service Research Paper INT-244
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE

THE AUTHOR

DONALD M. FUQUAY has conducted research on thunderstorms, lightning physics, weather modification, and forest fuel ignition by lightning for the Forest Service since 1958. Prior to this, he performed research on forest and mountain meteorology for the University of Washington and the Munitalp Foundation. He has B.S. and M.S. degrees in meteorology from the University of Washington and a Ph.D. from Colorado State University. He is currently the Project Leader for Forest Fire Meteorology at the Northern Forest Fire Laboratory.

RESEARCH SUMMARY

This report summarizes the concepts, development, and application of a system for forecasting Lightning Activity Level (LAL) as required for the 1978 version of the National Fire-Danger Rating System. The report is organized into two sections. The first section presents a format and guidelines for the forecasting of lightning area density. The second section guides the fire weather observer in making observations, verifying the forecast, and providing feedback to the fire weather forecaster. The appendix includes data on the occurrence and behavior of mountain thunderstorms not available from other sources.

The LAL guide, containing instructions for both fire weather forecasters and observers, was developed in three steps. First, cloud-to-ground lightning density was related to a common predictor-maximum height of radar echos for thunderstorms. Second, LAL index values were assigned to specific ranges of radar heights according to their relative frequency of occurrence to form a five-level index. Third, distributions of lightning events and associated weather were related to the LAL index based on the predictor variable, maximum radar echo height. Other variables used were maximum cloud development, intensity and coverage of radar echos, amount and coverage of precipitation, and cloud-to-ground lightning density and flash rates.

The fire weather forecaster uses primarily the expected cloud development and radar height to assign LAL index values to forecast zones. The fire weather observer uses observations of cloud development, precipitation, and cloud-to-ground lightning flash rates to verify or correct the forecasts.

USDA Forest Service
Research Paper INT-244
April 1980

FORECASTING LIGHTNING ACTIVITY LEVEL AND ASSOCIATED WEATHER

Donald M. Fuquay

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

CONTENTS

INTRODUCTION

The National Fire-Danger Rating System (NFDRS) (Deeming and others 1972) has been odated; the revised system will be in use in 1978 (Deeming and others 1977). One of he changes in the NFDRS is treatment of lightning-caused fires. A model based on physcal and stochastic processes was adapted to the NFDRS for estimating the number of new ightning-caused ignitions (Fuquay and others 1979).

The fireweather forecaster will be asked to forecast some of the inputs to the odel, namely: (1) Area density of cloud-to-ground (CG) lightning, (2) storm movement, nd (3) precipitation duration. This is an entirely new area of forecasting for most orecasters. Techniques and procedures will need to be developed.

This report shares our experience and data from thunderstorm and lightning field tudies that might be useful to the fireweather forecaster and observer. Data on ightning and related events were gathered for other specific purposes and are not xactly suited to the topics presented here. The limited data base prevents the rigorous nalyses we would like to make. In many cases, the grouping of data and the form of he output reflect the author's opinions. Nonetheless, this report should remain a seful guide and provide a basis for further investigation.

Our approach to predicting lightning related events follows the basic philosophy f the NFDRS, namely:

1. The NFDRS rates only the *potential* for fires.

2. It addresses only those aspects of fire control strategy affected by fire occurrence and behavior.

3. It uses a linear index structure wherever possible.

4. The rating is done with a *worst* case approach. Thus, weather forecasts and observations should be for the time that conditions are most severe and at midslope on southerly and westerly exposures.

e latter requirement strongly influences how the forecaster views the input to the DRS. The forecast should be biased towards events that will define the *upper* limit fire ignition and behavior.

The basic assumption in developing our Lightning Activity Level (LAL) Guide was at lightning activity and accompanying meteorological conditions within a forecast ea can be adequately represented by a single index value. This report describes how use the LAL Guide, how it was developed, and guidelines for assigning and interpretg LAL index values.

THE LIGHTNING ACTIVITY LEVEL GUIDE

The LAL Guide is a table relating several meteorological variables to CG lightning a density. The 1978 version of the NFDRS requires the forecaster to select a Lightig Activity Level (LAL) for each forecast zone. The forecast thus assigns *predetermined* aues for the following: (1) Area density of CG lightning, CG's/2,500 mi^2 (CG's/6 500 m), (2) area intensity of radar echoes, (3) area intensity of rainfall, and (4) storm ie and duration.

The LAL Guide (table 1) is structured according to the following outline:

A. Typical cloud and precipitation conditions

1. Cloud and storm development
2. Radar echoes--coverage and intensity
3. Precipitation--area and amount

B. Lightning

1. Amount per area
2. Lightning occurrence rates

The LAL Guide was developed with both forecasting and verification in mind. The forecaster can verify by using available radar data (maximum radar height of storms, precipitation coverage and duration), pilot reports, satellite data, and network meteorological data. Field personnel verify by means of cloud description, rate and amount of observed CG lightning, and area coverage of storms.

The basic data set for the LAL Guide consists of measured lightning and associat meteorological events during the summer months of 1965-1967 in western Montana (table appendix). This 3-year period included seasons of high and low lightning occurrence. Basic data were supplemented by lighting measurements, radar, and other meteorologica data from the Black Pine area near Philipsburg, Mont., lookout network data covering five-State area, and data from Arizona and New Mexico. This broad data base builds confidence that the guide should be applicable over most of the Rocky Mountain area, particularly after scaling the events to local conditions.

The basic unit of area used in the guide is 2,500 mi^2 (a square 50 miles on a si or 6 500 km^2). This is almost the smallest area for which a generalized forecast can be made. Also, it is about the largest area that lightning activity can be effective observed from a surface observation point, such as a forest fire lookout. The area within a 28-mile radius from an observer corresponds roughly to 2,500 mi^2 (6 500 km^2) or 1.5 million acres--about the size of a typical National Forest.

Although the basic area used is 2,500 mi^2 (6 500 km^2), the forecaster can adapt the descriptors to subunits or multiples of the area through proportionality factors. Of course, the forecaster must feel confident in forecasting for the area selected.

Little precedence exists for forecasting the area density of CG lightning. A coherent thunderstorm model covering both cumulus dynamics and electrification process has not been developed. Based on observation and theory, however, we believe that th amount of electrification and lightning is associated with the characteristics of a storm, such as dynamic instability, precipitation intensity, and rate of vertical development. After correlating the amount of lightning to many different variables, we found that the maximum height of radar echoes seemed the best for linking lightnin with associated weather.

Our forecasting system was developed as follows:

1. The maximum radar echo height was selected as the basis for classifying ligh ning activity on a given day.

2. All thunderstorm days over the 3-year period were classified according to maximum radar height and each day was assigned an LAL.

3. Distribution of related meteorological events was determined within each of the LAL's.

TYPICAL CLOUD AND PRECIPITATION CONDITIONS (2,500 mi^2 or 6 500 km^2 area)

Lightning activity level	Cloud and storm development	Rel. freq. on T/S days (percent)	Fraction of area covered by radar echoes of indicated strength: Very Light	Light	Moderate	Heavy	Percent of area receiving less than the amount of rain indicated: 0-T	<0.1"	<0.3"	<0.9"
1	No thunderstorms[1]	0	0	0	0	0	100	100	100	100
2	Few building cumulus only occasionally reaching cumulus congestus stage; single CB in forecast area. Visual tops: <30,000 ft (9 100 m) m.s.l.	10	0.1	<0.1	0	0	90	91	100	100
3	Scattered cumulus to cumulus congestus; widely scattered CB's cloud-to-ground lightning averaging 1 to 2 per min, max.	35	.2	.1	0.05	0	70	90	98	100
4	Growing cumulus and cumulus congestus stage over 1/10 to 3/10 of the area; scattered cloud-to-ground lightning in area averaging 2 to 3 per min max.	35	.2	.1	.05	0	65	80	95	100
5	Cumulus congestus common over area, occasionally obscuring the sky; moderate to heavy rain associated with CB's; light to moderate rain preceding and following lightning activity. Lightning flashes occurring steadily at some place in or during storm period; maximum CG flash rate greater than 3 per min.	18	.3	.1	.05	0.02	50	75	85	100
6	Scattered towering cumulus with a few at thunderstorm stage; very limited horizontal extent; high bases (15,000 to 17,000 ft m.s.l.). Virga in most prominent hydrometeor form. Lightning flash rate is low, averaging less than 1 to 3 per 5 min period each storm.[2]	<2								

LIGHTNING - AMOUNT AND RATE

Lightning activity	Maximum radar echo height, m.s.l.: Feet	Meters	Cloud-to-ground lightning per 2,500 mi^2 (6 500 km^2)	Occurrence rates, maximum: CG/5 min	CG/15 min	Aver. rate/min
2	<28,000	<8 500	20	--	--	--
3	26,000 - 32,000	7 900 - 9 700	40	0-10	0-17	1-2
4	30,000 - 36,000	9 100 - 11 000	80	4-19	6-32	2-3
5	>36,000	>11 000	160	9-32	19-77	>3
6 (See text for explanation)						

[1] In most general terms, 2 days out of 3 will not be thunderstorm days during a typical fire season in the mountainous areas of the western continental United States.

[2] Used with red-flag warnings of extreme fire activity.

4. Generalized descriptors were developed for each LAL.

5. Results were summarized as the LAL Guide.

Figure 1 illustrates the events occurring over a selected area in the course of day. Note that in the course of a day, conditions normally become progressively more severe, going from LAL 2 in mid-morning to LAL 3 around noon and reaching a peak of severity in mid-afternoon. Because we want to predict the most severe level (worst case) representing events over *all* of the area, we might select LAL 4 for this exampl

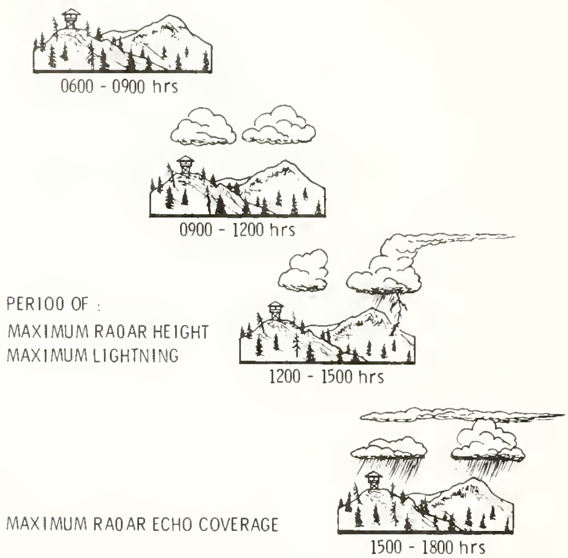


Figure 1.--Events within a forecast area for successive time periods during a thunderstorm day.

We do not look for a *single* maximum radar height in the area. In our example, LAL 4 says, rather, to expect maximum vertical development of radar echoes distribute over the area to range within the limits of 30,000 to 36,000 ft m.s.l. (9 100 to 11 000 m) with a representative maximum height for all echoes of about 33,000 ft m.s.l (10 000 m).

FORECASTING OR VERIFYING LAL

Ideally, a single value should describe lightning and associated weather in each forecast area. Although a single value can only be derived from a gross generalizatio of the weather, such a value is vital to determining lightning-caused fire risk in the NFDRS.

We have established an association between specific LAL and the following phenome maximum cloud development, maximum height of radar echoes, radar echoes--intensity and area coverage, precipitation--amount and area coverage, and CG lightning--density and flash rates.

As many of the above phenomena can be used as there are available data on which to base a decision. The final step, arriving at a composite LAL value, requires subjective judgment by the forecaster or the observer. Each user should consider the reliability and representativeness of the data available and give most weight to the better data when making an LAL decision.

In figures 2 through 7 we relate general descriptors of each phenomena to LAL levels. he idea is to progress through each description until an upper limit is reached for the xisting situation. Use the highest LAL reached as representative of that phenomena or the day.

The subjective nature of an LAL selection has already been mentioned. For that eason we can expect that skill in selecting the best LAL to improve as the user becomes etter acquainted with the reliability of each predictor for a particular area. For xample, a forecaster may find cloud development (fig. 2) as most useful in forecasting omorrow's LAL and radar echoes (fig 3) as best for verifying the forecast. A forest ispatcher may find observations of cloud development (fig. 2) most reliable when onfirmed by lightning counts (fig. 6) or maximum flash rates (fig. 7) from a nearby ookout Figures 4 and 5 provide estimates of the percent of an area receiving rainfall rom storms associated with each LAL level. In general, the storms become more intense ith higher LAL's but do not show a corresponding increase in area covered by the storm. ven with LAL 5, over 50 percent of a forecast area will receive no measurable rain.

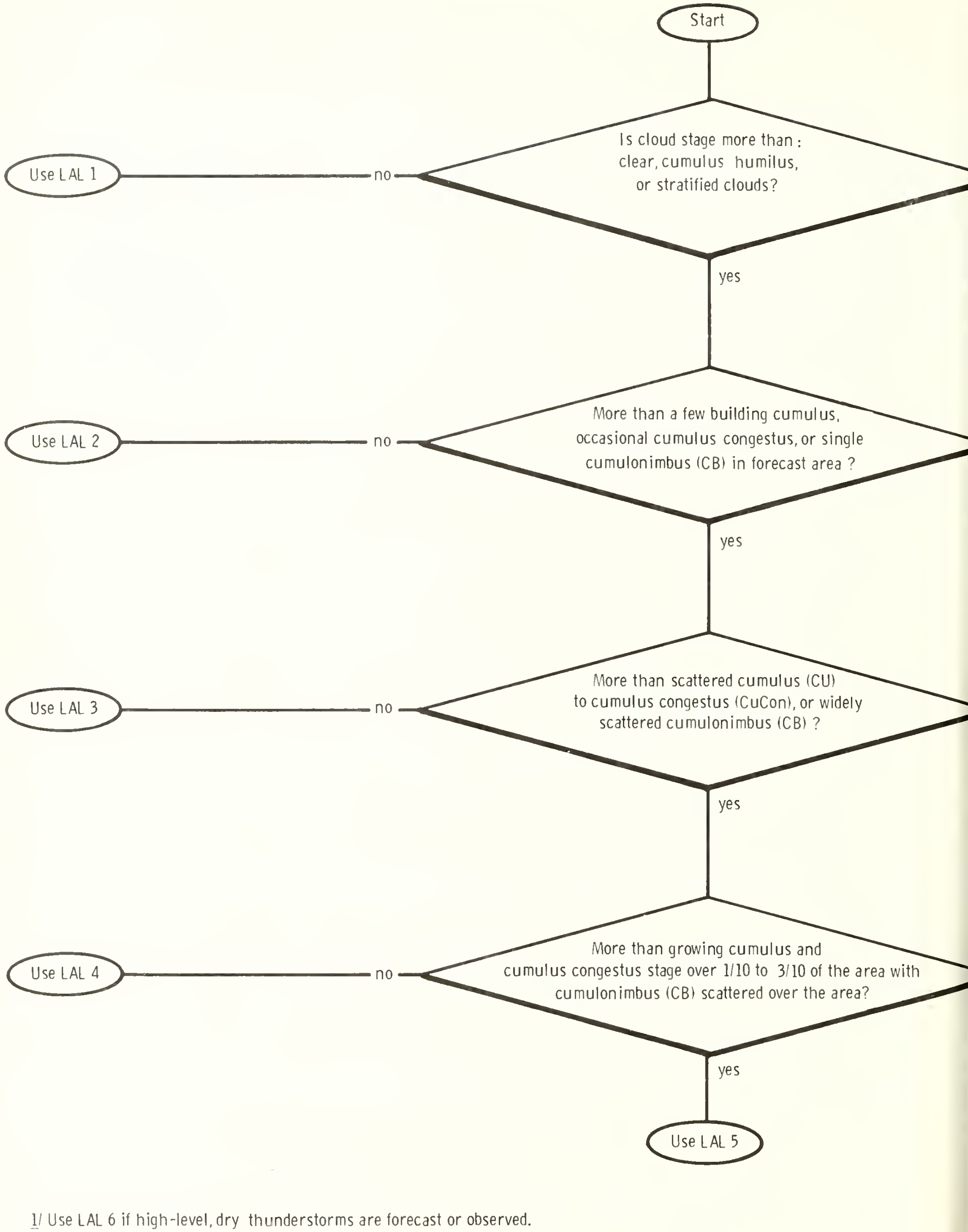
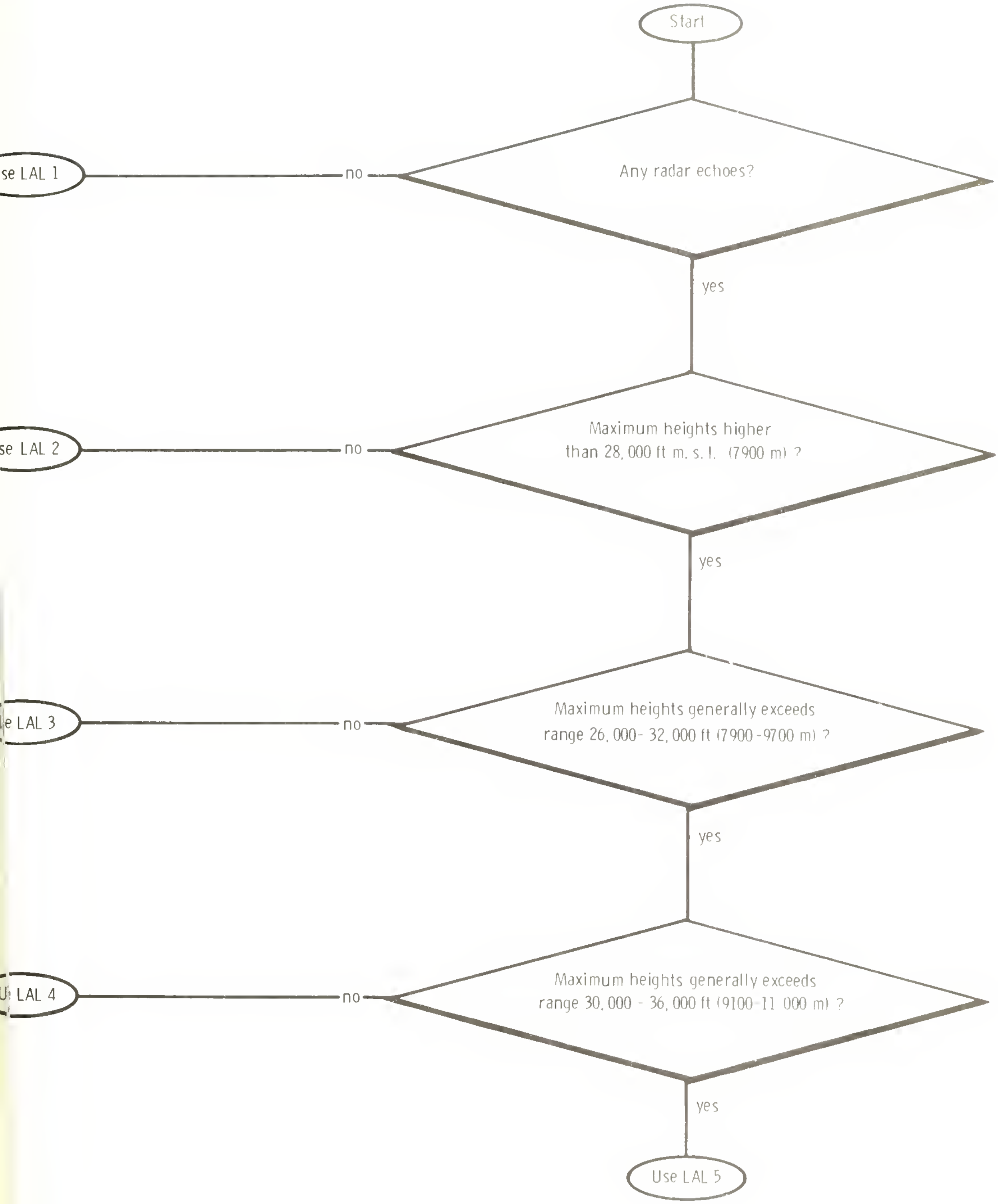
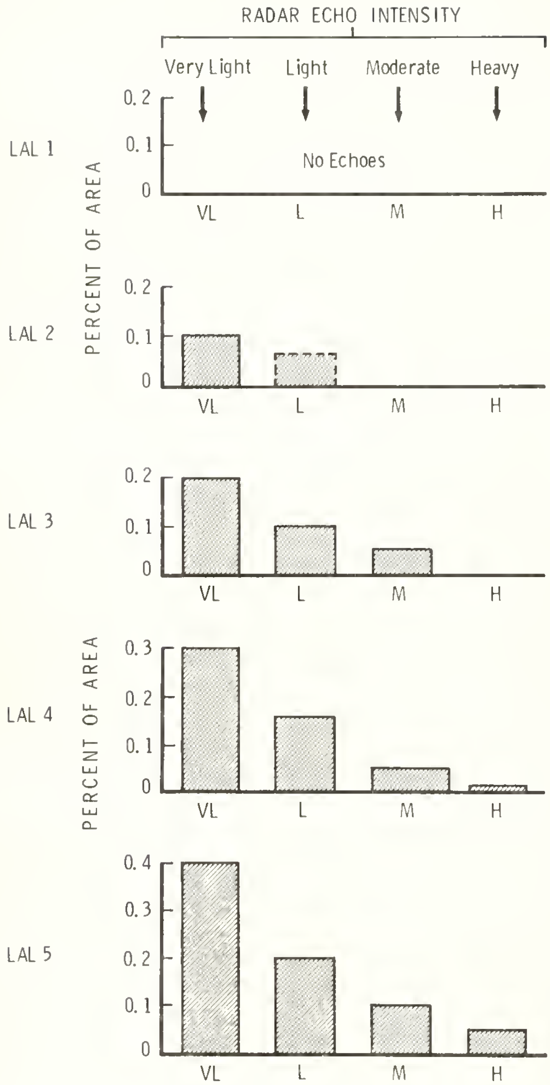


Figure 2.--Maximum stage of cumulus cloud development (after Fischer and Hardy 1972). Use LAL 6 if high-level dry thunderstorms are forecast or observed.



1/ or visual tops, add 2, 000 ft (about 600 meters).

iure 3.--Maximum radar echo height. For visual tops, add 2,000 feet (about 600 meters).



1/ The description of LAL 3 reads :
2/10 of the area covered by Very Light (VL) echoes
1/10 of the echo area is Light (L)
1/20 of the echo area is Moderate (M) intensity
No part of the echo area is of Heavy (H) intensity

Figure 4.--Radar echoes - intensity and area coverage (midseason, nonfrontal thunderstorm). The description of LAL 3 reads: 2/10 of the area covered by Very Light (VL) echoes; 1/10 of the echo area is Light (L); 1/20 of the echo area is Moderate (M) intensity; No part of the echo area is of Heavy (H) intensity.

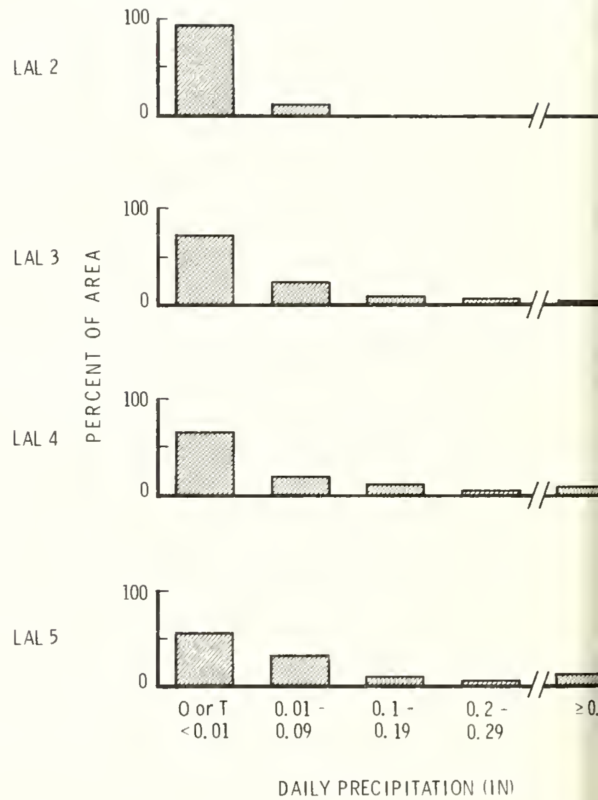


Figure 5.--Amount of daily precipitation and area coverage (midseason, nonfronta thunderstorms).

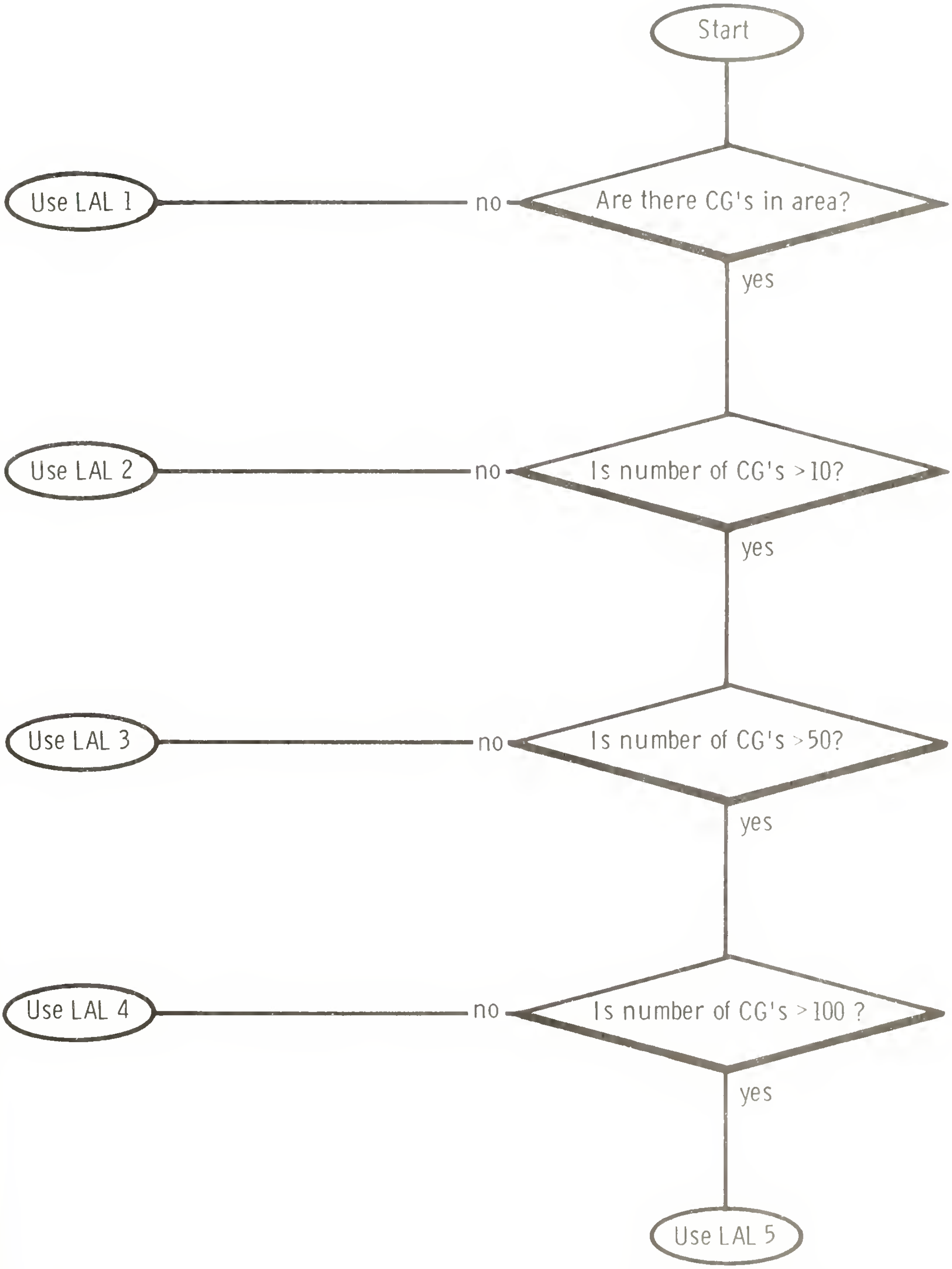
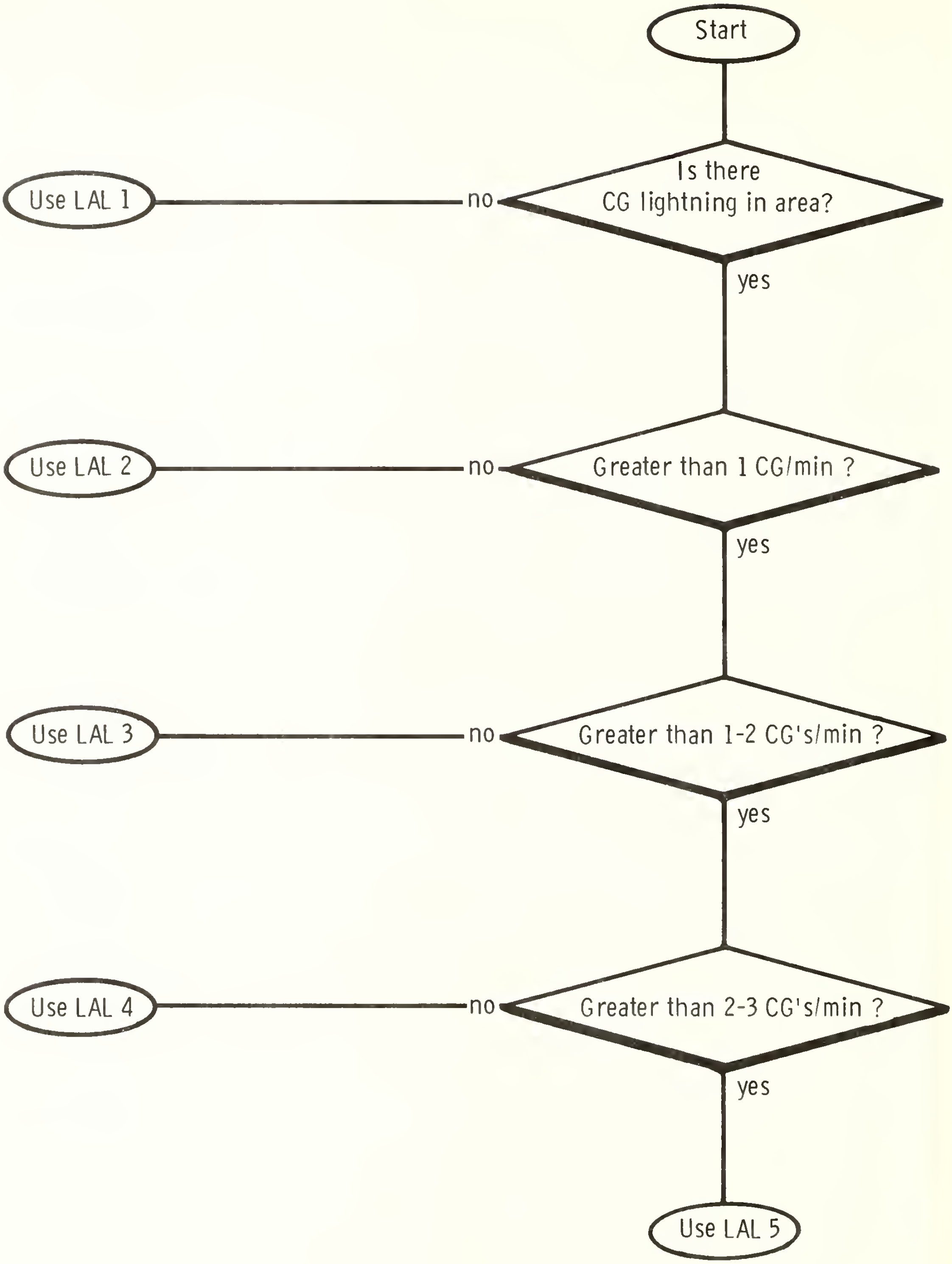


Figure 6.--Cloud-to-ground (CG) lightning within 2,500 mi (6 500 km) area for rating period.



1/ CG count averaged over at least a 5-min period.

Figure 7.--Average CG flash rate (CG's per minute). CG count averaged over at least a 5-min period.

DEVELOPMENT OF THE LAL FORECAST GUIDE

Bases for the Lightning Activity Levels

An index should be easily related to a prescribed range of events. In this case, t should relate to the severity of situations involving lightning caused fires even hough the lightning activity is only a part of this problem. So, we start out with he postulate that the *potential* lightning-caused fire severity is directly related to he amount of CG lightning that an area experiences. It then follows that we can build ur index on the basis of area density of CG lightning. Other factors influencing the umber of ignitions, such as rainfall, can be related to the same index.

An index ranging from 1 to 5 was selected because it is compatible with the NFDRS nd because users have said that five levels are sufficient. We use LAL 1 to denote ll situations in which no lightning is forecast. The remaining four values in the ndex represent the following situations:

LAL 2--The marginal case where lightning-caused fires may or may not occur. The maximum expected fireload would be *light*.

LAL 3 and 4--Delineate conditions where the lightning fireload might be described as *moderate* and *heavy*.

LAL 5--The upper limits of lightning activity are characterized by large, wet storms.

The selection of a 5-level index does not prevent the forecaster from developing dditional levels or sublevels within the present system if valid reasons exist. For nstance, some areas might use LAL 4*a* and *b* to denote conditions over grasslands and orested areas. In fact, we have already added LAL 6 to represent the high-level, dry hunderstorm situation.

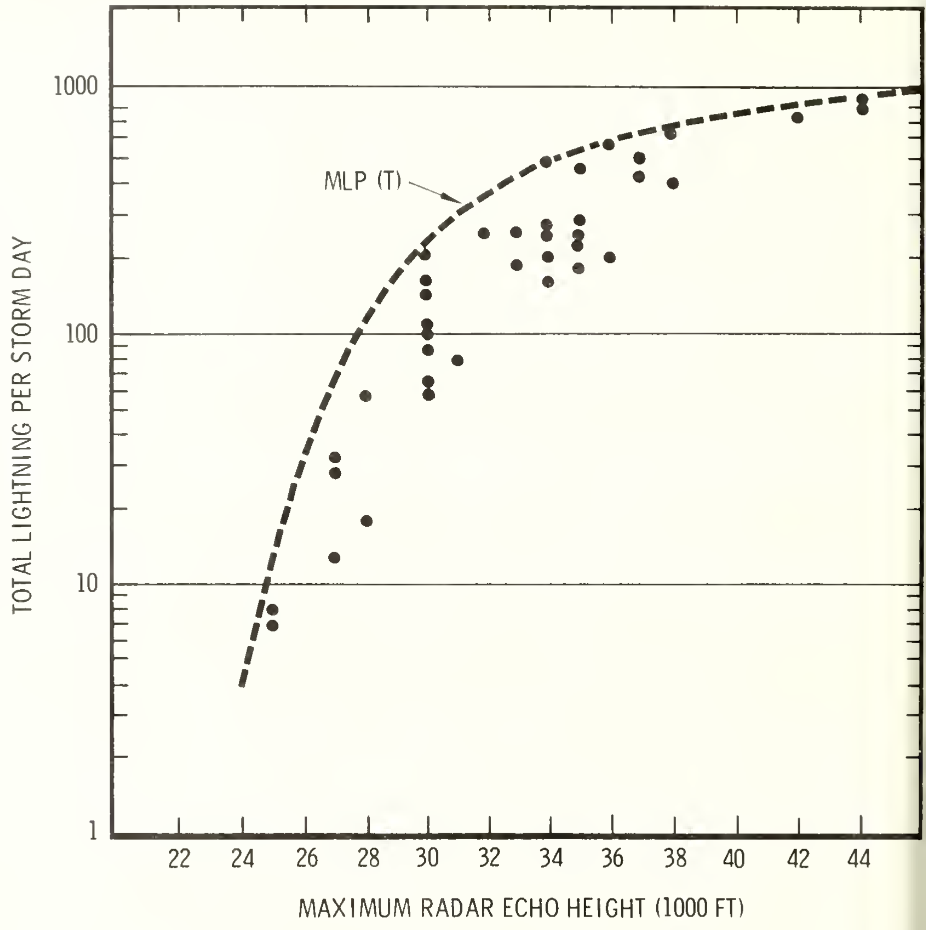
IGHTNING

Forecasting the number of CG lightning flashes expected in a given area is a emanding task because a formidable array of meteorological variables can be expected t influence the formation, electrification, and discharge of cumulus clouds. Numerical nthods are virtually nonexistent. Further, although data on the occurrence of storms based on visual observations are available from some stations, there is a paucity of measurements of lightning frequency and rates. In this section, we bring together the dta, experience, and methods that are available to help forecast lightning activity lvels.

The yield of lightning from a thunderstorm varies widely in both space and time. Frther, the proportion of CG's within storms on a single day and between storm days aso varies. The high variance in lightning further complicates the predicting of lghtning density. The problems in handling high natural variance of lightning can be rduced through the use of predictor variables or covariants.

Fuquay (1967) found a strong association between maximum radar echo height and the ttal amount of lightning experienced in the immediate area. This relationship for sorms in western Montana in the summers of 1965-1967 is shown in figure 8. Total lghtning varies considerably within each radar echo height class. In addition to ntural variability, we had errors in measurement because: (1) the radar scan missed the acual echo maximum in following fixed observing procedures, (2) location of the measured lightning was incorrect, and (3) sampling errors were introduced by the relatively smal area that could be observed in relation to the high variability of lightning occurrence

Figure 8.--Total lightning flashes per storm day versus maximum radar echo height.



We are concerned with the *maximum* density of CG lightning for predicting lightning caused fire ignitions. We must estimate the maximum lightning density expected during the day, knowing only the maximum radar height. To do this, we define a variable calle Maximum Lightning Potential (MLP) which is a covariant with the maximum area density of lightning. In figure 8, a smooth curve is drawn as an upper boundary to the data point A least-squares fit to this curve is defined as the continuous variable MLP (T), which is a function only of maximum radar height. The lightning data for figure 8 covered about 500 mi^2 (1 300 km^2). Only about 20 percent of a 2,500 mi^2 (6 500 km^2) area will receive lightning from a nonfrontal thunderstorm on a single day. Further, on most days only one continuous period of lightning activity will occur over an area. Thus, MLP derived from figure 8 approximates maximum lightning density per 2,500 mi^2 (6 500 k per day.

A least-squares fit to the upper envelope in figure 8 gave the following relationship with an R^2 value of 0.978:

$$MLP\ (T) = -1102 + 45.8\ H \qquad (1)$$

where MLP (T) = maximum lightning density of total lightning per 2,500 mi^2 (6 500 km^2) per day; H = maximum measured radar echo height (1,000 ft, m.s.l.). A second-order polynomial fit to this curve only slightly improved the fit, i.e., R^2 = 0.980.

Counting the number of lightning events, or flashes, from an isolated storm using lightning counters or analog recordings is relatively simple; relating these counts to a specific area to obtain lightning density presents problems. However, what we really need is an estimate of the density of *CG lightning*. Two approaches are available—estimating CG lightning from total lightning counts and direct measurements of CG lightning. Each approach has merits, depending on the situation.

The distribution of the ratio of CG to total lightning for 46 storm days in 1965-1967 is shown in figure 9. We have a mean CG/T ratio from the expression.

$$\overline{CG/T} = \sum_{1}^{N} \frac{CG/T}{N} = 0.19 \qquad (2)$$

where N = number of storm days (46).

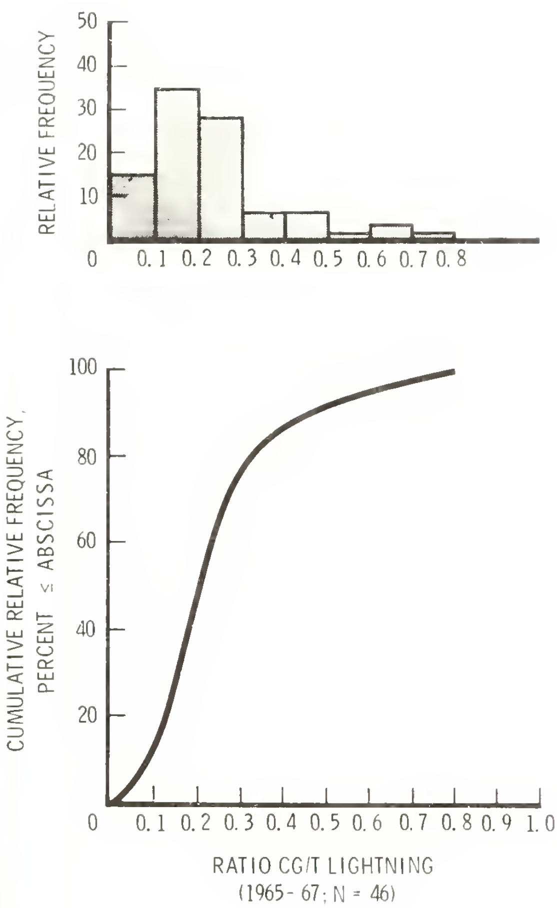


Figure 9.--Distribution of the ratio of CG and total lightning per storm day.

The proportion of CG lightning for all storm days compares favorably with that drived from a sample of 11 individual storms (i.e, single storms tracked throughout teir life cycle) where $\overline{CG/T}$ = 0.23. Based on this, a reasonable long term estimate of te ratio of CG lightning and total lightning is 1/4. However, figure 9 shows variations t expect when this rule is applied to specific storm days.

We will now examine data from direct measurement of CG lightning. We can remotely sense electrical and light signals emitted by lightning discharges. These signals form characteristic signatures for cloud, air, and ground discharges (Fuquay 1967; Fuquay and others 1972), but the attributes for each type of discharge overlap to some degree. Thus within any group of lightning signatures, some of the discharges cannot be classified as cloud, air, or ground. These indeterminate signals make up only about 3 percent of all flashes measured during the 3-year test period. For example, on 7/12/66 only 2 out of 635 flashes were indeterminate. However, in some storms, these flashes can be an appreciable proportion of the total measured lightning. For example, on 8/26/66, 126 of a total of 427 measured flashes were classed indeterminate. Thus, we cannot identify the amount of CG lightning as accurately by direct measurement as we can determine the total number of flashes that occur.

The measured CG lightning versus maximum radar height on 35 storm days in 1965-1967 is plotted in figure 10. The X's denote days on which the indeterminate class of discharges was greater than 5 percent of the total. A least-squares curve was fitted t the upper boundary of the CG data points. This is the MLP (CG) curve. The first order linear curve

$$H = -575 + 21\ H \qquad (3)$$

yielded $R^2 = 0.917$.

A second-order polynomial of the form

$$MLP\ (CG) = 700 - 56.4\ H + 1.14\ H^2 \qquad (4)$$

gave $R^2 = 0.998$.

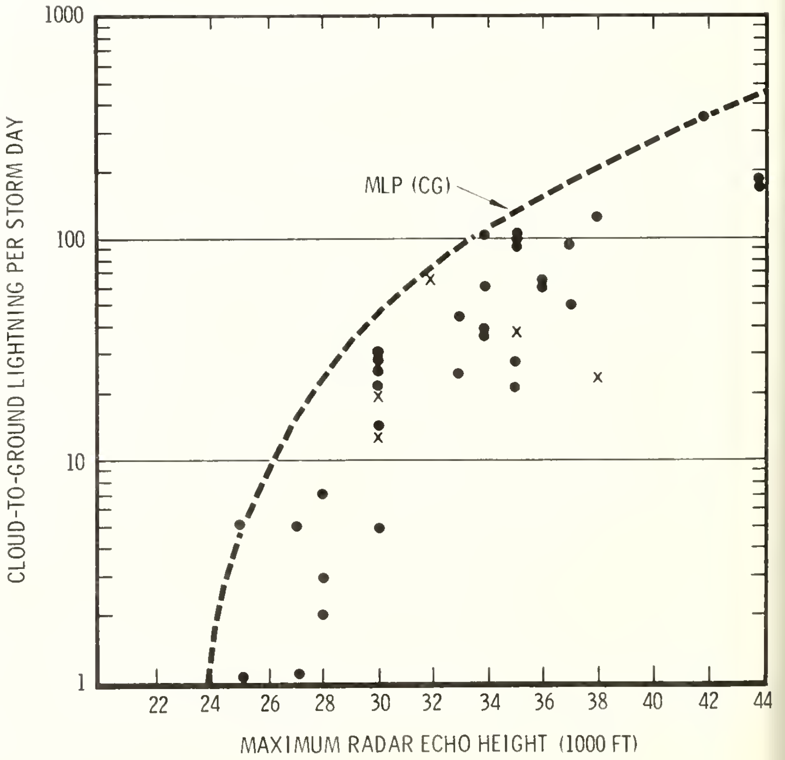


Figure 10.--Measured cloud-to-ground lightning for 35 storm days, 1965-1967.

The estimate of MLP (CG) derived from measured CG lightning and from taking 0.[illegible] f MLP (T) for all days with measured H was compared for each day for data from 196[illegible]-196[illegible]. e found that both methods yield about the same value over the long term. However, the ethod of estimating lightning density should be known when using field observation of G and total lightning to verify a forecast LAL.

Keep in mind that we are estimating only the *maximum* amount of lightning to be xpected based on *maximum* radar echo height. Thus, the high R^2 values for equations 1 nd 3 reflect only the fit to the MLP curves on figures 8 and 10. Just to illustrate he broad scatter of the data points, we have the following least squares fit to all he data points in figures 8 and 10:

$$T = -1215 + 44.6\ H \tag{5}$$

R^2 = 0.82) and

$$T = 498 - 58.1\ H \tag{6}$$

R^2 = 0.85), where T = total lightning on a storm day and H = maximum radar height 1,000 ft, m.s.l.) measured during the day. Also,

$$CG = -170 + 7.1\ H \tag{7}$$

R^2 = 0.71) where CG = cloud-to-ground lightning per storm day and H = maximum radar eight measured during the day. Again, we see that the maximum radar height explains ore of the variance in T than for CG in the corresponding equations.

The NFDRS value shown in table 2 is the lightning density (CG's/2,500 mi^2 or CG's er 6 500 km^2) assigned to each LAL for computing the number of lightning-caused fire gnitions. Note that the assigned lightning density, which is also lightning risk, icreases geometrically with LAL values.

Table 2.--*Assignment of maximum radar height and lightning density to LAL*[1]

LAL	Relative frequency (percent)	Maximum radar height, m.s.l.		Lightning density, CG's/2,500 mi^2 (6 500 km^2)	
		Feet	Meters	Range	NFDRS value
2	15	≤28,000	≤8500	1-25	20
3	35	26-32,000	7900-9700	10-75	40
4	35	30-36,000	9100-11000	50-150	80
5	15	>36,000	>11000	>150	160

[1]All tabulated values are approximate or rounded.

The cumulative frequency of maximum radar heights during 41 thunderstorm days is sown in figure 11. A corresponding distribution for nonthunderstorm days is not availale. Therefore, we do not know if a forecast of maximum expected radar echo height is auseful estimator of the probability of occurrence of thunderstorms, although we srongly suspect a close association exists for summer air mass storms. Rather, *if* a tunderstorm occurs, the maximum radar echo height can be used to estimate the amount o lightning to be expected over a given area (fig. 12).

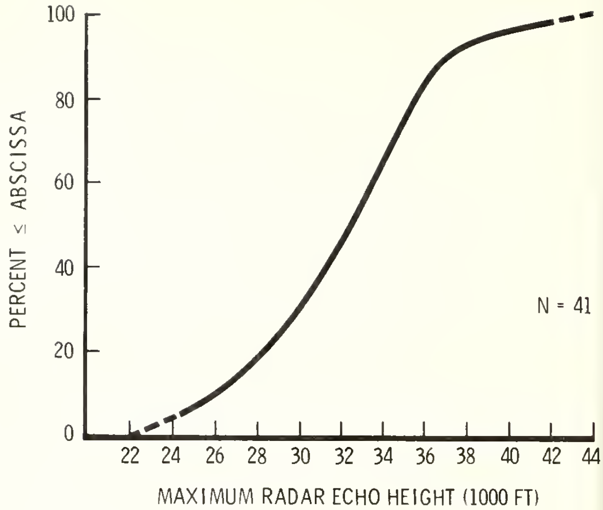


Figure 11.--Distribution of maximum radar echo heights per storm period, July-August, 1965-67.

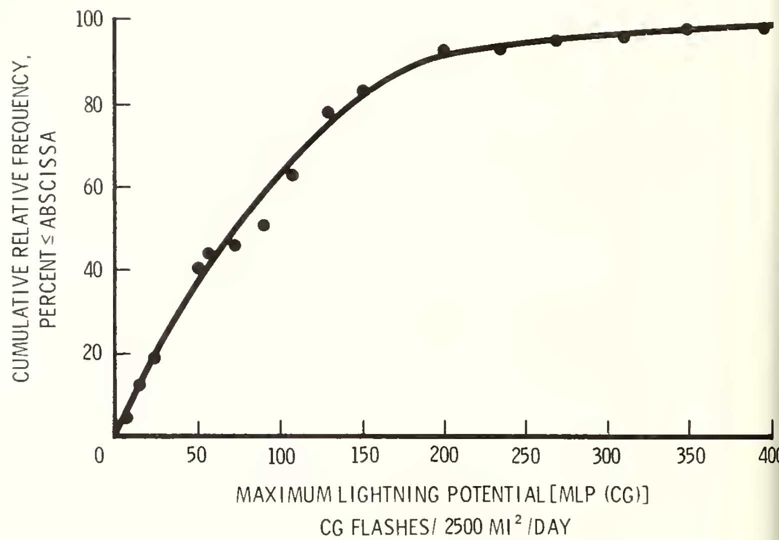


Figure 12.--Cumulative frequency of maximum lightning potential.

We would like to use observed lightning flash rates to estimate an LAL value for the day. In general, local lightning storms are coherent groups of cells covering less than 500 mi^2 (1 300 km^2). Two or more of the localized storms may occur within a forecast area during a thunderstorm day. Usually, the maximum flash rate will occur during the middle one-third of the storm period.

CG lightning flash rates from localized storms were related to LAL values in the following manner. First, individual storm periods were identified on lightning recordings taken during the summers of 1965-1967. Second, each storm was assigned an LAL value using the criteria for storm heights shown in table 2. Third, flash rates were analyzed and summarized (table 3). The analysis indicated only a casual association between lightning rates and LAL. Therefore, observed flash rates should not be given strong weight in setting the LAL. Rather, they should be used to support other evidence of a specific LAL.

Table 3.--*Maximum flash rates versus LAL*

LAL	Maximum flash rates CG's/5 min	CG's/15 min	Average CG's/min
2	--	--	1
3	0-10	0-17	1-2
4	4-19	6-32	2-3
5	9-32	19-77	>3

RADAR ECHOES

The 1972 NFDRS used the percentage of forecast area covered by radar echoes over a 24-hour period as a significant factor in assigning an LAL value. The 1978 NFDRS uses both echo intensity and area coverage during only the period of lightning activity as significant indicators of LAL.

There have been few previous attempts to relate lightning to precipitation and radar echoes. Kuettner (1950), from a mountaintop location, observed that the most active lightning occurs in the region of heaviest precipitation. Workman and Holzer (1942) reported that the most severe lightning activity was associated with clouds of greatest vertical extent. Since the highest clouds produce the heaviest rainfall, we would expect a correlation between lightning and precipitation (Battan 1965).

Kinzer (1972) made several observations relating radar echoes to lightning activity. After analyzing a limited sample of Oklahoma storms, he suggested that areas of greater reflectivity are apt to be areas of higher rates of CG lightning and that, on the average, the lightning activity increases rapidly with an increase in the radial depth of reflectivity. He answered the question, "Is there a radar reflectivity threshold for the occurrence of CG lightning?" with a qualified, "Yes,"--the threshold being about 55 mm^6/m^3 when larger reflectivities exist in the nearby storms. Of particular interest is his observation that with squall-line storms, maybe 9 out 10 CG's occur within areas of radar reflectivity. On airmass storms, however, only about 6 out of 10 flashes occur within areas of reflectivity.

In the revision of the NFDRS, we demonstrated that both radar echo intensity and area coverage can be useful in determining LAL and produced guidelines for their application. We also compared LAL values arrived at using the 1972 and the 1978 criteria . The following data were used in that comparison:

1. Lightning records for all storm days on which lightning was recorded in the period June-September, 1965-1967, near the Northern Forest Fire Laboratory, west of Missoula, Mont. The description of this data base and how it was obtained is covered by Fuquay and Baughman (1969) and other published reports available from the Northern Forest Fire Laboratory (NFFL) (table 8, appendix).

2. Maximum radar echo height data for each storm day obtained by WSR-57 and SO-12 radar at Missoula (table 9, appendix).

3. Hourly radar overlays from the WSR-57 radar at Missoula that show the boundaries of radar echoes with intensity classes: Very Light, Light, Moderate, and Heavy (U.S. Department of Commerce 1962). (*Note*: operational designation of intensity classes has been changed since 1967).

A day was accepted for analysis as a thunderstorm day if: (a) there was a complete record of lightning occurring within a 20 mi (32 km) radius of NFFL, and (b) a maximum radar height value for the same area could be estimated from available radar records. In all, 41 thunderstorm days in June-September 1965-1967 fit the criteria and were used in the analysis.

These steps were followed in analyzing the data:

1. The hourly overlays from the WSR-57 radar were integrated over time to give a radar echo-intensity map for the total period of lightning activity.

2. A simulated forecast area grid was randomly fit over the composite radar echo map. The percentage of the forecast area covered by echoes having standard intensity levels--Very Light (VL), Light (L), Moderate (M), and Heavy (H)--was estimated for each position of the grid. A representative area coverage for each intensity level was then estimated.

The representative echo intensity and coverage values for 41 days are shown in table 4. Each of the 41 days was assigned a "new" index value using the following maximum radar echo height (HMAX) criteria:

HMAX, m.s.l.		Index value
Feet	*Meters*	
<27,000	<8 200	2
27-33,000	8 200-10 000	3
33-36,000	10 000-11 000	4
>36,000	>11 000	5

The arbitary LAL value vs. Hmax assignment differs slightly from the final versions shown in table 1 and 2. This difference does not significantly change the conclusions drawn from this earlier study.

For comparative purposes, an "old" LAL value for each thunderstorm day was guessed by judging the radar echo overlays using the criteria for radar echo coverage from Deeming and others (1972). Note the differences in values in table 4. Under the "old" criteria, over half of the storm days were assigned the highest value (LAL 5), while the "new" criteria assigned only a fifth of the days as LAL 5.

We need a method for recognizing seasonality in comparing storms, particularly where radar echoes and precipitation amounts are concerned. We have subjectively noted the sharp transition from spring to summer thunderstorm regimes. A similar transition occurs in the fall and marks the end of the summer storms. An objective method for noting these transitions is not available. In this analysis, the author's experiences and judgment were the only bases for classifying storms as pre-, mid, or postsummer season.

We next classified the data by storm type (Finklin 1971)[1]:

Type A: "pure" airmass. No defined frontal influence. No indication of upper-level disturbance or divergence factors.

Type AU: Upper-level disturbance or divergence factor superimposed upon airmass situation.

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[1]Unpublished report titled "Classification and meteorological characteristics of lightning storms in western Montana," on file at the Northern Forest Fire Laboratory, Missoula, Mont.

4.--*Radar echo intensity and coverage, lightning frequency, and maximum radar height, 1965-1967*

values New	Maximum radar ht. x 1000 ft (ht x 305 m)	Storm date	Lightning CG	Lightning Total	Radar echo intensity and fraction of area covered: Very light	Light	Mod.	Heavy	Storm type
2	25	8-20-67	5	7	0.1	<0.1			AU
2	25	7-28-65	1	8	.1	<.1			AU
3	27	6-12-65	1	13	<.7	.7			F
3	27	6-23-65	1	29	<.1	.1			AU
3	27	6-24-65	5	32	.1	<.1			F
3	28	7-14-67	2	10	<.1	<.1			F
3	28	7-19-67	3	18	.2	.1			AU
3	28	7-18-67b	7	57	<.1				msg.
3	30	8-11-65	14	60	>.3	.3	dot		AU
3	30	9-05-67	*13	64	.1	<.1			AU
3	30	8-04-67	22	90	msg.	msg.	msg.	msg.	AU
3	30	6-18-67	*0	104	.1	<.1	dot		F
3	30	7-15-66	27	107	.1	<.1	dot		AU
3	30	9-07-66	*20	152	.1	<.1			F
3	30	8-19-65	30	158	<.2	.2			U
3	30	7-26-67	5	163	msg.	msg.	msg.	msg.	AU
3	30	9-08-67	47	217	.5	.1	<0.1		AU
3	31	7-06-66	29	79	msg.	.1	<.1		AU
3	32	8-29-66	*65	259	.1	<.1			F
3	33	8-04-66	24	196	.1	.1	<.1		AU
4	33	7-08-65b	45	256	<.2	.2	.1		F
4	34	7-07-66	104	161	msg.	.2	<.1		F
4	34	7-29-65	36	204	msg.	.1	<.1	<0.1	AU
4	34	7-08-65a	39	350	<.1	.1	<.1		F
4	34	5-29-65	61	264	>.7	.7	<.1		F
4	34	9-14-66	107	500	.2	.1	<.1		U
4	35	8-25-65	21	111	msg.	msg.	msg.	msg.	U
4	35	8-21-65	95	189	msg.	.1	<.1		U
4	35	9-06-66	90	232	msg.	.1	.1		F
4	35	8-02-65	100	251	<.2	.2	.1		AU
4	35	7-07-65	*38	289	.4	.3			AU
4	35	8-27-65	28	493	<.1	<.1	<.1	dot	F
5	36	7-14-66[1]	67	205	.2	.1	<.1		F
5	36	7-02-65	62	543	msg.	msg.	msg.	msg.	AU
5	37	7-04-65	95	439	msg.	.2	.1	<.1	U
5	37	7-18-67a	50	506	.3	.1	<.1		F
5	38	6-21-67	*23	404	.4	.2	<.1		F
5	38	7-12-66	123	635	msg.	.7	.2		F
5	42	9-12-66	356	714	msg.	msg.	msg.	msg.	F
5	44	7-27-65	178	831	msg.	msg.	msg.	msg.	AU
5	44	7-03-67	192	864	.4	.1	<.1		AU

*ndeterminate class exceeds 5 percent of total.

[1]eginning of storm that moved out of area to NE 75 nmi and became intense (max. height 0ft).

Type F: Frontal. This category includes cold (or occluded) fronts, quasi-stationary fronts with or without wave and deep low development, and the combination of a cold front moving into a frontal wave system.

Type U: Upper level. A storm situation where the dominant feature is an upper-level trough or closed low (500 mbar or 300 mbar) located overhead or somewhat upwind; a surface front is not a contributing factor. It is distinguished from the AU type in that troughs are more entrenched and large scale, rather then briefly denting a prevailing warm ridge.

In our study, no storm days in 1965-1967 were Type A. Out of 41 days, 18 were Type AU; 17 were Type F; and 5 were Type U.

Within any of the LAL's, storm Type F shows the greatest range of area coverage, that is, the greatest variation between storms within the type (table 7, appendix). For example, the fractional area coverage by radar echo intensity VL (Very Light), L (Light), M (Moderate), H (Heavy) in LAL 3 varied from VL>0.7, L = 0.7 on 6/11/65, to VL<0.1, L<0.1 on 7/14/67. In LAL 4, the differences between F and AU storms are still strong (note storm on 5/29/65).

Storms occurring in June and September have the highest percentage of the area covered by the storm. For this study, storms in June and early July were coded preseason, and September frontal storms were coded postseason. Preseason storms associated with the spring storm regime can extend well into July. Also, postseason storms can start soon after mid-August or, as in 1967 and 1970 in the Northern Rocky Mountain region, not until late in September. In these years, the midseason storm description was applicable into September until the arrival of more extensive, wet storms (characterized by a heavy influx of cool, moist air) signaled the postseason regime.

Next, we stratified the data by LAL, season, and storm type. Representative value for radar echo intensity and coverage for each stratification were then determined. Th results are summarized in table 5.

Table 5.--*Radar echo intensity and fraction of area covered*

LAL	Storm	Frontal (F)				Nonfrontal (AU,U)			
index	season	VL	L	M	H	VL	L	M	H
2	Preseason	0.7	0.5	-	-	-	-	-	-
	Midseason	.1	.1	-	-	0.1	0.1	-	-
	Postseason	-	-	-	-	-	-	-	-
3	Preseason	.7	.5	-	-	.2	.1	-	-
	Midseason	.3	.1	0.05	-	.2	.1	0.05	-
	Postseason	.5	.1	.05	-	.5	.1	.05	-
4	Preseason	.7	.5	.1	-	-	-	-	-
	Midseason	.4	.2	.1	-	.2	.1	.05	-
	Postseason	.5	.2	.1	-	.5	.1	.05	-
5	Preseason	.7	.5	.1	-	-	-	-	-
	Midseason	.4	.2	.1	0.05	.3	.1	.05	0.02
	Postseason	.5	.2	.1	.05	.4	.2	.1	.05

The midseason nonfrontal storm characteristics shown in table 5 have a unique feature--an apparent gradation of both radar echo coverage and echo intensity over the LAL range. The gradient is greatest going from LAL 2, the marginal lightning occurrence level, to LAL 3 and 4, where we would expect the most severe potential lightning-caused fire conditions to prevail. The transition to LAL 5 is marked by an increase in the intensity of echoes with little increase in area coverage.

PRECIPITATION

Because the intensity and coverage of radar echoes could be associated with the LAL, a similar relationship should exist with precipitation. Again, there are very little available data associating precipitation with lightning. Battan (1965) compared visual counts of CG lightning with rainfall on a network covering 1 000 km^2. About 0.03 mm of rainfall was measured for each CG lightning flash observed. This amounted to $3X10^{10}$ grams of rainfall per CG flash, on the average, for Arizona storms.

Two aspects of precipitation distribution and amounts were of particular interest in developing the criteria for assigning LAL:

1. The percentage of the total forecast area receiving precipitation.

2. The area-depth relationship for precipitation.

We estimated these two factors from precipitation data from 22 gages located in the area covered by our lightning measurements. A total of 28 storm days for July, August, and September 1965-1967 were analyzed as follows:

1. Precipitation maps were prepared showing both storm and daily total rainfall for those of the 22 stations that reported.

2. An LAL value was assigned for each day based on the number of CG lightning flashes recorded over the area.

3. The fraction F of the area covered by increments of precipitation (0, T, 0.01 to 0.99..., 0.9 to 0.99) was determined from

$$F = \frac{n_i}{N}$$

where n is the number of stations reporting precipitation in amount increment i, and N is the total number of stations reporting on that day.

The available data for LAL's 2-5 are shown in table 10, appendix. The area coverage and amount of precipitation associated with each LAL are summarized in table 6. As an example of how to apply the information in table 6, the following percentages of the forecast area will have zero or only a trace of precipitation for each LAL:

LAL	Percent of area
2	91
3	72
4	64
5	18

Table 6.--*Percentage of stations reporting less than the given amount of precipitation on storm days classed by LAL index*

Precipitation	Lightning activity level index				
	1	2	3	4	5
Inch			*Percent*		
0.8-0.89					100
.7- .79				100	99
.6- .69				99	98
.5- .59				99	98
.4- .49			100	99	94
.3- .39			99	97	88
.2- .29			99	96	85
.1- .19			98	93	80
.01-.09		100	93	83	75
Trace		91	72	64	48
0		79	58	54	34
Number of storms	-	5	10	6	7
No. of station reports		105	185	98	127

The High-Level Thunderstorm (LAL 6)

The high-level dry thunderstorm (LAL 6) is a special situation not fully covered by this report. We know that this type of storm, although relatively rare, can present a severe fire problem. At the present time, a forecast for such a storm is always accompanied by a red flag warning issued by the forecaster. The determination of appropriate values for calculating the fire risk associated with such a storm will require additional study and development. In the interim, the amount of lightning associated with LAL 3 (40 CG's) will be used in the NFDRS for internal calculation of fire risk.

The term "high-level dry thunderstorm" should be reserved for the situation where sufficient moisture and instability for thunderstorm initiation are found in the upper levels only. Cloudbases in the Northern Rockies will be in the 15,000- to 17,000-ft (4 600-5 200-m) levels. Thunderstorm activity is generally triggered by the advection of cold air aloft, an upper cold front passage, or widespread vertical motion. This situation is often preceded by *altocumulus castellanus* clouds in the early- to mid-morning hours. The actual speed of storm movement varies considerably, from near stagnant conditions to rapidly moving systems. The local cells may show considerable precipitation in the form of virga, but virtually no precipitation reaches the ground from the high bases. Strong downdrafts may develop as the rain evaporates below cloud base. Downdrafts reaching the ground can cause strong erratic surface winds.

In situations with relatively high moisture content at all levels, storms may be triggered by the same mechanisms. However, bases will be generally lower and considerably more moisture will reach the ground. This situation would be better described by LAL 2 or 3.

FURTHER APPLICATION

In this report we have shared our experience and available data to aid in the evelopment of forecasting techniques for lightning and weather associated with forest ire ignition. The concepts described in this paper will be applied in a real-time ense in conjunction with the new lightning-locating system being installed by the ureau of Land Management in the western United States and Alaska. The objective is to stimate the expected number of new lightning-caused fire starts based on forecast and easured parameters. We look forward to the development of a system which uses these arameters to improve our ability to predict, locate, and manage the lightning-caused orest fire.

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APPENDIX

Storm Data 1965-1967

Table 7.--*Storm day data, 1965-1967*

Date	Time of recording (m.s.t.)	Maximum radar height[1] (feet, m.s.l.)	Cloud base[2] Ht x 1000 ft	Cloud base[2] Temp. °C	Cloud thickness x 1000 ft	Stability index	Precipitable water[3]	Storm type[3]
1965								
5-29	1627-1743	34,000	8	msg.	26			F
6-12	0045-0215	27,000	8.5	msg.	18.5			F
6-23	1524-1641	27,000	10	+08	17			AU
6-24	1554-1737	27,000	9	+07	18			F
7-2	1632-1920	36,000	10	+06	26	-1.0		AU
7-4	1238-1658	37,000	8	+09	29	- .5	.65	U
7-7	1042-1736	35,000	10	+08	25	0	--	AU
7-8a	1718-1902	34,000	10	+06	24	0	--	F
7-8b	2209-0037	33,000	10	+06	23	--	.60	F
7-20	1242-1726	no data	10	+05	--	0	.70	F
7-21	1252-1634	no data	10	+05	--	.5	.60	F
7-26	1454-1853	no data	10	+05	--	-2.0	.70	AU
7-27	1600-1813	44,000	11	+08	31	-2.5	.73	AU
7-28	1805-1913	25,000	13.5	+03	11.5	-1.5	.65	AU
7-29	1305-1930	34,000	12	+04	22	-1.0	.65	AU
8-2	1531-1951	35,000	12	+04	23	- .5	.83	AU
8-3	1245-1719	no data	8	+11	--	.5	.78	U
8-11	2237-0026	30,000	12	+04	18	- .5	.92	AU
8-19	1627-1931	30,000	11.5	+03	18.5	1.5	.87	U
8-21	1650-1930	35,000	12	+08	23	2	.65	U
8-25	1304-1429	35,000	8.5	+06	26.5	2	.60	U
8-27	1738-2005	35,000	10	+03	25	2	--	F
1966								
7-6	1716-2018	31,000	12	+05	19	- .5		AU
7-7	2030-2249	34,000	12	+05	22	0	.54	F
7-12	1018-1810	38,000	12	+02	26	-1.5	--	F
7-14	1340-1915	36,000	13	+02	23	-2	.63	F
7-15	1423-1908	30,000	13	+03	17	-2.5	.5	AU
8-4	1350-1809	33,000	13	+0	20	-1.5		AU
8-13	2118-2208	--	9.5	+05	--	1.0	.68	U
8-19	1225-1833	--	10	-01	--	2.5	--	U
8-26a	0656-0706	--	13	+01	--		.70	F
8-26b	1319-1537	--	10	+05	--		.70	F
8-28	2239-0138	--	10	+05	--	2.5	.52	F
8-29	1300-1842	32,000	10	+06	22	1.5	.55	F

(continued)

Date	Time of recording (m.s.t.)	Maximum radar height[1] (feet, m.s.l.)	Cloud base[2] Ht x 1000 ft	Cloud base[2] Temp. °C	Cloud thickness x 1000 ft	Stability index	Precipitable water[3]	Storm type[3]
9-6	1617-2105	35,000	15	-04	20			F
9-7	1705-1821	30,000	12	+05	18			F
9-12	1907-2245	42,000	--	--	--			F
9-14	1222-1656	34,000	9	+02	25			H
1967								
6-18	1511-1652	30,000	10	+05	20			F
6-21	1948-2131	38,000	7	+02	31			F
7-3	1647-2126	44,000	10	+11	34	-2.5	.75	AH
7-14	0820-0947	28,000	11	+06	17	0	.70	F
7-18a	0930-1731	37,000	11	+05	26	1.5	.51	F
7-18b	2125-2254	28,000	11	+05	17	0	.63	AH
7-19	1049-1155	28,000	13	-02	15	1.0	--	F
7-26	1730-1921	30,000	13	+0	17	1.0	.52	AH
8-4	1446-1520	30,000	13	+02	17	- .5	.57	AH
8-20	2046-2125	25,000	12	+07	13	1.0	.54	AH
9-5	1741-1900	30,000	12	+06	18			AH
9-8	1650-1930	30,000	12	+03	18			AH
9-10	1450-1757	--	11	+01	--			AH

[1] From analysis of SO-12 and WSR-57 radar data (see text).
[2] Measured or estimated for beginning of storm period.
[3] From Classification and Meteorological Characteristics of Lightning Storms in Western Montana, by Arnold Fin[illegible]

Table 8.--*Lightning records, 1965-1967*

Date	Time of recording (m.s.t.)	Duration of recording (minutes)	Lightning		
			CG	IC	Total
1965					
5-29	1627-1743	73	61	196	264
6-12	0045-0215	90	1	12	13
6-23	1524-1641	77	1	28	29
6-24	1554-1737	103	5	27	32
7-2	1632-1920	168	62	481	543
7-4	1238-1658	260	95	335	439
7-7	1042-1736	418	*38	189	289
7-8a[1]	1718-1902	104	45	210	256
7-8b	2209-0037	148	39	207	250
7-20	1242-1726	284	91	444	535
7-21	1252-1634	222	4	16	21
7-26	1454-1853	239	65	211	279
7-27	1600-1813	133	178	651	831
7-28	1805-1913	86	1	7	8
7-29	1305-1930	385[2]	36	167	204
8-2	1531-1915	224	100	151	251
8-3	1245-1719	274	87	127	214
8-11	2237-0026	109	14	44	60
8-19	1627-1931	184	30	123	158
8-21	1650-1930	160	95	93	189
8-25	1304-1429	85	21	87	111
8-27	1738-2005	147	28	444	493
1966					
7-6	1716-2018	182	29	49	79
7-7	2030-2249	139	104	55	161
7-12	1018-1810	472	123	510	635
7-14	1340-1915	335	67	138	205
7-15	1423-1908	285	27	80	107
8-4	1350-1809	259	24	170	196
8-13	2118-2208	50	6	4	10
8-19	1225-1833	368	0	3	3
8-26a	0656-0706	10	*0	2	3
8-26b	1319-1537	138	*49	252	427
8-28	2239-0138	179	39	388	427
8-29	1300-1842	342	*65	175	259
9-6	1617-2103	286	90	141	232
9-7	1705-1821	76	*20	119	152
9-12	1907-2243	216	256	358	714
9-14	1222-1656	274	107	386	500
1967					
6-18	1511-1652	101	*0	60	104
6-21	1948-2131	103	*23	293	404
7-3	1647-2126	279	192	665	864
7-14	0820-0947	87	2	8	10
7-18a	0930-1731	481	50	456	506
7-18b	2125-2254	89	7	50	57
7-19	1049-1155	66	3	14	18
7-26	1730-1921	111	5	158	163
8-4	1446-1520	34	22	67	90
8-20	2046-2123	37	5	2	7
9-5	1741-1900	79	*13	47	64
9-8	1650-1930	160	47	169	217
9-10	1450-1757	187	*25	315	472

[1]Subdivided into afternoon and other storms.
[2]Weak lightning except for one active period, about 1430-1530.

* Note high number in indeterminate class; asterisk denotes indeterminate class >5 percent of total.

Table 9.--*Storm periods ranked by maximum radar height*

Max. radar height x 1000 ft (ht. x 305 m)	Storm date	Lightning [illegible]	Total
25	8-20-67	[illegible]	[illegible]
	7-28-65	1	8
27	6-12-65	1	[illegible]
	6-23-65	1	[illegible]
	6-24-65	5	32
28	7-14-67	2	10
	7-19-67	3	18
	7-18-67b	7	57
30	8-11-65	14	60
	9-05-67	*13	64
	8-04-67	22	90
	6-18-67	*0	104
	7-15-66	27	107
	9-07-66	*20	152
	8-19-65	30	158
	7-26-67	5	163
	9-08-67	47	217
31	7-06-66	29	79
32	8-29-66	*65	259
33	8-04-66	24	196
	7-08-65b	45	256
34	7-07-66	104	161
	7-29-65	36	204
	7-08-65a	39	250
	5-29-65	61	264
	9-14-66	107	300
35	8-25-65	21	111
	8-21-65	95	189
	9-06-66	90	232
	8-02-65	100	251
	7-07-65	*38	289
	8-27-65	28	493
36	7-14-66	67	205
	7-02-65	62	543
37	7-04-65	95	139
	7-18-67a	50	506
38	6-21-67	*23	104
	7-12-66	123	635
42	9-12-66	356	711
44	7-27-65	178	831
	7-03-67	192	864

*Indeterminate class exceeds 5 percent of total lightning.

Table 10.--*Number of precipitation stations reporting by precipitation amounts on 28 storm days, 1965-1967, grouped into LAL classes*

Storm date	Precipitation amount										
	0	T	0.01-0.09	0.1-0.19	0.2-0.29	0.3-0.39	0.4-0.49	0.5-0.59	0.6-0.69	0.7-0.79	0.8-0.89
	- - - - - - - - -				Inches	- - - - - - - - -					
LAL 2 (0-10 CG's)											
7-28-65	20		1								
7-14-67	16	2	3								
7-19-67	10	5	5								
8-20-67	17	5									
7-26-67	20	1	1								
LAL 3 (11-50 CG's)											
9-05-67	12	2	4								
9-07-66	5	3									
8-04-67	18	2	1								
8-04-66	13	3	2	4							
7-15-66	18	3	2								
7-06-66	17	3	2								
7-29-65	12	4	4	1							
7-07-65	1	1	11	4							
9-08-67	6	4			2		1				
7-18-67	5	2	12	1							
LAL 4 (51-100 CG's)											
7-02-65	10	2	2								
8-29-65	3		6	3							
7-14-66	18	3	2								
9-06-66	10	3	2								
7-04-65	3	1	1	3	2	1	2				
8-02-65	9	1	5	4	1						
LAL 5 (>100 CG's)											
7-08-65	1	1	3		3	2	6	3			
7-07-66	17	1	3								
9-14-66	7	4	3								
7-12-66	2	5	8	2	2	2					
7-27-65	9	2	9	2				1			
7-03-67	6	4	3	1	1			1			1
9-12-66	1	1	5	2	1		1	1			1

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Fuquay, Donald M.
1980. Forecasting lightning activity level and associated weather. USDA For. Serv. Res. Pap. INT-244, 30 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Describes concepts, development, and application guidelines for forecasting Lightning Activity Level (LAL) for the National Fire-Danger Rating System (Deeming and others 1977). The LAL is a five-level index designating the expected area-density of cloud-to-ground lightning within selected forecast zones. Additional index numbers denote special cases: LAL 6 is the high-level, dry thunderstorm situation in the northern Rocky Mountains. The LAL guide is a two-part table relating generalized weather variables to the index. Part 1, for the fire weather forecaster, relates maximum radar echo heights, cloud development, and precipitation to LAL values. Part 2, for the fire weather observer to use in verifying or correcting forecasts, relates cloud development, precipitation amount and coverage, and lightning amount and flash rates to LAL values. Data and distributions of lightning and associated weather variables are included as an appendix.

KEYWORDS: Fire danger rating, lightning-caused fires, lightning, fire weather.

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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.

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.

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IMPROVING RUST-RESISTANT STRAINS OF INLAND WESTERN WHITE PINE

RAYMOND J. HOFF and GERAL I. McDONALD

USDA Forest Service Research Paper INT-245
Intermountain Forest and Range Experiment Station
U.S. Department of Agriculture, Forest Service

THE AUTHORS

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RESEARCH SUMMARY

Twenty-five years of research and development has succeeded in producing a new rust-resistant variety of western white pine. Nonetheless, this new variety has limited levels of resistance and no improvements in other traits. The authors describe a nursery test designed to produce a population of western white pine possessing many mechanisms of resistance, broad adaptability, and increased growth. Mechanisms of resistance (low needle spot frequency, slow canker appears, slow canker growth or tolerance) and growth rate will be selected on a family basis. Individuals exhibiting needle spot prevention, low needle spot frequency, premature needle shed, short shoot reaction, bark reactions, and accelerated growth will be selected from within these families and used to establish seed orchards. The authors propose separating the inland region into hazard zones and managing natural stands to develop resistance.

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IMPROVING RUST-RESISTANT STRAINS OF INLAND WESTERN WHITE PINE

Raymond J. Hoff and Geral I. McDonald

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

CONTENTS

INTRODUCTION

Development of blister rust-resistant western white pine (*Pinus monti... l.*) ha- een underway in the Inland Northwest since 1950. The first 25 years, known as the hase 1 program, resulted in the establishment of three seed orchards. The trees in hese orchards are the results of two cycles of selection. The level of resistance, nder nursery conditions, is expected to be about 60 percent (Hoff and others 1973) nd field resistance will probably be as high as 80 percent (Bingham and others 973). Selection of the phase I material was based mostly upon testing candidate rees with four tester trees. Candidates with high ability to transmit resistance ere chosen (Bingham and others 1969).

During the early selection work on western white pine, a considerable knowledge as accumulated on the mechanisms of resistance and the existence of blister rust aces (Bingham and others 1971). This knowledge was available early enough to enable s to do some last minute selection changes in the proportion of the types of resistance oing into the phase 1 orchards. We had found that one mechanism of resistance premature needle shed) was disproportionately high in a previously selected F_2 opulation (Hoff and others 1973). Adjustments were made and now only 30-40 percent f the resistance in the phase 1 seed orchards will result from this mechanism.

This knowledge also made us aware that resistance in western white pine to lister rust is due to many mechanisms of resistance. Some mechanisms are controlled y single genes, others are controlled by many genes (Bingham and others 1971; table). This knowledge, together with the need to provide a larger gene base to enable s to select for growth and form and to maintain adaptability to its environment, ncluding native pests, resulted in the initiation of a new program to develop esistance in western white pine to blister rust -- phase II.

The purpose of this paper is to review resistance in western white pine to lister rust and describe a breeding program that has a high chance of stabilizing ne resistance but at the same time maintaining the native adaptability of western nite pine.

The breeding program includes four main elements. One element is a nursery test nat will provide data on resistance and secondarily on growth since the nursery nase will keep trees until 6 years old. The 15-25 percent slowest growing families .ll be excluded. A second element is a field test, mainly for growth and form, but .so for comparing resistance to blister rust in the nursery and field. A third .ement is a plan to allocate the resistant strain according to the degree of blister ıst hazard. And the fourth element is to describe a method for developing resistance ısing natural selections.

LIFE CYCLE OF WHITE PINE BLISTER RUST

The heteroecious, full cycle white pine blister rust requires two hosts--white nes and *Ribes* spp., i.e., currants and gooseberries. Dicaryotic aeciospores are oduced on pine, and infect the leaves of *Ribes* bushes. These spores have two nclei per cell and are believed to behave genetically as 2N. The *Ribes* infection oduces urediospores which aid in the spread of the fungus on the *Ribes* host. They ae also dicarytic and behave genetically as 2N.

Teliospores appear on the old uredial infection usually after about 2 weeks of cool weather. The dicaryotic nuclie fuse to become 2N and upon germination meiosis occurs producing four 1N basidiospores. These spores close the cycle by infecting white pine.

Germ tubes produced by germination of the basidiospore generally enter the pine via stomata of the secondary needles. Less important infection courts are stomata of the primary leaves and stomata of succulent stem tissue.

In the secondary needles, the fungus produces a large mass of mycelium that causes the cells of the pine needle to change color and this becomes visible as a "needle spot." The fungus then grows toward the stem where it grows profusely within cortex and phloem tissue.

Often there is little or no growth impact on pine resulting from fungus growth. The damage is the result of the killing of branches or the whole tree after the fungus completely encircles the stem. Death probably results from disruption of the phloem and cortical tissues as the fungus produces the aeciospore stage.

RESISTANCE IN WESTERN WHITE PINE

Mechanisms of resistance in western white pine are most easily described if presented according to the infection and growth sequence of the fungus as it develops starting in the secondary needles.

The first mechanism is prevention of needle infection. In the past, trees with no needle spots were thrown out as escapes. But some recent data (Hoff and others in press) show that there is a continuous increase of this type from the most susceptible white pine (*Pinus ayacahuite*), with 1 percent uninfected seedlings, to the most resistant (*Pinus parviflora*), with 96 percent. In this same test, 24 percent of the *Pinus monticola* seedlings were uninfected. However, the trait appears to be a threshold character because it varies with the intensity of the inoculation. In another test (Hoff and others 1973) the F_1 seedlings were 1 percent clean and F_2's were 15 percent clean, indicating that a selection had been made for the trait.

The frequency of needle spots also varies. There is a tenfold difference between number of spots on seedlings of families with low and high numbers of spots (table 1 and Hoff and McDonald in press). The data resemble those that might be produced by a single nondominant gene. Families can be grouped into classes (low, medium, high), according to frequency of needle lesions.

Needle spots also come in a variety of colors, shapes, and sizes. We have published data and photographs of some (McDonald and Hoff 1975). So far, we have observed the following phenotypic variations in needle spots caused by the blister rust fungus:

1. Yellow needle spots of normal size; rust fungus with normal virulence.

2. Yellow needle spots of normal size; rust fungus with very high virulence (observed in Oregon, Region 6, USDA Forest Service, blister rust program).

3. Yellow needle spots, very small size.

4. Red needle spots, normal size; rust fungus with normal virulence.

Red needle spots, normal size; rust fungus with very high virulence (observed in Oregon, Region 6, USDA Forest Service, blister rust program).

Red needle spots, very small size.

Yellow island spots.

Red island spots.

Table 1.--*Average number of yellow needle spots on one lineal meter of needle tissue per seedling within full-sib crosses*

	Pollen parent				
Seed parent	58	19	17	22	$\bar{x}$
57	3	5	7	12	[illegible]
227	2	7	6	14	[illegible]
382	11	8	8	8	[illegible]
355	4	11	19	15	12
121	8	10	11	20	13
232	4	15	12	19	13
230	12	15	7	18	13
95	11	12	16	11	13
179	6	15	13	19	13
33	14	14	18	22	17
$\bar{x}$	6	11	12	16	12

Because resistance and suceptibility of seedlings and families to these various nces" affects the number of needle spots that develop on a seedling, spot tallies ıt include a description of the spot type.

Tentative segregation data indicate that there is a typical gene-for-gene eationship between the host and the red-normal, yellow-normal, and island-type ts. Resistance in western white pine to red appears to be controlled by a dominant ee, to yellow by a recessive gene, and for the island charactersitic by a dominant ee.

The fungus then grows down the needle and the next resistance reaction observed sthe shedding of infected needles (McDonald and Hoff 1970). This reaction begins tabout 9 months after inoculation and is complete at about 12 months after inoculation. eetic control appears to be due to a recessive gene (McDonald and Hoff 1971).

A rust-resistance reaction is apparent in seedlings that keep their infected edles but never develop stem symptoms. This reaction appears to be initiated at h junction of the short shoot and needle fascicles when the fungus reaches the hrt shoot (Hoff and McDonald 1971). Genetic control of this reaction also appears o be by a recessive gene (McDonald and Hoff 1971).

The next rust symptom is the appearance of cankers in the stem. The rate of appearance of cankers varies with families (table 2). This trait appears to be controlled by several genes with a heritability of 46 percent.

Table 2.--*Number and percentage of blister rust cankers observed in the stems of western white pine seedlings 1 year after inoculation*

Family	Cankers following inoculation			
	1st year	2nd year	1st year/2nd year[1]	4th year[2]
	Number	*Number*	*Percent*	*Percent*
17 x 121	38	60	63	63
17 x 250	11	38	30	39
17 x 57	23	65	35	74
19 x 121	18	54	33	54
19 x 250	21	61	34	61
19 x 57	14	60	23	60
22 x 121	35	61	57	61
22 x 250	26	48	54	51
22 x 57	30	62	48	65
58 x 121	37	64	58	65
58 x 250	23	65	35	66
58 x 57	2	27	7	27

[1]Heritability (0.46) calculated from a 4 x 10 factorial including these crosses (author's unpublished data).
[2]By the 4th year after inoculation all cankers that will show up are observable.

After the fungus reaches the stem, a series of reactions can occur that--depending on individual and family--result in the death of the fungus. The effectiveness of this resistance depends on two separate reactions: (1) the ability of a seedling to initiate a necrotic response in the cortex after invasion by the rust; (2) the ability of a seedling to rapidly produce a strong wound-periderm. We observe in western white pine (unpublished information) and in Armand pine (Hoff and McDonald 1972), that only the host cells seem to be killed; the fungus, although not healthy, appears still to be alive, at least the cytoplasm and the nucleous of the fungus was not disrupted. Also, the small amount of data on Armand pine indicates that the effectiveness of the resistance varies with the phenology, i.e., the necrotic reaction is apparent when diameter growth begins and it is not operating during other periods.

The rate of growth of the fungus in the stem varies with individuals and families In many trees, of the progeny tests set up by R. T. Bingham and A. E. Squillace in 1952 through 1955, the fungus had not girdled the stem by 1970, even though the fungus had reached the stem of the seedlings probably by the time the seedlings were 2-3 years old, i.e., 1 year after artificial inoculation (table 3).

Table 3.--*Number of trees per test, percentage dead due to blister rust, percent of resistant seedlings lifted and percentage still living with cankers in 1970 in the Elk Creek progeny test plot*

Test year	No. trees	Percent Dead rust 1970	Cankered and percent living in 1970 with old cankers[1]	with basal cankers[2]	with young cankers[3]	Percent lifted
1952	2333	78.5	1.5	0.8	1.2	18.8
1953	740	83.4	1.4	.6	1.1	14.2
1954	941	73.4	4.7	1.0	1.2	20.7
1955	1678	60.5	8.5	.8	16.4	14.5
All controls	405	94.3	0.2	.2	1.7	3.7

[1]Old cankers are cankers that resulted from infection soon after the trees were outplanted.

[2]Basal cankers appear to be cankers that resulted from the initial inoculation when the seedling was 2 years old when in the nursery.

[3]Young cankers are those that have shown up recently--3 years prior to the 1970 rust inspection.

[4]Bingham lifted these seedlings with "high" resistance and moved them to the Moscow Arboretum 1957-1960.

The last reaction type that we have observed is what is called tolerance. This is a reaction of one seedling that enables it to sustain a great amount of infection without serious growth reduction or mortality. This reaction shows up at very low frequencies.

The mechanisms of resistance are summarized in table 4, with an indicated epidemiological type and hypothetical genetic control.

Table 4.--*Observed resistance mechanisms in* Pinus monticola: Cronartium ribicola *system*

	Mechanism of resistance	Resistance type	Hypothesized inheritance	h^2
1.	Resistance in secondary needles to a yellow-spot forming race	Vertical	Recessive gene	
2.	Resistance in secondary needles to a red-spot forming race	Vertical	Dominant	
3.	Resistance in secondary needles to a yellow-green-island spot forming race	Vertical	Dominant gene ?	
4.	Resistance in secondary needles to a red-green-island spot forming race	Vertical	Dominant gene ?	
5.	Resistance in secondary needles that prevents spot formation	Vertical	?	
6.	Reduced frequency of secondary needle infections	Horizontal	Nondominant gene ?	0.37
7.	Slow fungus growth in secondary needles	Horizontal	Polygenic	.46
8.	Premature shedding infected secondary needles	Vertical	Recessive gene	
9.	Fungicidal reaction in short shoot	Vertical	Recessive gene	
10.	Fungicidal reaction in stem	Vertical	Oligogenic ?	.367
11.	Slow fungus growth in stem	Horizontal	Polygenic ?	0.21-0.46
12.	Tolerance to infection	Horizontal	?	

SELECTION OF STANDS AND PHENOTYPICALLY RESISTANT TREES

This base of knowledge has enabled us to recommend a program for the development of resistance in western white pine to blister rust that would have higher stability and genetic diversity. The methods for doing this are the topics of the remainder of this paper.

Stand Selection

There are hundreds of stands and thousands of individuals to choose from. A little time spent in the selection of "good" stands can make the program more efficient and very effective. The criteria that we feel are important in selection follows.

1. Blister rust infection is uniformly heavy, ranging upwards from a low average of 10 cankers per tree.

2. Stand age 25+ years, height 10-30 m, meaning that all trees have been exposed to natural inoculation by the rust fungus for at least 25 years, that they are climbable, and are producing cones.

3. Stand density open to moderately open, especially in older (50-to 70-year-old) stands, meaning that white pine crowns can be seen or examined with binoculars from some distance.

Selection of Individual Trees

1. Candidate trees must be relatively free from blister rust cankers under locally heavy rust conditions. Past experience has shown that under conditions of heavy infrection candidates with one or a few cankers are likely to be just as valuable as those completely free of rust. Thus flexible criteria (allowable number of cankers increasing with local rust intensity) will hold for selecting candidate trees, as follows:

Rust intensity in the stand (average number of cankers/tree)	Maximum allowable infection per candidate (number of live or dead cankers)
10-20	none
21-40	1
41-75	2
76-150	3
151+	4-5

2. Candidate trees should be close to roads so that time and effort is not wasted in their relocation (by hand compass and pacing) for examination, pollination, cone collection, or when revisited for a variety of other purposes. Generally, in denser stands where visibility is limited it is best not to locate candidates more than 100 m from the road.

3. Runty, seriously deformed (especially multi-forked), seriously diseased (other than by blister rust), or seriously insect-attacked trees should be avoided, because these poor characteristics could be inherited. This includes open-grown trees that are one-fourth or more shorter than surrounding trees of equivalent age and crown class, trees that have repeated stem forks, trees that have several whorls bearing 10 or more large branches, and trees with sinuous or crooked stems not associated with likely mechanical injuries.

INOCULATION OF SEEDLINGS WITH RUST

Bingham (1972) reviewed inoculation procedures that have been used for developing blister rust resistant western white pine at Moscow. Briefly, these procedures are as follows:

1. Inoculate seedlings after the second growth period. The typical 2-year-old seedling is about 10 cm tall, has mostly secondary needles with a few remnant primary leaves. Much of the resistance is in the secondary needles; therefore if 1-year-old seedlings were inoculated many mechanisms of resistance would be missed.

2. Use natural inoculum from several sites and thoroughly mix the infected *Ribes* leaves before placing them over the seedlings. This will assure a good mixture of rust races.

3. The *Ribes* leaves are layered on wire screening 30-40 cm above the seedlings.

4. Humidity is kept as near 100 percent as possible and the temperature between 15°-20°C. This is achieved by either enclosing the set-up with plastic that is shaded by canvas (Bingham 1972) or by layering wet burlap over wire screens (Patton and Riker 1966). Maintain test conditions for 72 hours.

In the Moscow, Idaho, environment seedlings are inoculated during the first 2 weeks of September.

RUST INSPECTION

First Rust Inspection

Timing: In Moscow, Idaho, environment, June, 9 months after inoculation.

Criteria: Count needle spots on secondary needles of each seedling by color type, on uppermost two fascicles and measure length of fascicles. This sampling method depends upon attaining at least 8 spots per lineal meter of needles. If it is much less, this sample will be inadequate and either more fascicles should be added to sample or all the spots on the tree counted. Adding more fascicles adds a lot of time and counting all spots decreases precision, so a strong effort must be given to the inoculation procedure to make sure that an adequate number of spots are produced.

Second Rust Inspection

Timing: In Moscow, Idaho environment, September, 1-year after inoculation.

Criteria: Determine the presence of needle spots on secondary needles plus stem symptoms of each seedling. Four major stem symptoms are: normal cankers; small circular, shallow necrotic areas of sunken bark associated with the base of a single needle bundle; shallow or deep necrotic areas in the needle portion of the seedling stem that partially encircle the stem; shallow or deep necrotic areas in the needle portion of the seedling stem that completely encircle the stem.

Third, Fourth, and Fifth Rust Inspections

Timing: In Moscow, Idaho, environment, September, 2, 3, and 4 years after inoculation.

Criteria: Determine the presence of stem symptoms as listed under second rust inspection plus health of each seedling.

SELECTION PHILOSOPHY AND METHODS

New varieties of western white pine resistant to blister rust must include as many of the known kinds of resistance as possible (table 4). Natural host:parasite systems evolve an optimum balance of the various mechanisms of resistance (Harlan 1976). We hope to anticipate such a balance in the proposed selection scheme, or at least come close enough so that natural adjustments could be accomplished without serious disruptions.

We have drawn freely from the literature and experience of the crop breeders to develop a selection scheme. Although there may be major differences between forest tree species and crop plants, in principles of selection they are very similar. The following principles exemplify the prevailing philosophy of the interaction host:parasite systems:

1. Resistance is the rule, susceptiblity is the exception.

2. Mechanisms of resistance vary in type and frequency.

3. Some mechanisms of resistance bestow to their carriers complete resistance, others slow the disease or curtail its development.

a. Mechanisms that bestow complete resistance are typically controlled by single genes and are called vertical or differential resistance.

b. Mechanisms that slow or curtail disease are typically polygenetically inherited and are called horizontal, uniform, or field resistance.

4. Vertical resistance can be neutralized by a complementary gene in the disease-causing organisms.

5. Horizontal mechanisms of resistance are not neutralized by new races; however, more aggresive races might decrease the effectiveness of the horizontal resistance.

6. Combinations of several vertical resistance genes exhibit characteristics of horizontal resistance.

7. Disease-causing organism are also restricted by their own natural fitness requirements.

8. Resistance is the observed expression of the interaction of host genes, pest genes, and environment. The level of resistance required changes with environment, weather, and disease cycle. Low levels of genetic resistance in a population often result in high levels of phenotypic expression.

9. Resistance composed of horizontal types exhibits more stability than resistance composed of vertical types.

These principals lead to the following guidelines for development of new varieties of western white pine:

1. Never base resistance on only one gene. A variety of western white pine could be produced that would be 100 percent resistant, but it probably would not last long.

2. Use combinations of resistance types--diversity is essential.

3. Incorporate as many horizontal resistance types as possible.

4. Maintain a fairly low gene frequency for all the vertical resistance types, i.e., 0.3 to 0.4 or less. Two recessive genes with a frequency of 0.5 would result in complete resistance in 42 percent of the progeny as tested in the nursery. Addition of single genes increases resistance rapidly, but since field resistance tends to be even higher than nursery resistance (Steinhoff, 1971; Bingham and others 1973), a high gene frequency of any one gene is just not needed.

SELECTION FOR RESISTANCE

Arrangement of Data and Selection Criteria

The method of rust inspection will permit the ranking of families according to: (1) fewest to highest number of needle spots--type 6, table 4; (2) slowest to fastest stem symptom appearance--type 7, table 4; (3) lowest to highest level of mortality--types 11 and 12, table 4. Individuals can be tagged for: (1) percentage of needle infections--type 5, table 4; (2) few needle spots--type 6, table 4; (3) premature shedding of infected needles--type 8, table 4; (4) the reaction type that maintains infected needles but does not develop stem symptoms (short shoot reaction)--type 9, table 4; (5) stem reaction types--type 10, table 4.

This management of data will permit the selection of the seed orchard trees as follows:

1. Individual and family selection for reduced frequency of secondary needle spots.

2. Family selection for slow fungus growth in the secondary needles.

3. Family selection for slow fungus growth or tolerance in the stem; at the seedling stage it is impossible to separate these mechanisms.

4. Individual selections for prevention of needle infections, premature shedding of infected needles, short shoot reactions, and stem reactions.

Selection Intensity

The amount of gain that will be made is directly dependent on the proportion of resistant families and individuals saved. Three major points that must be considered are first the number of families available, second the minimum number of families that will be included in a seed orchard, and third the regional planting area for each seed orchard.

So far, over 3,000 phenotypically resistant white pine have been located within the inland range of western white pine. This is just a small sample of the number available. Several more thousand could be added if necessary to increase the selection intensity.

The number of families required in a regional planting area, i.e., breeding zone or adaptive provenance, is difficult to predict. Alfalfa breeders, who are working with a species that has high genetic variations, and who have gone through several generations of breeding, suggest 75 nonrelated individuals per planting area (Hanson and others 1972). Because white pine also contains high genetic variation (Steinhoff 1979) we recommend 100 families per regional planting unit.

There is very little variation in inland western white pine that is associated with latitude, longitude, or elevation (Steinhoff 1979), meaning that there is only one regional planting unit or breeding unit. And only one seed orchard is needed for the entire inland area of white pine.

With 3,000 families to start with and with inclusions of 100 families in the seed orchard, only 1 out of 30 of the candidate trees need to be saved. One-hundred families with the highest combinations of horizontal resistance would be chosen. Individual seedlings with the various vertical resistance types will be chosen from within these families.

We recommend that the level of resistance imparted by the vertical resistance genes be in the range of 50-60 percent. This will provide trees within the population upon which the fungus can grow, but because these trees will by chance also contain genes for horizontal resistance, they will not all die. Although there is much argument in the agronomic field, it is possible that permitting the "old" races to survive will have a stabilizing effect on the rust, i.e., the rust is not apt to develop a new race to survive.

Natural Selection — An Alternative Breeding Method

There are probably at least 20-30 genes that control blister rust resistance in western white pine. There are many genes that cause the death of the fungus and there are many more genes that slow the epidemic or slow the fungus growth so that fewer trees die. With this kind of genetic variation, we could just let nature run its course. The only real drawback is nature's way takes too long. But what could be done is to manage white pine stands to speed up nature's process.

UTILIZATION OF RESISTANCE — HAZARD MAPPING

In the previous section of this paper we recommended that the production of a variety of western white pine contain moderate levels of complete resistance (50-60 percent) on a base of horizontal resistance. A variety with this level of resistance would be planted throughout the inland range of white pine. However, at this time and for a decade or two in the future, there will not be enough seed to fill the planting needs.

More seed would be available if the level of resistance was matched to the degree of hazard: the intensity of blister infection. The degree of hazard faced by white pines depends on the temperature, moisture, and wind conditions during periods of basidiospore release. The seasonal weather pattern influences the multiplications of the rust on the ribes patches as does the species of *Ribes*. The point is, that various features of weather, ribes species, and distribution and topography can be measured to produce hazard maps (McDonald and others, in press). Then seed with varying levels of resistance can be matched to each site. For example, on the highest hazard sites, seedlings with the best resistance would be planted, on less hazardous sites seed could be collected from candidate trees (level of resistance 25-

30 percent) or from the surviving trees within stands that have had high mortality due to blister rust (level of resistance 10-15 percent).

Shelterwood or seed trees of white pine that have survived the epidemic could be left to regenerate a prepared site. In many stands (60-80 years old) mortality of white pine by blister rust is 90 percent. Nonetheless, there are usually 20-30 living trees per acre that survive. When such a stand is cut or salvaged, several of these trees can be left to provide seed for regeneration. According to our data about 20 percent of the seedlings will be resistant under nursery conditions (Hoff and others 1976).

Besides regenerating a stand, this approach has other benefits. In contrast to artificial selection, nature selects for all mechanisms of resistance. Man selects for only those he can see. Also, nature uses all races of blister rust over the many inoculation years. Man uses only those he collects and usually only once for each progeny test.

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1980. Improving rust-resistant strains of inland western white pine. USDA For. Serv. Res. Pap. INT-245, 13 p. Intermt. For. and Range Exp. Stn., Ogden, Utah. 84401.

Describes a nursery test designed to produce western white pine possessing a variety of mechanisms of rust-resistance, broad adaptability, and increased growth rate. Mechanisms of resistance (low needle spot frequency, slow canker appears, slow canker growth or tolerance) and growth rate will be selected on a family basis. Individuals exhibiting needle spot prevention, low needle spot frequency, premature needle shed, short shoot reaction, bark reactions, and accelerated growth will be selected from within these families and used to establish seed orchards. Also discusses recommendations to separate the inland region into hazard zones, and the management of natural stands to develop resistance.

KEYWORDS: *Cronartium ribicola,* resistance natural selection, resistance mechanisms

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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.

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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INFILTRATION AND EROSION ANALYSIS OF PHOSPHATE STRIP MINE OVERBURDEN

Christopher M. Knopp
Eugene E. Farmer

USDA Forest Service Research Paper INT-246
Intermountain Forest and Range Experiment Station
U.S. Department of Agriculture, Forest Service

COVER PHOTO

A phosphate mine overburden waste dump in southeastern Idaho. Surface wastes h differing hydrologic responses, i.e., different water infiltration and soil erosion rates. Soil color is a useful indicator of the differences. Light yellowish-brown soils, Munsell 10YR 6/4, have the greatest erosion rates, while very dark gray-brown soils, Munsell 10YR 3/2, have the smallest erosion rate. The brown soils, Munsell 10YR 5/3, are intermediate.

The open pit is at the top left.

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INFILTRATION AND EROSION ANALYSIS OF PHOSPHATE STRIP MINE OVERBURDEN

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RESEARCH SUMMARY

The objective of this study was to identify separate sedimentary strata on the surface of one phosphate mine overburden dump and to compare those strata in terms of their respective infiltration and erosion characteristics.

Sedimentary strata were initially identified solely by color. This identification was then verified by comparing the following physical characteristics: minerology bulk density, texture, antecedent moisture, and modulus of rupture.

Three geologic strata on soil types were identified. Of those three, two soils were believed to originate from distinct separate strata of rock, while the third is believed to be a mixture of several strata.

The two elemental soil types exhibited significantly different infiltration constants (f_c) and soil loss quantities as a result of tests run with a drip type infiltrometer. The dark soil type had an average f_c of 1.73 inches/hour (4.39 cm/h) and an average soil loss of 2.1 tons/acre (4.7 MT/ha), while the light soil type had an average f_c of 0.95 inch/hour (2.41 cm/h) and an average soil loss of 23.2 tons per acre (52.0 MT/ha) for the 30-minute infiltrometer test.

Using the soils' physical characteristics, a stepwise multiple linear regression equation was derived in order to permit future identification of desirable soil types.

The implications of this research are that by separating individual geologic strata for use as topsoil, significant improvements in dump stability and erosional losses may be possible.

CONTENTS

INTRODUCTION

The Maybe Canyon phosphate mine is one of six currently active strip mines in southeastern Idaho. Continued operation of this mine will produce 130 acres (52.6 ha) of pit and 200 acres (80.9 ha) of new overburden dumps (U.S. Geological Survey 1977). To limit erosion and promote revegetation, specific dump construction procedures have been recommended. One of the most important involves surfacing the dumps with native topsoil. The surface covering is a critical element because it serves as the foundation for future reclamation and as the source of potential sediments.

Because of the generally shallow soils, the stockpiling of topsoil was not practical in this case. Instead, the Maybe Canyon mine is primarily surfaced with overburden shales and mudstones.

The objective of this study was to analyze the infiltration rates and soil erodibilities of the surface materials on one completed phosphate mine overburden dump. Secondly, we wished to isolate some specific characteristics which could be used to identify those strata exhibiting desirable hydrologic properties.

SITE DESCRIPTION

The Maybe Canyon mine, dump No. 2, is located northeast of Soda Springs, Idaho, (fig. 1). It is approximately 4.9 acres (2.0 ha) in area, has a northeast aspect, and is at about 7,700 feet (2 350 m) elevation. Slopes on the overburden material range from 15 to 34 percent. At the time of this study, the dump was approximately 2 years old, and had only a sparse covering of grass, despite having been machine seeded.

The average annual precipitation is estimated to be 22 inches (56 cm), 54 percent of which occurs as snow, the rest predominantly as summer thundershowers. Temperatures are estimated to range from -42°F to 92°F (-41°C to 33°C). Winds are predominantly from the southwest (Jeppson and others 1974).

The surface of the overburden dump appears to be composed of natural topsoil. It contains little rock since the shales and mudstones used to surface the dumps are soft and subject to rapid decomposition as a result of carbonate leaching. For the sake of brevity, these surface materials will be referred to as "soils", even though they exhibit no noticeable pedogenic features.

METHODOLOGY

Organization

Infiltrometer sampling sites consisted of 12 slope-soil combinations each containing one of four slope categories (15-19 percent, 20-24 percent, 25-29 percent, and 30-34 percent) and one of three soils which were initially identified only by the Munsell soil color. The dark soil is a Munsell 10YR3/2 (very dark gray brown); the medium soil is 10YR5/3 (brown); and the light soil is 10YR6/4 (light yellowish brown). For ease of discussion, the dark, medium, and light soil type labels have been retained throughout this paper. Four infiltration runs were made on each slope-soil combination. One slope-soil combination was not present over a large enough area for four sampling runs; so the total number of sampling plots was 45 instead of the planned 48.

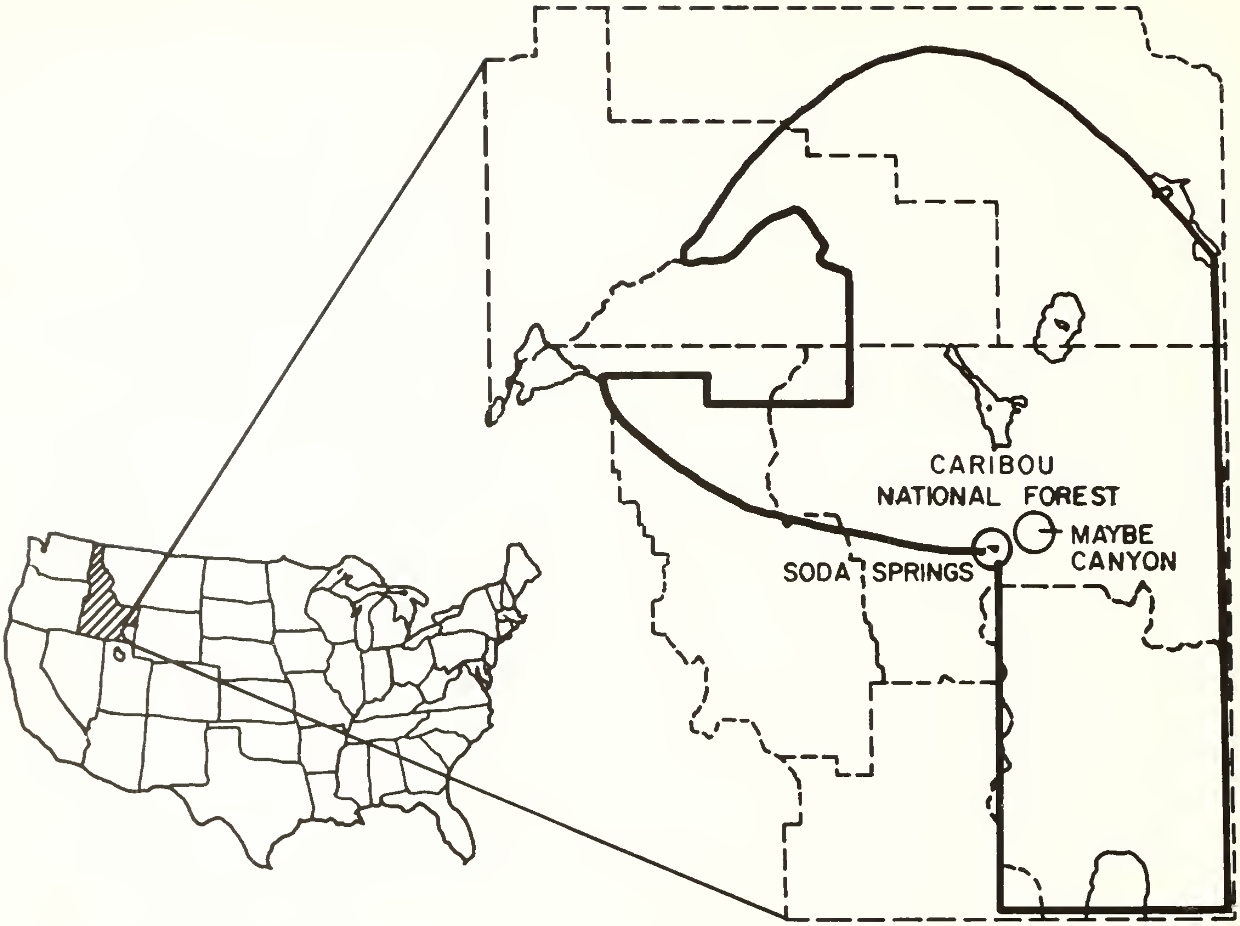

Figure 1.--Map of southeastern Idaho. Heavy lines enclose general phosphate mining areas (U.S. Geological Survey 1977).

Field Procedure

Infiltration rates were determined using a Nevada type drip infiltrometer, designed by Meeuwig (1970). All infiltrometer runs were of 30-minute duration, with runoff samples being collected every 5 minutes. Application intensity was 3.0 inches per hour (7.6 cm per hour). This intensity was required in order to define an infiltration curve on the dry soils.[1] Instrument height was 4.0 feet (1.22 m) on the downslope side with the infiltrometer level.

From each infiltrometer run, six infiltration rates were obtained corresponding to the 0.042, 0.125, 0.208, 0.292, 0.375, and 0.458 hour times.

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[1]Under natural conditions, overland flow will only occur when the soil surface layers are saturated. This condition occurs regularly during the spring snowmelt period or during a rare high-intensity rainstorm.

The weight of soil washed from each plot by raindrop splash and overland flow uring the 30-minute run is considered an index of soil erodibility (Meeuwig 1970). unoff water was collected for each plot. A quart sample of thoroughly mixed water as ovendried and weighed to determine sediment yield. The sediment samples were then sed as a comparative measure of erosivity.

Concurrent with the infiltrometer runs, soil samples of the surface 4 inches 10.2 cm) were taken to determine bulk density, soil texture (coarse, sand, silt, and lay percents), antecedent soil moisture, mineral constituents, and modulus of rupture. udulus of rupture (MOR) is primarily a measure of the crusting potential of a soil (a igh MOR value indicates strong crusting potential) (Richards 1953).

RESULTS

An X-ray diffraction analysis of the three soils showed no significant differences mong the three soils for the minerals tested. A one-way analysis of variance (AOV) f the bulk density, antecedent moisture, percent sand, silt, clay, coarse fraction, and odulus of rupture indicated that some significant differences did exist among the hree soils. Bulk density and percent sand were very similar for the three soils and howed no significant differences. Antecedent moisture, coarse fraction, silt and lay textural fraction, and modulus of rupture, however, all showed significant differnces among the three soil groups at the 0.05 level (figs. 2-5). The dark soil exhibited he highest average antecedent moisture content (5 percent), while the light soil had he lowest (2 percent). The medium soil's antecedent moisture content was similar to the ight soil's (2.5 percent), but slightly higher.

The textural differences were generally small. The light colored soil appears to ave approximately 15 percent less coarse material (greater than 2 mm in diameter), hows a corresponding increase in its silt fraction, and a slight increase in its clay ontent. Other textural categories among the three soils displayed no statistically ignificant differences.

Modulus of rupture values displayed clear differences among the three soil types. he dark soil group exhibited the lowest modulus of rupture, indicating low structural rength in its surface crusts, while the light soil group had the highest average MOR lues. The light soil's MOR values were approximately eight times the dark soil's OR values. Modulus of rupture figures for the medium soil type fell midway between he values of the light and dark soil types.

Infiltration

Horton's (1940) infiltration equation was used to describe the three soils' ifiltration characteristics because of its accuracy and simplicity of application.

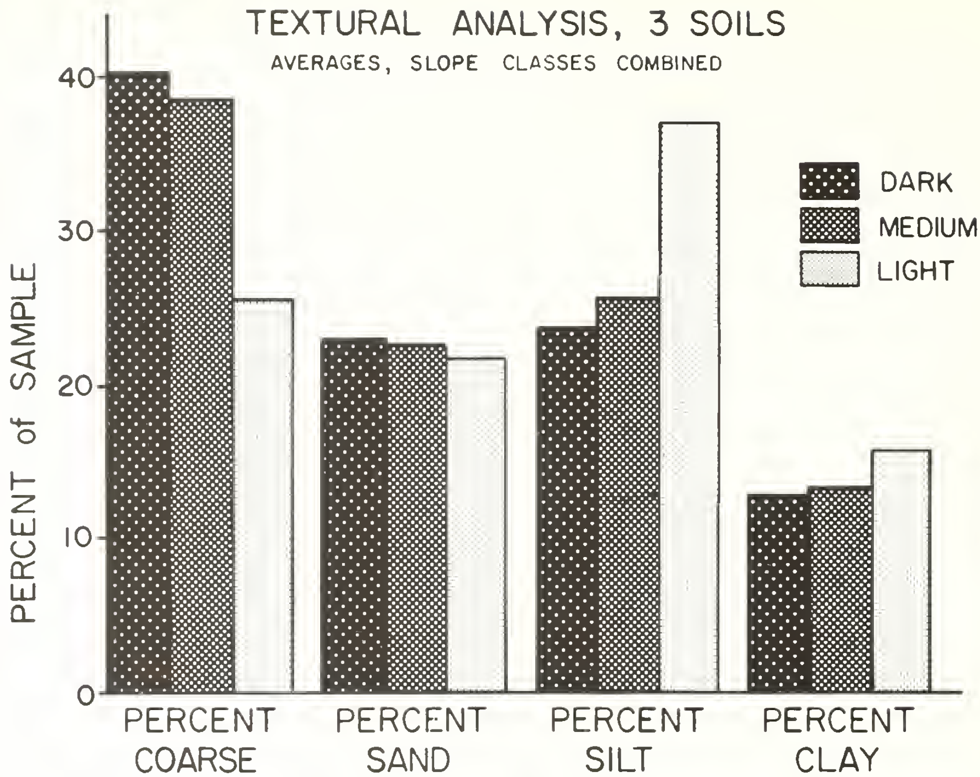
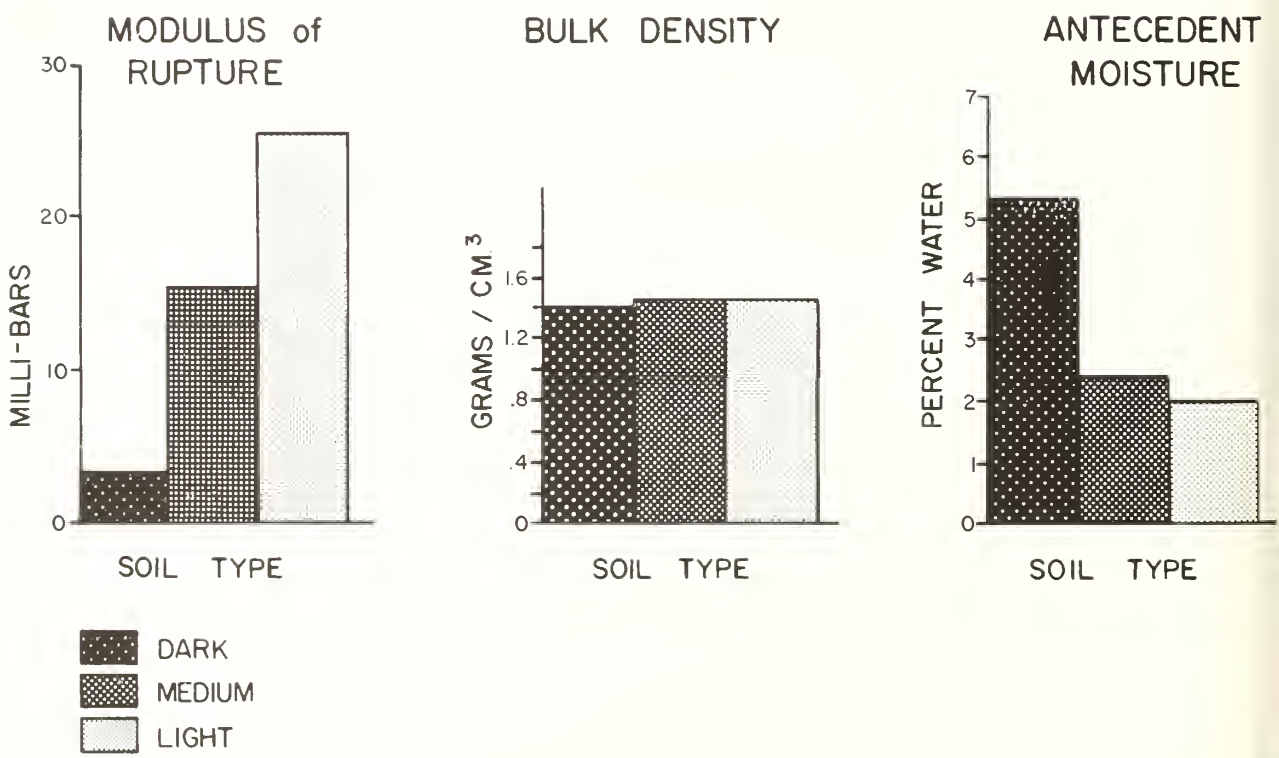


Figure 2.--Textural analysis of the three soils used to surface the Maybe Canyon mine, dump No. 2.



Figures 3 to 5.--Physical characteristics of the three soils present on the surface of the Maybe Canyon mine, dump No. 2.

Horton's equation is:

$$f_t = f_c + (f_o - f_c)\, e^{-kt}$$

where

f_t is the infiltration rate at time t (inches/hour)

f_o is the initial infiltration rate (inches/hour)

f_c is the infiltration constant (inches/hour)

k is the infiltration curve decay factor

t is the time in hours.

The procedure to fit generalized infiltration equations for each slope category and each soil type was to average the six corresponding infiltration rates produced by the infiltrometer runs within each group (the six rates corresponded to the 0.042, 0.125, 0.208, 0.292, 0.375, and 0.458 hour times).

This resulted in a set of six average infiltration rates. These averaged rates were then utilized in a computer solution of Horton's infiltration equation. This was done for all three soil types and for the four slope classes within each soil type (the light soil type only ranged over three slope classes).

The dark soil exhibited the highest calculated infiltration constant, with an f_c of 1.73 inches per hour (4.39 cm/h), the medium soil group had an average f_c of 1.08 inches per hour (2.74 cm/h), and the light soil reflected the lowest average infiltration constant of 0.95 inch per hour (2.41 cm/h) (fig. 6).

The fit of the generalized infiltration equations for the three soils was dependent upon the degree of variability in infiltration rates that particular soil exhibited with respect to different slopes. All of the soils exhibited trends of decreasing infiltration constants with increasing slopes (figs. 7, 8, 9). The dark soil group displayed the greatest variability of infiltration constants among slope classes and so its generalized infiltration equation had the poorest fit.

The medium soils had a much reduced response, while the light soil type showed no statistically significant differences of infiltration constants between slope classes. Because of this slope-induced variation, the r-square values for the three soil types average infiltration equations were: dark soil, r^2=0.27, medium soil, r^2= 0.84, and light soil, r^2 = 0.98.

An analysis of variance (AOV) indicated that significant differences did exist among the three soils f_c's at $\sigma = 0.05$. A Duncan's multiple range test did not show significant differences among any of the three soils f_c values at 0.05; however, the dark and light soils f_c's were extremely close to being significantly different. The failure of the multiple range test to reveal significant differences is probably the result of the less conservative nature of analysis of variance and at least partially because of the fairly high slope-induced variability of the infiltration rates.

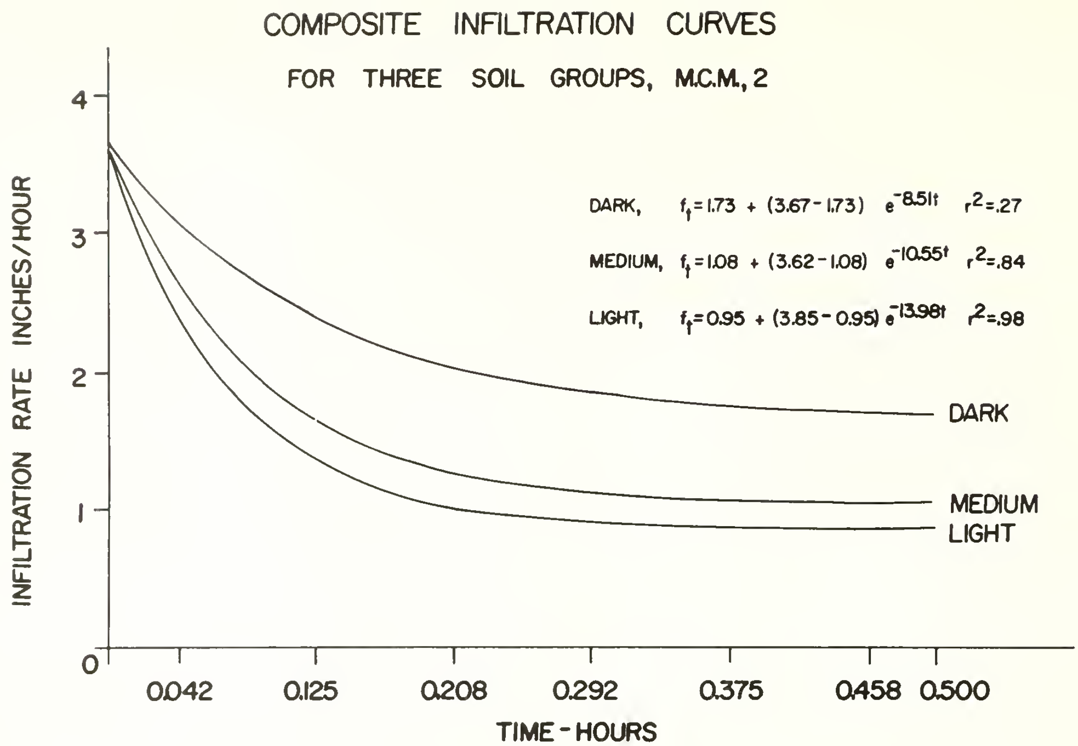


Figure 6.--Horton's average infiltration equation for three surface soils at the Mayb Canyon mine, dump No. 2. The dark and medium curves represent 16 infiltrometer run of 6 observations each. The light curve represents 13 runs of 6 observations.

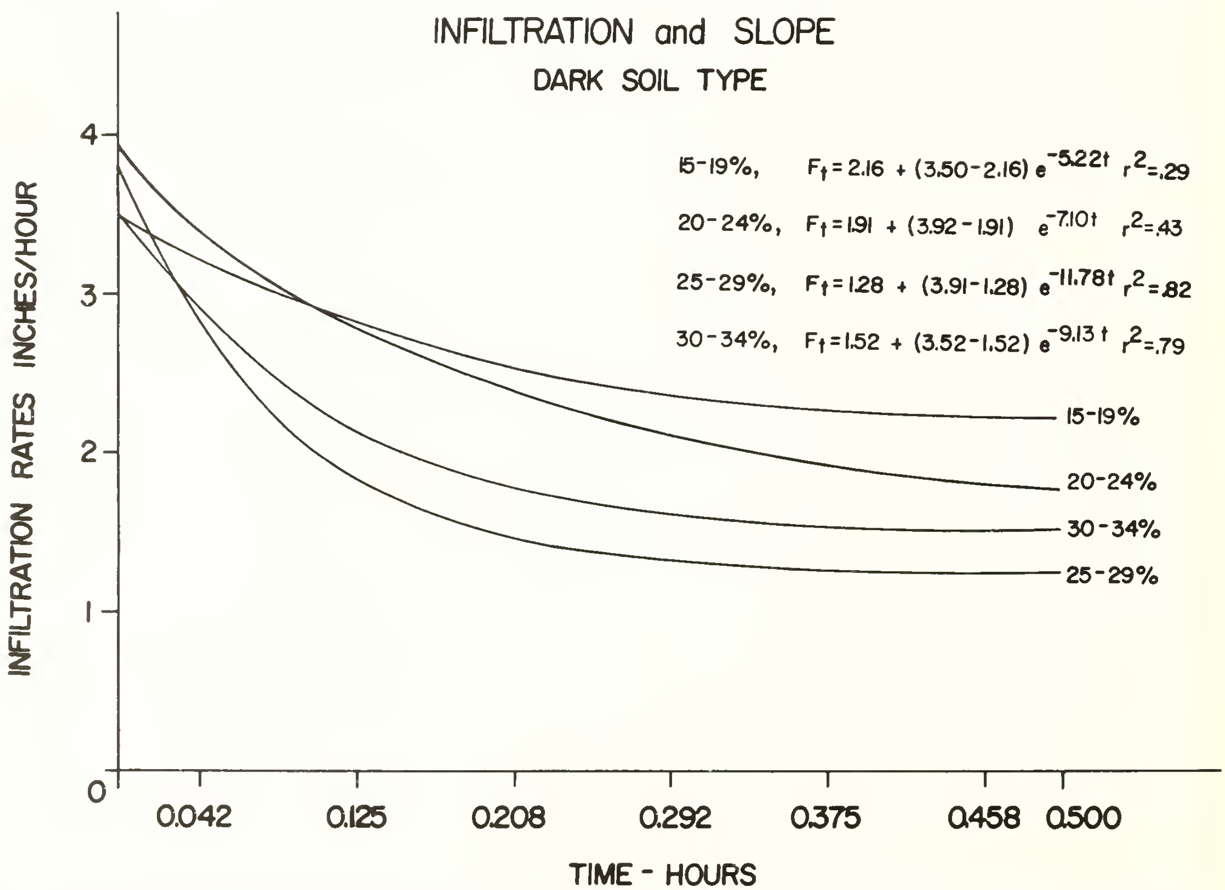
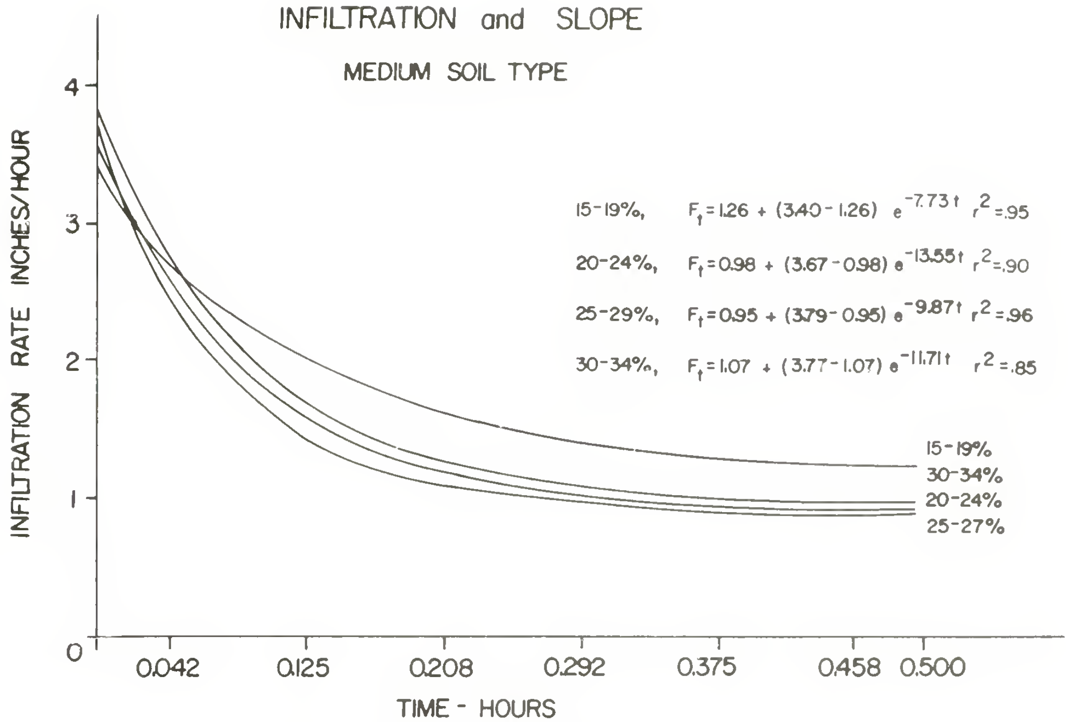
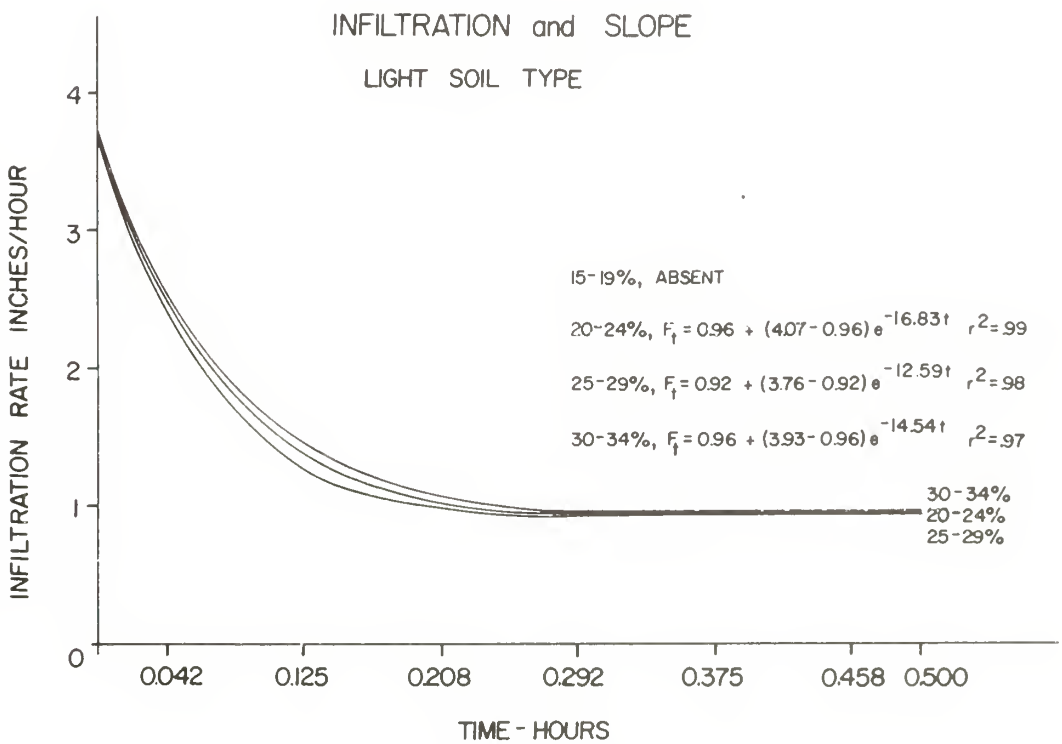


Figure 7.--Horton's average infiltration equations for four slope classes within the dark soil type. Each curve represents four infiltrometer runs of six observations.



gure 8.--Horton's average infiltration equations for four slope classes within the nedium soil type. Each curve represents four infiltrometer runs of six observations.



ire 9.--Horton's average infiltration equations for three slope classes within the ght soil type. Each curve represents four infiltrometer runs of six observations.

SOIL EROSION

The dark soil eroded least during the 30-minute run (2.1 tons/acre; 4.71 MT/ha) followed by the medium soil (10.1 tons/acre; 22.6 MT/ha) and then the light soil (23.2 tons/acre; 52.0 MT/ha), (fig. 10).

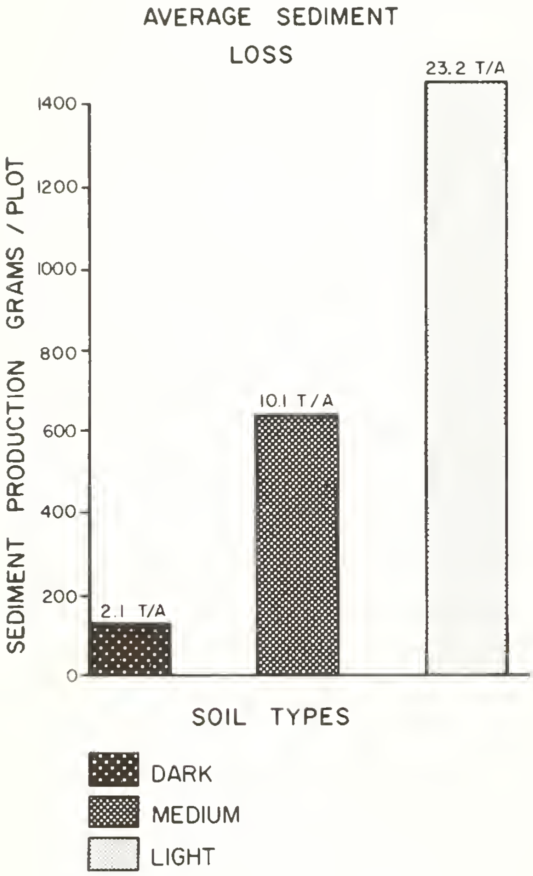


Figure 10.--Average sediment loss for three soil types resulting from 3-inch per hour, 30-minute duration infiltrometer run. A "1-way AOV" and Duncan's multiple range test indicated that significant differences are present between the dark and light soils at $\alpha = 0.05$.

An AOV test and Duncan's multiple range test indicated the erosional losses of the dark soil were significantly different (at 0.05) from the light soil groups, but that the medium soil's sediment production was not significantly different from either.

Sediment production varied between slope classes for the dark and medium soils, although within the range of slopes tested, erosion and slope did not show a reliable relationship. The light soil type illustrated no significant response of soil loss to slope.

A cluster analysis was performed using the infiltration constants and the erosional losses from each plot (fig. 11). This test organizes the data into groups of similar infiltration and erosion rates. The greater the similarity within the calculated groups the greater the likelihood that real difference among groups exists. The fit of the data to the calculated groups can be assessed by the cophenic correlation value, which varies between zero (no correlation of data points) and one (where all the data points within the clusters are identical). Since the initial stratification of the soils was based soiely on color, this test can be interpreted as a measure of how closely soil color is indicative of soils having different infiltration and erosion rates.

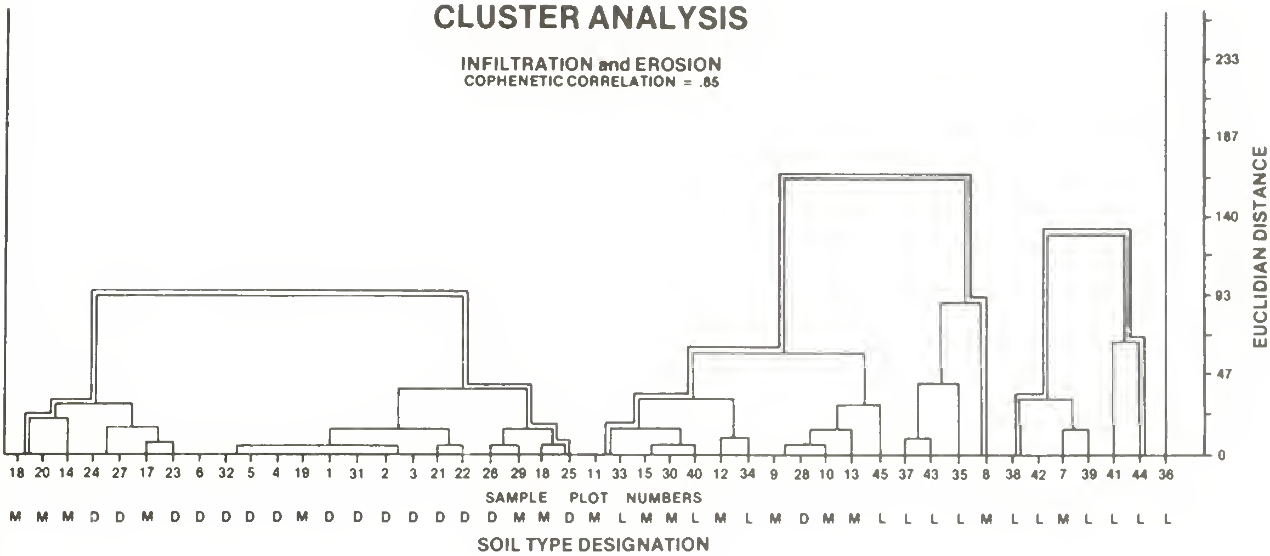


Figure 11.--Euclidian Distance Cluster Analysis of infiltration and erosion rates. The double line depicts the three clusters which broadly correspond to the dark, medium, and light soil types. They were orginally stratified on the basis of color.

The cluster analysis depicted three distinct groups with a cophenetic correlation of 0.85 (a high value, indicating the groups are generally separate and distinctly different). These groups broadly correlated with the orginal three groups based upon soil color. The first cluster was composed of 68 percent dark soil and 32 percent medium soil. The second cluster was made up of 50 percent medium soil, 45 percent light soil, and 5 percent dark soil. The remaining cluster was 86 percent light soil type and 14 percent medium soil type. The observed variability is probably the result of some mixing of soil types during dump construction and the subsequent unintentional sampling of those mixtures.

DISCUSSION

The MOR, antecedent moisture, and textural values of the three soils do display some separate and distinct physical characteristics. Together they tend to separate the dark and light soils into elemental soil units and indicate that the medium soil type is probably a mixture of the dark and light.

As regards infiltration and erosion rates, the medium soil type consistently fell between the dark and the light soils. This, in conjunction with the results of the cluster analysis, which showed the medium soil was made up of a mixture of dark, light, and medium soil types, indicates that the medium soil type is probably a mixture of the dark and light.

The fact that a medium soil group cluster appeared at all in the analysis, indicates this mixture does have enough unique properties to still be considered a separate soil group.

The differences between soil types with respect to erosion were inversely correlated with infiltration. The light soil's low infiltration rates resulted in higher overland flow volumes, which in turn transported greater sediment loads. This partially explains the light soil's ability to produce about 10 times the volume of sediment from the same infiltrometer storm as did the dark soil.

While color was a useful indication of separate soils in this study, under normal field conditions it probably would not be a consistently reliable predictor of soil characteristics. For that reason, a stepwise multiple linear regression was done using the physical characteristics of the soils in order to try to identify another means of labeling hydrologically desirable soil types.

The resulting equation for sediment production is:

$$S = 46.4 \text{ (percent silt)} + 13.8 \text{ (MOR-milli-bars)} - 824, \quad r^2=0.614$$

S = Grams of sediment (infiltrometer-based comparison).

This equation provides an objective methodology for ranking any number of soils in relation to those soils' relative erosivities. Because of the artificial nature of rainfall simulation, this equation cannot be expected to predict soil losses occurring from a natural rainfall event. It is intended to display only the relative magnitudes of differences between the tested soils (under the conditions of an essentially vegetation-free surface).

The inclusion of silt in this instance confirms earlier research which shows increased susceptibility to erosion with increasing silt content (Packer and Christensen 1977; Farmer and Van Haveren 1971; Wishmeier, Johnson, and Cross 1971).

The MOR test is not reflective of just one specific soil property, but rather is a response to many soil characteristics. Specifically what MOR is measuring is unknown, although it has been strongly correlated with high levels of exchangeable sodium and infiltration rates (Farmer and Richardson 1976).

CONCLUSIONS

1. Different sedimentary strata within the phosphate-bearing formations of southeastern Idaho, when used as surfacing material on overburden dumps, exhibit different infiltration and erosion characteristics.

2. The magnitude of these differences is such that separation and stockpiling of specific strata for use as surfacing material is a viable consideration.

3. On the Maybe Canyon mine, dump No. 2, the light colored surface material displayed a 10-fold difference in erosional losses compared to the dark material [23.2 tons/acre (52 MT/ha) as compared with 2.3 tons/acre (5.2 MT/ha)]. Infiltration constants for the dark, medium, and light soil types were:

1.73, 1.08, and 0.95 inches per hour (4.39, 2.74, and 2.41 cm per hour).

4. Future comparisons of geologic strata are possible and fairly easily accomplished through measurments of the strata's silt percent and modulus of rupture. Both of these tests are relatively fast and inexpensive (Black 1965).

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Infiltration and erosion characteristics of three phosphate mine overburden soils were compared using a drip type infiltrometer. A comparative analysis of the soils' physical properties, and their infiltration and erosion rates, revealed distinct differences between soil types. The study concluded that successive layers of sedimentary rock overburden (the top soils tested) can exhibit significantly different hydrologic properties when used as surface fill.

KEYWORDS: phosphates, infiltration, erosion, overburden dumps, soil properties

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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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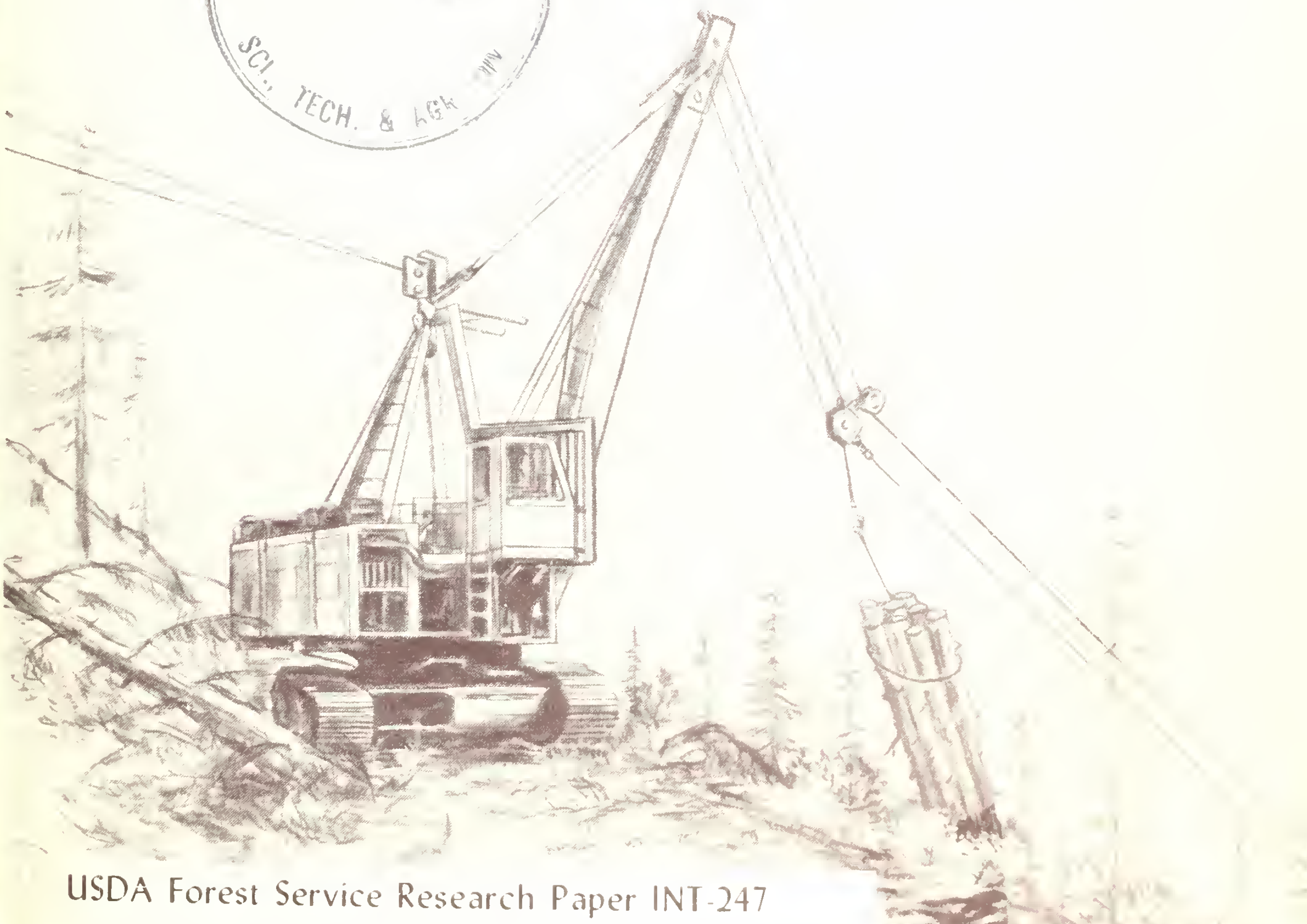
KYLINE LOGGING PRODUCTIVITY UNDER LTERNATIVE HARVESTING PRESCRIPTIONS ND LEVELS OF UTILIZATION IN LARCH-FIR STANDS

lulon B. Gardner



USDA Forest Service Research Paper INT-247
Intermountain Forest and Range Experiment Station
U.S. Department of Agriculture, Forest Service

THE AUTHOR

RULON B. GARDNER was principal research engineer (now retired), stationed at the Forestry Sciences Laboratory in Bozeman, Montana. He was involved in logging and road construction in National Forest Systems and Research for 25 years--the last 17 years in a research capacity.

RESEARCH SUMMARY

Little information is available to assess the economic and environmental feasibility of harvesting timber at more intensive levels of utilization in steep terrain. In this study in a larch-fir stand, four levels of wood utilization, ranging from conventional saw log to almost total fiber recovery, were harvested using running skyline and live skyline yarding equipment. All four levels of utilization were applied under each of three silvicultural prescriptions--shelterwood, group selection, and clearcut harvesting.

The general objectives of the study were to determine the influence of intensive levels of wood utilization upon skyline system productivity under each silvicultural prescription, and to determine the important variables influencing rates of production.

The highest average production experienced, in total cubic feet of fiber removed, occurred in group selection cutting units for the running skyline yarding downhill in treatment 4--1,047 ft^3/h (29.3 m^3/h). The least productive logging occurred with the running skyline logging uphill in shelterwood cutting in treatment 3--353 ft^3/h (10.0 m^3/h.

The most important variables influencing rate of production were yarding distance, lateral yarding distance to the skyline, and number of pieces per turn, in that order.

USDA Forest Service
Research Paper INT-[illegible]
June 19[illegible]

SKYLINE LOGGING PRODUCTIVITY UNDER ALTERNATIVE HARVESTING PRESCRIPTIONS AND LEVELS OF UTILIZATION IN LARCH-FIR STANDS

Rulon B. Gardner

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
U.S. Department of Agriculture
Forest Service
Ogden, Utah 84401

CONTENTS

INTRODUCTION

The broad objective of the study on which this report is based was to evaluate skyline harvesting feasibility (economic and environmental) under the full array of silvicultural and utilization practices that could be used in managing a larch-fir timber stand.

Intensive wood utilization would reduce the waste of a valuable resource and extend an ever-shrinking wood fiber supply. Reductions in land available for growing timber because of urbanization and removal for other uses such as recreation, wildlife habitat, and wilderness, come at a time when demand for wood products continues to increase. Utilization of forest residues, estimated at 6 billion cubic feet (0.17 billion m^3) annually, could increase the total fiber yield by as much as 50 percent on a national basis.

Intensive wood utilization can have positive or negative environmental impacts, depending on the level of utilization, harvesting methods, and ecosystem response. Although some general information is available from past studies about responses--hydrology, flora, and fauna--the net results of applying increasing levels of timber utilization have not been adequately determined. Hence, a study was designed for the larch-fir type in Montana (fig. 1) to monitor biological-ecological responses to an array of alternative silvicultural and utilization timber harvesting prescriptions.

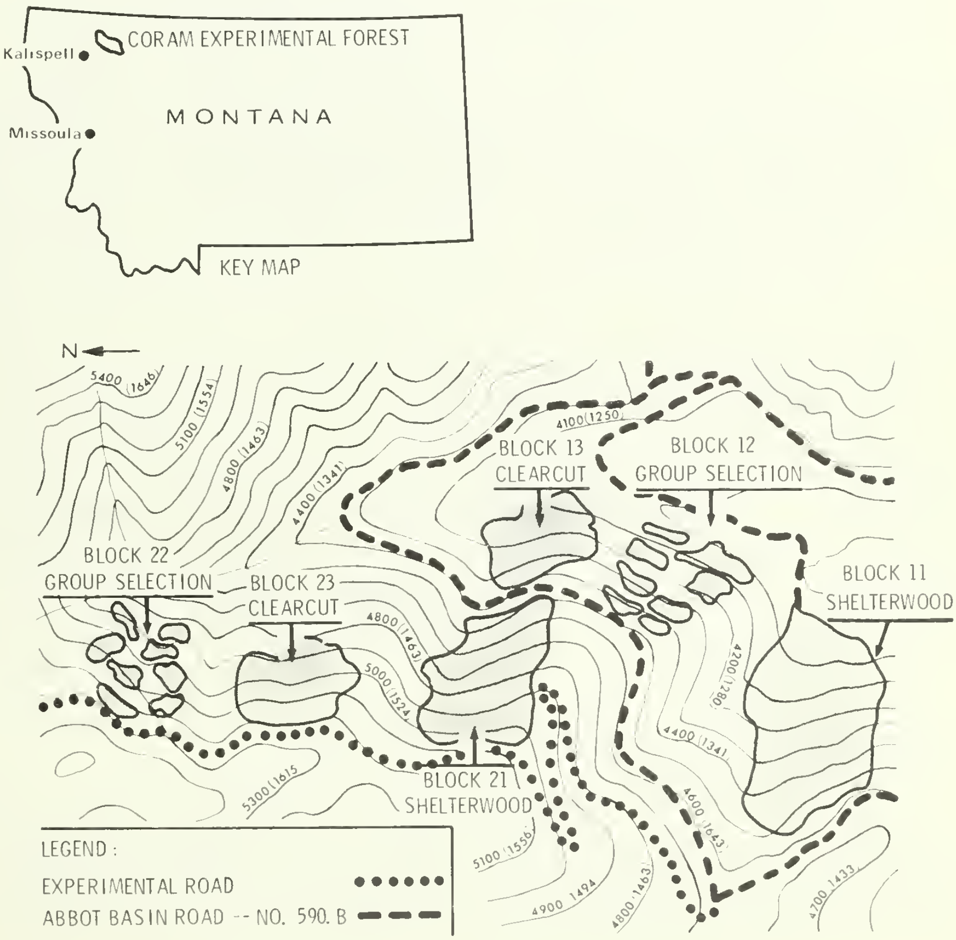


Figure 1.--Experimental road and logging location.

Because of the relatively steep slopes (45 to 60 percent) on the study area, cable yarding was appropriate. Past experience in the Rocky Mountain area has been largely with Idaho jammers or high-lead systems that require dense road networks because of limited skidding capabilities--300 to 500 ft (91 to 152 m) for jammer skidding and slightly more, 400 to 700 ft (122 to 213 m) for high-lead yarding.

For this experimental harvesting study, where one of the objectives was to reduce environmental impacts, it was decided to use a running skyline system to reduce road requirements. Road spacing was to be on the order of 1,500 to 2,000 ft (457 to 610 m); thus, the requirement for the basic system was a 1,000-foot (305 m) yarding capability uphill or downhill. Because of road width limitations and landing restrictions, the yarding equipment also had to be able to swing logs to the road. This report describes the logging methods, logging equipment, productivity, and factors affecting productivity

OBJECTIVES

The specific objectives of the harvesting study were as follows:

1. Determine the influence of successively more intensive levels of wood utilization upon harvesting productivity for skyline systems operating under clearcut, shelterwood, and group selection silvicultural prescriptions.

2. Identify and quantify the stand and operation variables that significantly affect harvesting productivity.

3. Develop a statistical data base for estimating system yarding productivity, given some measure of the important variables describing the harvesting situation.

4. Develop, field test, and demonstrate harvesting practices and techniques that can improve the efficiency of running skyline systems, and thus enhance the opportunitie for increased utilization.

In this report, the productivity experienced in each harvesting situation is presented and identified with the variables that influenced production.

The report further develops and illustrates procedures for estimating yarding turn time and associated productivity--a major cost determinant for the system.

EXPERIMENTAL HARVESTING UNITS

Logging Area and Blocks

Two blocks of each silvicultural prescription were laid out as shown in figure 1.

In each block, four levels of utilization were prescribed as shown in table 1. Treatment units run perpendicular to the slope.

The topography is generally steep (45 to 60 percent) and loggable only with cable equipment. To reduce hydrologic, esthetic, and biological impacts, logging equipment wa needed that would reduce both the impacts from logging and attendant roads. The system also had to be portable and relatively easily rigged. The running skyline system was best for satisfying all of these requirements.

Table 1.--*Logging area treatments and utilization prescriptions*

Prescribed utilization	Material removed	Postharvest treatment	Treatment designation[1]
Conventional sawlog	Green and recent dead logs, to 5-1/2 inch (14 cm) top; 1/3 or more sound	Remaining understory slashed; broadcast burned	1
Close log utilization, trees 7 inches (17.8 cm) d.b.h.+ (sawtimber trees)	Green logs, to 3 inches x 8 ft (7.6 cm x 2.4 m); dead and down logs, to 3 inches x 8 ft (7.6 cm x 2.4 m), if sound enough to yard	Understory retained; left as is	2
Close log utilization, trees 5 inches (12.7 cm) d.b.h.+	Green logs, to 3 inches x 8 ft (7.6 cm x 2.4 m); dead and down logs to 3 inches x 8 ft (7.6 cm x 2.4 m), if sound enough to yard	Remaining understory slashed; broadcast burned	3
Close fiber utilization, all trees	Green 1-5 inches (2.5-12.7 cm) d.b.h. material tree length, in bundles;[2] green trees >5 inches (12.7 cm) d.b.h., tree length; dead and down, to 3 inches x 8 ft (7.6 cm x 2.4 m), sound enough to yard	Remaining understory slashed; left as is	4

[1]Treatment designation numbers used in this report are assigned in successive order of utilization intensity, 1 through 4. They do not correspond to the random treatment numbers assigned and used on the ground, which appear in various other reports based on this study site.

[2]Trees 1-5 inches (2.5-12.7 cm) d.b.h. cut and prebundled prior to logging activity on the site.

The upper part of blocks 11 and 12, all of 13, and the lower part of 21 were loggable from Abbott Basin Road 590-B, built in the 1950's (fig. 1). New access was needed for upper 21, 22, 23, and lower 11 and 12. Whenever it is desired to reduce road spacings in steep areas, it is usually efficient to gain elevation by switching back at favorable locations on the terrain and then log with a cable system with a fairly long reach. Figure 1 shows the new section of road that started from 590-B, near the upper part of block 11, and switched back on the gentle terrain of broad ridges to gain access above blocks 21, 22, and 23. A new short section of road was also built to access lower 11 and 12, as shown in figure 1. (A separate report by the author [Gardner 1978] describes the road portion of the study.)

PLANNING AND CONDUCTING HARVESTING

Equipment

YARDERS

The contractor selected a Skagit GT-3 (fig. 2) to meet the requirements for loggin Initial logging was done with the GT-3; later, two sides were logged simultaneously whe a Link Belt 78 Log Mover (fig. 3) was put on the job. Both yarders had 1,000-foot (305 yarding capability. The Link Belt 78 was rigged as a live skyline using a gravity retu carriage and, therefore, only able to log uphill. Figures 4 and 5 show how each system is rigged and operates (specifications for the yarder are in appendix A).

Figure 2.--Skagit GT-3 loca at fan-shaped set below block 21.

Figure 3.--Link Belt 78 Log Mover logging block 23.

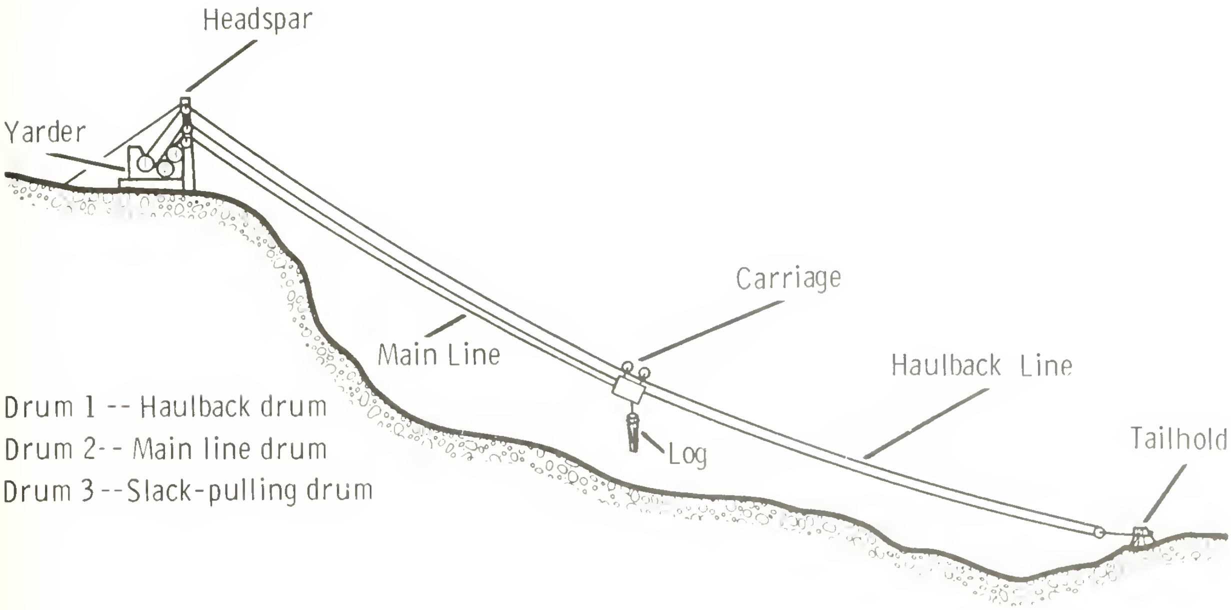


Figure 4.--Running skyline. Drums 1 and 2 on the yarder are interlocked for horsepower exchange during yarding operation, drum 3 operates the slack puller.

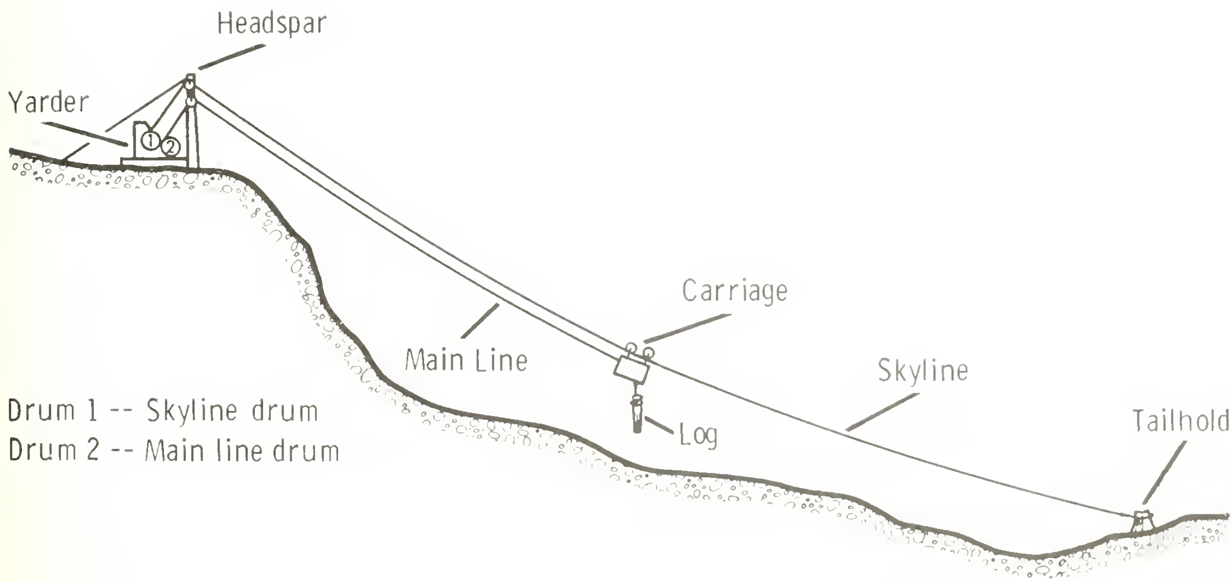


Figure 5.--Live skyline, gravity carriage. The skyline drum is powered so skyline tension can be varied during yarding operation.

LOADERS

Three different types of loaders were used in situations that were normally hot logging operations (hot logging means skidding, loading, and hauling are going on simultaneously). For the first setting (block 21), which was downhill logging in a shelterwood cut, a jammer or heel boom loader was used (fig. 6). For all other loading, either a long boom (fig. 7) or a rubber-tired, front-end (fig. 8) loader was used. All loaders loaded both logs and currently unmerchantable material designated for removal under the more intensive utilization standards.

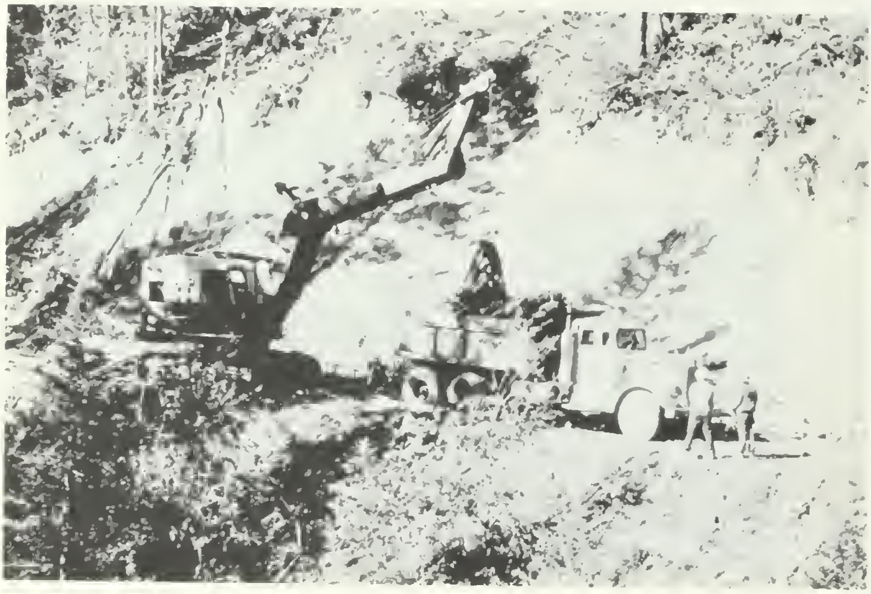


Figure 6.--Heel boom loading dump truck with residue from block 21.

Figure 7.--Long boom loader.

Figure 8.--Front-end loader working with Link Belt yarder keeping loading area clear on 14-foot (4.2 m) road without landings.

TRUCKS

Because of the large amount of currently nonmerchantable material that had to be removed to meet the previously discussed utilization standards, dump trucks were used for hauling this material. Conventional tractor-trailer units were used for the merchantable material.

Layout and Operation

The layout of blocks is shown in figure 1. Treatment units are numbered (1-4) and run perpendicular to the slope for clearcut and shelterwood blocks.

Planning logging sets and skyline roads is the key to successful operation of any cable logging system, particularly live or running skyline systems, which require deflection for suspension of the haulback line. In the generally uniform terrain (as seen by the contours in figure 1) of this logging chance, it was usually necessary to rig tail spar trees for deflection. The number and location of rigged tail spar trees are shown in table 2. Figure 9 shows a typical rigging, with nylon strap, block, and guylines. Only 14 of the 69 skyline sets did not require rigging to provide deflection.

Table 2.--*Number of trees rigged when additional deflection was needed*

Block	Direction yarded	No. of sets	No. of roads	No. of trees rigged	No. of roads withou[t] rigged tree[s]
11 (Selection cut)	up	7	10	9	1
	down	1	12	5	7
12 (Group selection cut)	up	6	6	6	0
	down	4	5	1	4
13 (Clearcut)	up	5	6	6	0
	--	--	--	--	--
21 (Selection cut)	up	5	10	9	1
	down	1	6	6	0
22 (Group selection cut)	up	4	6	5	1
	--	--	--	--	--
23 (Clearcut)	up	7	8	8	0
	--	--	--	--	--
Total	--	40	69	55	14

Figure 9.--Typical tail sp[ar] rigging with nylon stra[p], block, and guylines.

For this study, the position of each skyline set was located cooperatively by the logger and research personnel. Potential sets were located on the topographic map and then investigated in the field. A field crew of two was trained to run levels from the set (road) to a suitable spar tree. A profile was then plotted to show the deflection needed to operate the set. A tree was rigged at the height necessary to provide the deflection. This step was done well ahead of the logging crew.

Topping of spar trees was deemed essential primarily for safety because of the risk of branches and dead tops shaking loose and dropping to the ground. Also, in the event of tail spar failure, the "radius of danger" would be less. Initially, topping was performed using about 60 sticks of dynamite with a Primacord belt wrapped around an 18- to 24-inch (45.7 to 56.9 cm) diameter tree. An improved technique was developed that utilized six or seven pouches of a liquid/powder mixture with holes through each pouch using Primacord like a string of beads. The belt of explosives was installed at the point of topping by a rigger who would climb the tree with conventional pole climbing apparatus and lower a rope to raise the belt of explosives. Then a length of Primacord sufficient to reach the ground was tied to the belt. Finally a detonating cap and a length of fuse were attached to the end of the Primacord that reached the ground. The fuse was of sufficient length to allow all personnel to walk several hundred feet from the impending blast. Before igniting the fuse, the yarder operator was contacted by radio, and he activated his whistle-signaling device to warn everyone in the area of the blast.

The explosion caused a relatively clean, horizontal severance, with a zone of crushing and ring separation extending no greater than about 12 inches (30.5 cm) from the cut.

All skyline roads were held to a maximum width of 10 ft (3.05 m) in the shelterwood blocks, and in leave strips between group selection blocks, to reduce visual impacts.

Logging for the most part was conducted as a hot logging operation. Landings were usually not available, with the exception of the downhill yarding in blocks 11, 12, and 21. Downhill yarding from blocks 11 and 12 was to open, near-level areas seen from the contours in figure 1. A stretch of wide road between the yarder and block 21 was used as a landing (fig. 3) for downhill yarding in that block. A typical set yarding to the road is seen in figure 4. This photograph illustrates why the yarders were required to have swing capability so they could land the logs on the road.

The yarding crews consisted of the operator, two choker setters, a knot bumper-chaser, and a side foreman, who supervised both yarding crews. The loading and hauling operations were required to keep logs clear of the yarder. Merchantable material and unmerchantable were separated at the landing by the loaders or loaded directly to the truck, depending on the situation at the yarder and availability of the trucks. The usual situation was trucks waiting for loads.

Logging by Utilization Prescription

Recall that the primary purpose of the study was to determine the economic and environmental impacts of different levels of utilization under alternative silvicultural practices. Previous studies had indicated that it may be possible to utilize sawtimber trees down to 3-inch (7.6 cm) diameters in lengths of at least 8 feet (2.4 m); i.e., treatment 3. Treatments 4 and 2 are respectively more and less intensive than 3 to adequately identify feasibility limits.

Conventional sawlog (1).--In this treatment, the logs were yarded in a conventional manner with the limbs and top removed. The slash was disposed of by broadcast burning.

Close log utilization (2, 3).--All of the material was yarded to meet the utilization prescriptions as defined in table 1.

Close fiber utilization (4).--In treatment 4, trees were yarded as whole trees (or as nearly so as possible) and the merchantable logs removed in the conventional manner. Limbing and topping was accomplished on the landing.

One operation in treatment 4 was unique to this study. The understory trees designated for removal (1 to 5 inches [2.54 to 12.7 cm]), were cut and bundled by research crews prior to any logging activity, and subsequently yarded by the contractor. Rope was used to make a bundle the size a choker could handle--about 3 ft (0.9 m) in diameter and tree length long. A choker was put around the bundle for yarding. Handling the understory material in this manner was the only practical way to achieve intensive fiber recovery because it is not economically feasible to yard very small pieces individually.

In systems other than clearcutting, it can be difficult to yard material laterally. Before logging began, it was thought that yarding downhill in selectively cut blocks could cause serious problems because the load would have to be turned downhill in a fairly narrow corridor when it reached the skyline road. However, this did not prove to be as difficult as anticipated.

TIMBER VOLUMES LOGGED

Preharvest inventory of all material was at a more intensive level than for ordinary sales because a good estimate of the total biomass was desired for estimating potential removals. All harvested and removed material was also measured at the landing except solid volumes for bundled material from treatment 4 that were estimated. Table 3 shows inventoried and removed volumes by block and treatment. Removals in treatment 4 for blocks 21 and 22 exceed inventoried estimates. Since removal measurements represent a 100 percent sample, it is believed they are more accurate. Inventoried merchantable volumes per acre in treatments varied from approximately 2,050 ft^3/acre (140 m^3/ha) (8,660 bd.ft./acre) to over 6,000 ft^3/acre (420 m^3/ha) (25,980 bd.ft./acre). From a total volume of fiber removed of 405,879 ft^3 (11 494 m^3), 298,455 ft^3 (8 452 m^3) (1,292,310 bd.ft.) was merchantable or 74 percent.

HARVESTING PRODUCTIVITY

The differences in timber composition, size, and density among blocks allows for productivity comparisons only between treatments within blocks. Therefore, conclusions about productivity differences between silvicultural prescriptions should not be attempted. Also, the differences in landing conditions along with the above tend to confound differences between uphill and downhill yarding production.

Table 5.--*Preharvest and* [illegible]

Block/treatment		Acres	Volume: Preharvest	Volume: Removal	Percent removal
	11-1	14.9	98,027	21,4[illegible]	[illegible]
	-2	6.2	37,321	17,368	47.[illegible]
	-3	6.7	17,603	17,51[illegible]	56.9
	-4	7.3	18,851	18,551	99.0
Subtotal		35.1	231,808	104,762	45.2
	12-1	2.3	14,823	6,557	44.1
	-2	1.7	16,232	8,668	53.4
	-3	1.7	14,341	10,407	72.6
	-4	1.9	18,344	16,241	86.5
Subtotal		7.6	63,740	41,856	65.7
	13-1	3.8	26,325	11,668	35.7
	-2	3.2	24,333	18,481	76.0
	-3	2.9	26,248	9,676	36.9
	-4	3.7	26,366	14,975	56.1
Subtotal		13.6	103,272	57,800	56.0
	21-1	4.8	31,834	12,539	39.4
	-2	4.6	25,056	19,554	78.0
	-3	6.7	42,572	30,946	72.7
	-4	5.4	26,881	29,572	110.0
Subtotal		21.5	126,343	92,611	73.3
	22-1	1.3	14,104	7,710	53.5
	-2	1.5	14,193	8,231	56.8
	-3	1.6	17,029	12,564	73.8
	-4	1.6	11,562	11,818	102.2
Subtotal		6.0	57,488	40,323	70.1
	23-1	3.4	34,476	11,343	32.9
	-2	3.4	25,711	8,721	33.9
	-3	5.1	39,414	26,738	54.1
	-4	4.7	32,002	21,740	67.9
Subtotal		16.6	131,603	68,542	52.1
Total		100.4	714,254	405,879	56.8

Tables 4, 5, and 6 summarize data related to each silvicultural system, including acreage, volumes, layout and equipment, and average yarding production by equipment type, treatment, and direction of yarding. The mean, standard deviation, and standard error by block and direction of yarding for pieces per turn, turns per hour, and pieces per hour are summarized in appendix B (table 9).

Productivity data were derived from time and motion studies. These studies extended over the entire duration of the logging, covering over 7,200 turns made by the running and live skyline systems.

Table 4.--*Skyline yarding summary--shelterwood units*

LOGGING UNITS

Block number	Block size		Total volume		Number pieces	Average piece size	
	Acres	*ha*	*Ft*^{3}	*m*^{3}		*Ft*^{3}	*m*^{3}
11	35.1	14.2	104,762	2 967	7,471	14.02	0.397
21	21.5	8.74	92,611	2 623	6,338	14.61	.414

YARDING LAYOUT

Block number	Number skyline roads		Yarding distance			
	Uphill	Downhill	Average		Range	
			Ft	*m*	*Ft*	*m*
11	10	12	508	155	0-1,050	0-320
21	10	6	557	170	25-1,150	8-350

EQUIPMENT

21 Yarding - Skagit GT-3 rigged as running skyline, yarding uphill and downhill
Loading - Both long boom and front end loader used at times
Hauling - 6.0 M bd.ft. truck and trailers for logs, and 10-yard dumps for residues

11 Yarding - Skagit GT-3 rigged as running skyline, yarding uphill and downhill
Link Belt 78 Log Mover rigged as a live skyline, yarding uphill
Loading - Same as Block 21
Hauling - Same as Block 21

AVERAGE PRODUCTION PER HOUR[1]

Treatment	System	Total volume	
		Ft^3	*m*^{3}
Conventional saw log (1)	Running skyline, uphill yarding	497	13.6
Close log, trees 7"+ (2)		358	10.1
Close log, trees 5"+ (3)		353	10.1
Close fiber (4)		568	16.1
Conventional saw log (1)	Running skyline, downhill yarding	644	18.2
Close log, trees 7"+ (2)		561	15.9
Close log, trees 5"+ (3)		615	17.4
Close fiber (4)		813	23.0
Close log, trees 7"+ (2)	Live skyline, uphill yarding	321	9.1
Close fiber (4)		747	21.2

[1]Production per hour includes foreign element delay time occurring within a turn cycle, but not nonproductive hours for rest breaks, repairs, rerigging, etc. Foreign element delays are those caused by machines, manpower, materials, or environmental factors.

Table 5.--*Skyline yarding summary--group selection unit*

LOGGING UNITS

Block number	Block size		Total volume		Number pieces	Average piece size	
	Acres	*ha*	*Ft*³	*m*³		*Ft*³	*m*³
12	7.60	3.04	41,856	1 185	2,670	15.65	0.11[illegible]
22	6.0	2.40	40,323	1 142	2,585	15.60	.11[illegible]

YARDING LAYOUT

Block number	Number skyline roads		Yarding distance			
	Uphill	Downhill	Average		Range	
			Ft	*m*	*Ft*	*m*
12	6	5	322	98	50-760	15-232
22	6	0	524	160	0-1,250	0-381

EQUIPMENT

12 Yarding - Skagit GT-3 rigged as running skyline and yarding downhill only
Link Belt 78 Log Mover rigged as a live skyline and yarding uphill
Loading - Both long boom and front end loader used at times
Hauling - 6.0 M bd.ft. truck and trailers for logs, and 10 yard dumps for residues

22 Yarding - Skagit GT-3 rigged as running skyline and yarding uphill only
Link Belt 78 Log Mover rigged as a live skyline and yarding uphill
Loading - Same as Block 12
Hauling - Same as Block 12

AVERAGE PRODUCTION PER HOUR[1]

Treatment	System	Total volume	
		*Ft*³	*m*³
Conventional saw log (1)	Running skyline, uphill yarding	500	14.2
Close log, trees 7"+ (2)		590	16.7
Close log, trees 5"+ (3)		590	16.7
Close fiber (4)		490	13.9
Conventional saw log (1)	Running skyline, downhill yarding	826	23.4
Close log, trees 7"+ (2)		815	23.1
Close log, trees 5"+ (3)		815	23.1
Close fiber (4)		1,047	29.7
Conventional saw log (1)	Live skyline, uphill yarding	511	14.5
Close log, trees 7"+ (2)		469	13.3
Close log, trees 5"+ (3)		605	17.1
Close fiber (4)		816	23.1

[1]See table 4 footnote.

Table 6.--*Skyline yarding summary--clearcut units*

LOGGING UNITS

Block number	Block size		Total volume		Number pieces	Average piece size	
	Acres	*ha*	*Ft*^{3}	*m*^{3}		*Ft*^{3}	*m*^{3}
13	13.60	5.44	57,800	1 637	3,906	14.80	0.419
23	16.6	6.64	68,542	1 941	5,201	13.18	.373

YARDING LAYOUT

Block number	Number skyline roads		Yarding distance			
	Uphill	Downhill	Average		Range	
			Ft	*m*	*Ft*	*m*
13	6	0	478	146	50-900	15-274
23	8	0	488	149	0-950	0-290

EQUIPMENT

13 Yarding - Skagit GT-3 rigged as a running skyline and yarding uphill only
Loading - Both long boom and front end loader used at times
Hauling - 6.0 M bd.ft. truck and trailers for logs and 10 yard dumps for residues

23 Yarding - Link Belt 78 Log Mover rigged as a live skyline and yarding uph
Loading - Same as Block 13
Hauling - Same as Block 13

AVERAGE PRODUCTION PER HOUR[1]

Treatment	System	Total volume	
		Ft^3	*m*^{3}
Conventional saw log (1)	Running skyline, uphill yarding	989	28.0
Close log, trees 7"+ (2)		622	17.6
Close log, trees 5"+ (3)		850	24.1
Close fiber (4)		583	16.5
Conventional saw log (1)	Live skyline, uphill yarding	930	26.4
Close log, trees 7"+ (2)		503	14.2
Close log, trees 5"+ (3)		632	17.9
Close fiber (4)		595	16.8

[1]See table 4 footnote.

Felling and Bucking

Time and motion studies did not include felling and [illegible]. [illegible] and cost were estimated for the sale, using Northern Region timber [illegible]. The base cost adjusted for average d.b.h., trees/acre, slope, and [illegible] was [illegible] bd.ft. ($2.62/m³) (1974). This cost was assumed to be applicable to [illegible] cut under conventional saw log specification, or treatment 1. It was adjusted [illegible] the requirements of the other treatments as follows:

+32.5 percent for cutting 5- to 7-inch (12.7 to 17.8 cm) d.b.h. in treatment [illegible].
+50.0 percent to avoid damaging residual in shelterwood units.
+50.0 percent to avoid damage to adjoining stands near group selection units.
+10.0 percent for limbing to 3-inch (7.6 cm) top in treatments 2 and [illegible].

It was assumed that production, and therefore cost, would be equal to Regional averages, with the above added for special treatment requirements.

Comparing observed sawyer production with estimated production shows a slight overestimation in some treatments and underestimation in others, with similar average 0.79 M bd.ft./h (3.58 m³/h) observed production rate vs. 0.87 M bd.ft./h (3.91 m³/h) estimated production rate (table 10 in appendix B).

Yarding

The greatest productivity for total solid volumes was from group selection units using a running skyline logging downhill--1,047 ft³ (29.6 m³) per hour in treatment 4. The least productive logging was in running skyline units logging uphill in shelterwood blocks--productivity was 353 ft³ (10.0 m³) in treatment 3. Factors affecting productivity are discussed in detail in the next section.

<u>Nonproductive time--yarding</u>.--The percentage of total yarding time actually spent yarding was estimated for each block from data recorded by research personnel (table 11, appendix B). These times could be expected to vary between organizations.

Loading

Time and motion studies were not made for the loading operation. However, a record was kept of the number and type of trucks loaded each day. In table 12 (appendix B) the mean, standard deviation, and standard error for trucks loaded per day are shown for each operation.

Waiting and loading times for log and dump trucks were recorded for a sample of logging sets as shown in table 7.

Hauling

Hauling distance for the dump trucks was approximately 7.5 miles (12.1 km) to the disposal area--an average of 1 mile (1.6 km) on the new road and 6.5 miles (10.1 km) of single-lane, unsurfaced road with turnouts (No. 590). Hauling distance for the logs to the Columbia Falls, Mont., mill consisted of approximately 1 mile (1.6 km) on the new road, 5.8 miles (9.3 km) of single-lane, unsurfaced road with turnouts, 1.5 miles (2.4 km) of lane and one-half [20 ft (6.1 m)] gravel surfaced, and 10 miles (16.1 km) of paved, double-lane (U.S. No. 2) for a total of 17.3 miles (27.8 km). A tabulation of transport mileages for logs and residue and estimated average speed and hours of travel one way is shown in table 8.

Table 7.--*Waiting and loading times for log and dump trucks (in hours)*

Statistic	Log trucks		Unmerchantable trucks	
	Waiting	Loading	Waiting	Loading
n	32	32	32	32
$\bar{x}$	2.43	1.89	1.05	0.86
Sx	1.56	1.18	1.31	1.24

n = number of observations.

$\bar{x}$ = mean waiting or loading time.

Sx = standard error of the mean.

Table 8.--*Transport distances and times for merchantable and residue material*

Road section	Distance		Average speed		Hour
	Miles	*km*	*Mi/h*	*km/h*	
			Residue		
New section 590B	1.0	1.6	15	24.1	0.06
Old section 590B	6.5	10.4	17	27.4	.38
				Total	0.44
			Logs		
New section 590B	1.0	1.6	15	24.1	.06
Old section 590B	5.8	9.3	17	27.4	.34
Country road	1.5	2.4	24	38.6	.34
U.S. No. 2	10.0	6.1	50	80.4	.20
				Total	0.67

Nonproductive time is not included.

FACTORS AFFECTING PRODUCTIVITY

In this study, the principal variables influencing yarding were distance, lateral distance, slope, volume, number of logs, and weight in various combinations, depending on the equipment and silvicultural prescription.

The principal variables influencing the production of logging systems and equipment are fairly well known from studies conducted over the years. However, the relative influence of some variables is still being debated by researchers. Therefore, all of the variables thought to be potentially significant for influencing production were recorded using a standardized methodology developed over the past several years by Intermountain Station's Engineering Research Work Unit at Bozeman, Mont.

The final equations for logging production were selected on the basis of the simultaneous consideration of the following criteria discussed in more detail by Gibson (1975).

1. R^2 or percent of variation explained by the equation.
2. F-ratio for significance of the regression.
3. Standard error of the independent variable (expressed as a percentage of the mean).
4. Analysis of residual plots.
5. Subjective consideration of information available to those who may use the equations for predicting production.

The principal variables retained for each equation as a result of the above criteria are shown in table 13 (appendix B). Also table 14 (appendix B) shows the significance of the variables. Distance was the major variable influencing production in every case. Lateral distance appears in every equation except for the live skyline in shelterwood units. All equations are for the conventional logging utilization treatments (1).

ESTIMATING TURN TIME AND PRODUCTIVITY

Harvesting productivity in general, and for the Coram sale in particular, was discussed under harvesting productivity (tables 4, 5, and 6). These statistics are useful for comparing production for different utilization standards, and equipment types used on the sale. They show what could be expected at other locations with conditions similar to those at Coram, but what about other areas and situations?

Regression equations (appendix B, table 13) can be used to estimate production when information is available about the independent variables. Most of this information is available whenever a sale is prepared or can be derived from timber surveys and topographic maps.

To facilitate the use of the regression equations and foreign element delay times derived from the study, tables 15 through 23 in appendix B were prepared. They can be used to estimate turn time computed from each equation in table 13, appendix B.

To illustrate how productivity can be estimated, the following examples are presented.

Computation of Turn Time and Productivity for Assumed Yarding Conditions (all tables used are in appendix B)

Case 1: Running skyline, shelterwood cut, uphill yarding
--Average yarding distance--500 feet (152 m)
--Average lateral yarding distance--60 feet (18.3 m)
--Average number of logs--4.0
--Average weight of load--2,800 lb (1,270 kg)
--Average piece size--14 ft^3 (0.33 m^3)

Estimating Turn Time (T.T.)

from table 15:

Matrix A, factor = 5.87 (extrapolated)
Matrix B, factor = 1.027
T.T. = 5.87 x 1.027 = 6.03 min

from table 22: Percent foreign element = 14.4

T.T. = 6.03 x 1.144 = 6.72

Estimating Productivity

Turn time = 6.72

from table 23:

4.0 logs, 14 ft^3 (0.33 m^3) piece size
V = 501 ft^3/h (14.2 m^3/h) (extrapolated)

(These are productive hours for all estimates.)

Case 2: Live skyline, clearcut, uphill yarding
--Average yarding distance--400 feet (122 m)
--Average lateral yarding distance--90 feet (27.4 m)
--Average number of logs--5.0
--Average slope--60 percent
--Average piece size--12 ft^3 (0.29 m^3)

Estimating Turn Time (T.T.)

from table 21:

Matrix A, factor = 10.16 (extrapolated)
Matrix B, factor = 0.612
T.T. = 10.16 x 0.612 = 6.22

from table 22: Percent foreign element = 10.8

T.T. = 6.22 x 1.108 = 6.89

Estimating Productivity

Turn Time = 6.89

from table 23:

5.0 logs, 12 ft^3 (0.29 m^3) piece size
V = 512 ft^3/hr (14.5 m^3/hr) (extrapolated)

(These are productive hours for all estimates.)

SUMMARY AND CONCLUSIONS

For shelterwood and group selection units, the cubic foot volume of material removed per hour was greatest in treatment 4, as would probably have been expected. However, cubic foot volume removed per hour in clearcut units was greatest in treatment 3 (conventional logging). Production per hour was generally greater for all treatments in clearcut units. This may have been due to greater ease of lateral skidding.

The important measured variables influencing turn cycles, and therefore production, were (1) distance, (2) lateral distance, (3) slope, (4) number of logs, (5) volume, and (6) weight. In table 14 (appendix B), the relative importance of these variables for each harvesting situation is shown by their contribution to the correlation coefficient (R^2). *Distance* was the most important variable in every case, and *lateral distance* appears in every equation. *Number of logs* appears in every equation except the running skyline yarding uphill in a shelterwood cut. If information is available for these three variables, a reasonably good estimate of production is possible.

The room to maneuver yarders, trucks, and loaders on this sale was rather restricted because of the 14-foot (4.3 m), single-lane road, few turnouts, and no planned landings. In fact, landing construction was prohibited. However, turnouts could be used effectively as could the relatively flat areas below blocks 11 and 12. These landing areas in blocks 11 and 12 were undoubtedly partly responsible for the greater production experienced from downhill yarding in these blocks.

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APPENDIX A--YARDER SPECIFICATIONS

GENERAL YARDER SPECIFICATIONS

Skagit GT-3

Dimensions: Boom Height - 38' 6" (11.7 m)
Working Height - 44' (13.4 m)
Overall Width - 12' 6" (3.8 m)
Ground Clearance - 1' 4" (0.4 m)

Drum Capacity:

Mains - 1,700' (518 m) - 5/8" (1.6 cm) dia. cable
1,100' (335 m) - 3/4" (1.9 cm) dia. cable

Haulback - 2,400' (732 m) - 3/4" (1.9 cm) dia. cable
2,600' (792 m) - 3/8" (1.0 cm) dia. cable

Guyline - 109' (33.2 m) - 1" (2.54 cm) dia. cable

Power Unit - Cummings NH 220 with Allison Torque Converter

Shipping Weight - 95,040 lb (43,110 kg)

Link Belt HC-78B

Dimensions: Boom Height - 35' 0" (10.7 m)
Working Height - 41' 5" (12.6 m)
Overall Width - 9' 0" (2.7 m)
Minimum Ground Clearance - 0' 10" (2.1 cm)

Drum Capacity:

Skyline - 1,100' (335 m) - 5/8" (1.6 cm) dia. cable

Mainline - 1,300' (396 m) - 1/2" (1.3 cm) dia. cable

Power Unit - General Motors 6V-53

Shipping Weight - 68,775 lb (29,958 kg)

APPENDIX B--PRODUCTIVITY AND STATISTICAL ANALYSIS

Table 9.--*Mean, standard deviation, and standard error for pieces per turn, turns per hour, and pieces per hour*

Block[1/]	Pieces/turn			Turns/hour			Pieces/hour		
	$\bar{x}$[2/]	Sx	S$\bar{x}$	$\bar{x}$	Sx	S$\bar{x}$	$\bar{x}$	Sx	S$\bar{x}$
				SKAGIT					
21D(S)	2.39	0.63	0.18	10.64	2.96	0.86	25.58	10.30	2.97
11D(S)	4.37	.59	.13	10.89	2.90	.63	47.09	11.17	2.44
21U(S)	3.63	.56	.16	8.82	3.25	.60	35.42	13.15	2.44
11U(S)	3.89	.55	.16	9.13	2.40	.62	34.37	11.67	3.01
22U(GS)	4.74	.74	.21	6.72	2.63	.73	31.79	13.22	3.67
12D(GS)	5.16	.84	.25	11.23	2.17	.65	57.98	14.63	4.41
13U(C)	4.47	.61	.14	9.73	1.65	.39	42.40	7.49	1.77
ALL	4.14	1.02	--	10.12	6.84	--	39.14	14.48	--
				LINK BELT					
22(GS)	4.60	1.52	.76	7.82	2.27	1.36	38.40	22.35	11.17
12(GS)	4.60	.44	.17	9.39	1.24	.44	43.46	6.61	2.70
11(S)	4.96	.65	.19	7.74	1.97	.57	36.60	10.65	3.08
23(C)	4.89	.96	.19	8.43	2.13	.43	45.71	19.44	5.39
ALL	4.84	.87	--	8.19	2.04	--	38.54	13.96	--

1/ D = downhill yarding, U = uphill yarding, S = shelterwood, GS = group selection, C = clearcut.
2/ $\bar{x}$ = mean, Sx = standard deviation, S$\bar{x}$ = standard error of the mean.

Table 10.--*Falling statistics*

Treatment and silvicultural cut	Observed production rate		Estimated production rate based on cost	
	h/M bd.ft.	*(h/m³)*	*h/M bd.ft.*	*(h/m³)*
1/ 1 - CC	0.58	(0.13)	0.58	(0.13)
1 - GS	.69	(0.15)	.87	(0.19)
1 - SW	.93	(0.21)	.87	(0.19)
4 - CC	.59	(0.13)	.77	(0.17)
4 - GS	.60	(0.13)	1.06	(0.23)
4 - SW	1.01	(0.22)	1.06	(0.23)
3 - CC	.68	(0.15)	.82	(0.18)
3 - GS	.74	(0.16)	1.11	(0.24)
3 - SW	1.15	(0.25)	1.11	(0.24)
2 - CC	.72	(0.16)	.64	(0.14)
2 - GS	.81	(0.18)	.93	(0.21)
2 - SW	1.21	(0.27)	.93	(0.21)
Average	.79	(0.17)	.87	(0.19)

1/ Basis for estimates.

Table 11.--*Estimates of productive hours*

Block	Percentage of total yarding time actually spent yarding
11	0.66
12	.70
13	.79
21	.67
22	.59
23	.65
Average	0.67

Table 12.--*Loading statistics for each operation*

SKAGIT

Trucks loaded per day

Loader	$\bar{x}$	Sx	$S\bar{x}$
Long boom	5.00	2.85	0.49
Front end	3.20	1.57	.40

Trucks loaded per day by class

Truck	$\bar{x}$	Sx	$S\bar{x}$
Logs-trailer	2.35	1.56	0.18
Residue-dump	3.19	2.29	.31

LINK BELT

Trucks loaded per day

Loader	$\bar{x}$	Sx	$S\bar{x}$
Long boom	3.79	1.44	0.33
Front end	4.44	2.50	.59

Trucks loaded per day by class

Truck	$\bar{x}$	Sx	$S\bar{x}$
Logs-trailer	2.21	1.10	0.21
Residue-dump	3.23	1.78	.33

Table 13.--*Regression equations*[1] *(equations apply to utilization level 1)*

Running, Shelterwood, Uphill

LN(TT) = 1.458050
+ (.001)(0.486540) Distance
+ .001145 Lateral Distance
+ (.001)(0.00896) Weight

Running, Shelterwood, Downhill

LN(TT) = 0.676830
+ .000240 (No. Logs)(Lateral Distance)
+ .132343 LN (Distance) - 0.000032 (Slope)(Volume)

Running, Group Selection, Uphill

LN(TT) = 0.580136
- .003076 (Slope)
+ .001928 (Lateral Distance) + 0,191832 LN (Distance)
+ (.00001)(0.400174)(No. Logs)(Weight)

Running, Group Selection, Downhill

LN(TT) = 0.689134
+ .002647 (Lateral Distance)
+ .337807 LN (Distance)
+ (.353655)(0.00001)(No. Logs)(Weight)

Running, Clearcut, Uphill

LN(TT) = 1.089454
+ .019567 (No. Logs) + 0.001065 (Distance)
+ .000617 (Volume) - (0.001)(0.000545)(Distance)
+ .000043 (Lateral Distance)(Slope)

Live, Group Selection, Uphill

LN(TT) = 1.812551
+ .000940 Distance
- .00950 Slope + 0.001721 Lateral Distance
+ (.00001)(0.277323)(No. Logs)(Weight)

Live, Clearcut, Uphill

LN(TT) = 1.910023
+ .000545 Distance
- .006795 Slope + 0.002118 Lateral Distance
- .4162 $(\text{No. Logs})^{-1}$

[1] LN = natural log. TT = Turn time.

Table 14.--*Independent variables and their contributions to* R^2 *for each regression equation (equations apply to utilization level 1)*

Harvesting situation, regression equation	Dependent variable	Independent variable and contribution to R^2		R^2 for equation
		Variable	Contribution to R^2	
Running Skyline, Shelterwood, Uphill	[1] LN(TT)	Distance	0.2957	0.34
		Lateral Distance	.0135	
		Weight	.0047	
Running Skyline, Shelterwood, Downhill	LN(TT)	LN (Distance)	.2134	.44
		(Slope) (Volume) (-)	.0353	
		(No. Logs) (Lateral Distance)	.0257	
Running Skyline, Group Selection, Uphill	LN(TT)	LN (Distance)	.3787	.68
		Lateral Distance	.0375	
		(No. Logs) (Weight)	.0348	
		Slope	.0121	
Running Skyline, Group Selection, Downhill	LN(TT)	LN (Distance)	.1039	.32
		Lateral Distance	.0715	
		(No. Logs) (Weight)	.0261	
Running Skyline, Clearcut, Uphill	LN(TT)	Distance	.2176	.48
		(Lateral Distance) (Slope)	.0478	
		Volume	.0252	
		$(\text{Distance})^2$ (-)	.0222	
		No. Logs	.0160	
Live Skyline, Group Selection, Uphill	LN(TT)	Distance	.2578	.42
		Lateral Distance	.0276	
		Slope (-)	.0270	
		(No. Logs) (Weight)	.0112	
	LN(TT)	Distance	.2660	.41
		$(\text{No. Logs})^{-1}$ (-)	.0476	
		Lateral Distance	.0294	
		Slope (-)	.0208	

[1] LN = natural log. TT = turn time.

Table 15.--*Turn time prediction factors, running, shelterwood, uphill*

Matrix A

Lateral distance ft (m)

Skyline distance ft (m)	0	10 (3.0)	20 (6.1)	30 (9.1)	40 (12.2)	50 (15.2)	60 (18.3)	70 (21.3)	80 (24.4)	90 (27.4)	100 (30.5)
25 (7.6)	4.350	4.400	4.451	4.502	4.554	4.606	4.660	4.713	4.767	4.822	4.878
125 (38.1)	4.567	4.620	4.673	4.727	4.781	4.836	4.892	4.948	5.005	5.063	5.121
225 (68.6)	4.795	4.850	4.906	4.962	5.019	5.077	5.136	5.195	5.255	5.315	5.376
325 (99.1)	5.034	5.092	5.150	5.210	5.270	5.330	5.392	5.454	5.517	5.580	5.644
425 (130.0)	5.285	5.346	5.407	5.469	5.532	5.596	5.661	5.726	5.792	5.858	5.926
525 (160.0)	5.548	5.612	5.677	5.742	5.808	5.875	5.943	6.011	6.080	6.150	6.221
625 (190.0)	5.825	5.892	5.960	6.028	6.098	6.168	6.239	6.311	6.384	6.457	6.531
725 (221.0)	6.115	6.186	6.257	6.329	6.402	6.476	6.550	6.626	6.702	6.779	6.857
825 (252.0)	6.420	6.494	6.569	6.645	6.721	6.798	6.877	6.956	7.036	7.117	7.199
925 (282.0)	6.740	6.818	6.896	6.976	7.056	7.137	7.220	7.303	7.387	7.472	7.558
1025 (312.0)	7.076	7.158	7.240	7.324	7.408	7.493	7.580	7.667	7.755	7.844	7.935
1125 (343.0)	7.429	7.515	7.601	7.689	7.777	7.867	7.957	8.049	8.142	8.236	8.330

Matrix B

Weight lb (kg)

30 (13.6)	1510 (685)	2990 (1356)	4470 (2028)	5950 (2699)	7430 (3370)	8910 (4042)	10390 (4713)	11870 (5384)	13350 (6056)	14830 (6729)
1.000	1.014	1.027	1.041	1.055	1.069	1.083	1.098	1.112	1.127	1.142

Table 16.--*Turn time prediction factors, running, shelterwood, downhill*

Matrix A

Lateral distance ft (m)

		0	10 (3.0)	20 (6.1)	30 (9.1)	40 (12.2)	50 (15.2)	60 (18.3)	70 (21.3)	80 (24.4)	90 (27.4)	100 (30.5)
Number of logs	1	1.968	1.972	1.977	1.982	1.987	1.991	1.996	2.001	2.006	2.011	2.015
	2	1.968	1.977	1.987	1.996	2.006	2.015	2.025	2.035	2.045	2.054	2.064
	3	1.968	1.982	1.996	2.011	2.025	2.040	2.054	2.069	2.084	2.099	2.115
	4	1.968	1.987	2.006	2.025	2.045	2.064	2.084	2.104	2.125	2.145	2.166
	5	1.968	1.991	2.015	2.040	2.064	2.089	2.115	2.140	2.166	2.192	2.218
	6	1.968	1.996	2.025	2.054	2.084	2.115	2.145	2.176	2.208	2.240	2.272
	7	1.968	2.001	2.035	2.069	2.104	2.140	2.176	2.213	2.251	2.289	2.328
	8	1.968	2.006	2.045	2.084	2.125	2.166	2.208	2.251	2.294	2.339	2.384
	9	1.968	2.011	2.054	2.099	2.145	2.192	2.240	2.289	2.339	2.390	2.442
	10	1.968	2.015	2.064	2.115	2.166	2.218	2.272	2.328	2.384	2.442	2.501

Matrix B

Volume bd.ft. (m^3)

		5 (0.02)	30 (0.14)	55 (0.25)	80 (0.36)	105 (0.48)	130 (0.59)	155 (0.70)	180 (0.82)	205 (0.93)	230 (1.04)	255 (1.16)
Slope (percent)	-30	1.005	1.029	1.054	1.080	1.106	1.133	1.160	1.189	1.218	1.247	1.277
	-25	1.004	1.024	1.045	1.066	1.088	1.110	1.132	1.155	1.178	1.202	1.226
	-20	1.003	1.019	1.036	1.053	1.070	1.087	1.104	1.122	1.140	1.159	1.177
	-15	1.002	1.015	1.027	1.039	1.052	1.064	1.077	1.090	1.103	1.117	1.130
	-10	1.002	1.010	1.018	1.026	1.034	1.042	1.051	1.059	1.068	1.076	1.085
	- 5	1.001	1.005	1.009	1.013	1.017	1.021	1.025	1.029	1.033	1.037	1.042
	0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	5	.999	.995	.991	.987	.983	.979	.976	.972	.968	.964	.960
	10	.998	.990	.983	.975	.967	.959	.952	.944	.937	.929	.922
	15	.998	.986	.974	.962	.951	.940	.928	.917	.906	.895	.885
	20	.997	.981	.965	.950	.935	.920	.906	.891	.877	.863	.849

Matrix C

Distance ft (m)

25 (7.6)	105 (32.0)	185 (56.4)	265 (80.8)	345 (105)	425 (130)	505 (154)	585 (178)	665 (204)	745 (227)	825 (251)
1.531	1.851	1.995	2.093	2.167	2.228	2.279	2.324	2.364	2.399	2.432

Table 17.--*Turn time prediction factors, running, group selection, uphill*

		Matrix A										
		Weight lb (kg)										
		200 (90.7)	1200 (544)	2200 (998)	3200 (1452)	4200 (1905)	5200 (2359)	6200 (2823)	7200 (3266)	8200 (3720)	9200 (4173)	10200 (4627)
	1	1.788	1.795	1.802	1.809	1.817	1.824	1.831	1.838	1.846	1.853	1.861
	2	1.789	1.804	1.818	1.833	1.847	1.862	1.877	1.892	1.907	1.923	1.938
	3	1.791	1.812	1.834	1.856	1.879	1.901	1.924	1.948	1.971	1.995	2.019
Number	4	1.792	1.821	1.850	1.880	1.910	1.941	1.973	2.004	2.037	2.070	2.103
of	5	1.793	1.830	1.867	1.904	1.943	1.982	2.022	2.063	2.105	2.147	2.191
logs	6	1.795	1.838	1.883	1.928	1.976	2.024	2.073	2.123	2.175	2.228	2.282
	7	1.796	1.847	1.900	1.954	2.009	2.066	2.125	2.185	2.248	2.311	2.377
	8	1.798	1.856	1.917	1.979	2.043	2.110	2.178	2.249	2.323	2.398	2.476
	9	1.799	1.865	1.934	2.004	2.078	2.154	2.233	2.315	2.400	2.488	2.579
	10	1.801	1.874	1.951	2.030	2.113	2.199	2.289	2.383	2.480	2.581	2.687
		Matrix B										
		Lateral Distance ft (m)										
		0	10 (3.0)	20 (6.1)	30 (9.1)	40 (12.2)	50 (15.2)	60 (18.3)	70 (21.3)	80 (24.4)	90 (27.4)	100 (30.5)
	22	.935	.953	.971	.990	1.009	1.029	1.049	1.070	1.090	1.112	1.133
	27	.920	.938	.956	.975	.994	1.013	1.033	1.053	1.074	1.095	1.116
	32	.906	.924	.942	.960	.979	.998	1.017	1.037	1.057	1.078	1.099
	37	.892	.910	.928	.946	.964	.983	1.002	1.021	1.041	1.062	1.082
Slope	42	.879	.896	.913	.931	.949	.968	.987	1.006	1.025	1.045	1.066
(per-	47	.865	.882	.899	.917	.935	.953	.972	.990	1.010	1.029	1.049
cent)	52	.852	.869	.886	.903	.921	.938	.957	.975	.994	1.014	1.033
	57	.839	.856	.872	.889	.906	.924	.942	.960	.979	.998	1.018
	62	.826	.842	.859	.876	.893	.910	.928	.946	.964	.983	1.002
	67	.814	.830	.846	.862	.879	.896	.914	.931	.949	.968	.987
	72	.801	.817	.833	.849	.866	.882	.900	.917	.935	.953	.972
		Matrix C										
		Distance ft (m)										
		50 (15.2)	170 (51.8)	290 (88.4)	410 (125)	530 (162)	650 (198)	770 (235)	890 (271)	1010 (308)	1130 (344)	1250 (381)
		2.118	2.678	2.967	3.171	3.331	3.464	3.579	3.679	3.770	3.852	3.927

Table 18.--*Turn time prediction factors, running, group selection, downhill*

Matrix A

Weight lb (kg)

		250 (113)	1150 (526)	2050 (930)	2950 (1338)	3850 (1746)	4750 (2155)	5650 (2563)	6550 (2971)	7450 (3379)	8350 (3788)	9250 (4196)
Number of logs	2	0.503	0.506	0.509	0.513	0.516	0.519	0.522	0.526	0.529	0.533	0.536
	3	.503	.508	.513	.518	.523	.528	.533	.538	.543	.549	.554
	4	.504	.510	.517	.523	.530	.537	.544	.551	.558	.565	.572
	5	.504	.512	.521	.529	.537	.546	.555	.564	.573	.582	.591
	6	.505	.514	.524	.534	.545	.555	.566	.577	.588	.599	.611
	7	.505	.517	.528	.540	.552	.565	.577	.590	.604	.617	.631
	8	.506	.519	.532	.546	.560	.574	.589	.604	.620	.636	.652
	9	.506	.521	.536	.551	.567	.584	.601	.618	.636	.655	.674
	10	.506	.523	.540	.557	.575	.594	.613	.633	.653	.674	.696
	11	.507	.525	.544	.563	.583	.604	.625	.648	.671	.695	.719

Matrix B

Distance ft (m)

		180 (54.9)	240 (73.2)	300 (91.4)	360 (110)	420 (128)	480 (146)	540 (165)	600 (183)	660 (201)	720 (219)	780 (238)
Lateral distance ft (m)	10 (3.0)	5.934	6.540	7.052	7.499	7.900	8.265	8.600	8.912	9.204	9.478	9.738
	20 (6.1)	6.093	6.715	7.241	7.701	8.112	8.487	8.831	9.151	9.450	9.732	9.999
	30 (9.1)	6.257	6.895	7.435	7.907	8.330	8.714	9.068	9.396	9.704	9.993	10.267
	40 (12.2)	6.424	7.080	7.634	8.119	8.553	8.948	9.311	9.649	9.964	10.261	10.543
	50 (15.2)	6.597	7.270	7.839	8.337	8.783	9.188	9.561	9.907	10.232	10.537	10.826
	60 (18.3)	6.774	7.465	8.049	8.561	9.018	9.434	9.817	10.173	10.506	10.819	11.116
	70 (21.3)	6.955	7.665	8.265	8.790	9.260	9.688	10.081	10.446	10.788	11.110	11.414
	80 (24.4)	7.142	7.871	8.487	9.026	9.509	9.947	10.351	10.726	11.077	11.408	11.720
	90 (27.4)	7.333	8.082	8.715	9.268	9.764	10.214	10.629	11.014	11.374	11.714	12.035
	100 (30.5)	7.530	8.299	8.948	9.517	10.026	10.488	10.914	11.309	11.679	12.028	12.357

Table 19.--*Turn time prediction factors, running, clearcut, uphill*

Matrix A

Volume bd.ft. (m^3)

Distance ft (m)	5 (0.02)	25 (0.11)	45 (0.20)	65 (0.29)	85 (0.38)	105 (0.48)	125 (0.57)	145 (0.66)	165 (0.75)	185 (0.84)	205 (0.93)
60 (18.3)	3.172	3.212	3.252	3.293	3.334	3.375	3.417	3.460	3.503	3.579	3.591
145 (44.2)	3.440	3.483	3.527	3.571	3.615	3.660	3.706	3.752	3.799	3.846	3.894
230 (70.1)	3.701	3.747	3.794	3.842	3.889	3.938	3.987	4.037	4.087	4.138	4.190
315 (96.0)	3.951	4.000	4.050	4.101	4.152	4.204	4.256	4.309	4.363	4.417	4.473
400 (122)	4.184	4.237	4.289	4.343	4.397	4.452	4.508	4.564	4.621	4.678	4.737
485 (148)	4.397	4.452	4.507	4.563	4.620	4.678	4.736	4.796	4.855	4.916	4.977
570 (174)	4.584	4.641	4.699	4.758	4.817	4.877	4.938	4.999	5.062	5.125	5.189
655 (200)	4.741	4.800	4.860	4.921	4.982	5.045	5.108	5.171	5.236	5.301	5.367
740 (226)	4.866	4.926	4.988	5.050	5.113	5.177	5.242	5.307	5.373	5.440	5.508
825 (251)	4.954	5.016	5.079	5.142	5.206	5.271	5.337	5.403	5.471	5.539	5.608
910 (277)	5.005	5.067	5.130	5.194	5.259	5.325	5.391	5.459	5.527	5.596	5.665

Matrix B

Lateral distance ft (m)

Slope (percent)	0	10 (3.0)	20 (6.1)	30 (9.1)	40 (12.2)	50 (15.2)	60 (18.3)	70 (21.3)	80 (24.4)	90 (27.4)	100 (30.5)
20	1.000	1.009	1.017	1.026	1.035	1.044	1.053	1.062	1.071	1.080	1.090
25	1.000	1.011	1.022	1.033	1.044	1.055	1.067	1.078	1.090	1.102	1.113
30	1.000	1.013	1.026	1.039	1.053	1.067	1.080	1.095	1.109	1.123	1.138
35	1.000	1.015	1.031	1.046	1.062	1.078	1.095	1.111	1.128	1.145	1.162
40	1.000	1.017	1.035	1.053	1.071	1.090	1.109	1.128	1.148	1.167	1.188
45	1.000	1.020	1.039	1.060	1.080	1.102	1.123	1.145	1.167	1.190	1.213
50	1.000	1.022	1.044	1.067	1.090	1.113	1.138	1.162	1.188	1.213	1.240
55	1.000	1.024	1.048	1.074	1.099	1.126	1.152	1.180	1.208	1.237	1.267
60	1.000	1.026	1.053	1.080	1.109	1.138	1.167	1.198	1.229	1.261	1.294

Matrix C

Number of logs

1	2	3	4	5	6	7	8	9	10
1.020	1.040	1.060	1.081	1.103	1.125	1.147	1.169	1.193	1.261

Table 20.--*Turn time prediction factors, live, group selection, uphill*

Matrix A

Lateral distance ft (m)

		0	10 (3.0)	20 (6.1)	30 (9.1)	40 (12.2)	50 (15.2)	60 (18.3)	70 (21.3)	80 (24.4)	90 (27.4)	100 (30.5)
Slope (percent)	40	4.189	4.262	4.336	4.411	4.488	4.566	4.645	4.726	4.808	4.891	4.976
	45	3.995	4.064	4.135	4.207	4.280	4.354	4.430	4.506	4.585	4.664	4.745
	50	3.810	3.876	3.943	4.012	4.081	4.152	4.224	4.297	4.372	4.448	4.525
	55	3.633	3.696	3.760	3.825	3.892	3.959	4.028	4.098	4.169	4.242	4.315
	60	3.464	3.525	3.586	3.648	3.711	3.776	3.841	3.908	3.976	4.045	4.115
	65	3.304	3.361	3.419	3.479	3.539	3.601	3.663	3.727	3.791	3.857	3.924
	70	3.150	3.205	3.261	3.317	3.375	3.434	3.493	3.554	3.615	3.678	3.742

Matrix B

Weight lb (kg)

		75 (34.0)	875 (397)	1675 (760)	2475 (1123)	3275 (1486)	4075 (1848)	4875 (2211)	5675 (2574)	6475 (2937)	7275 (3300)	8075 (3663)
Number of logs	1	1.000	1.002	1.005	1.007	1.009	1.011	1.014	1.016	1.018	1.020	1.023
	2	1.000	1.005	1.009	1.014	1.018	1.023	1.027	1.032	1.037	1.041	1.046
	3	1.001	1.007	1.014	1.021	1.028	1.034	1.041	1.048	1.055	1.062	1.069
	4	1.001	1.010	1.019	1.028	1.037	1.046	1.056	1.065	1.074	1.084	1.094
	5	1.001	1.012	1.023	1.035	1.046	1.058	1.070	1.082	1.094	1.106	1.118
	6	1.001	1.015	1.028	1.042	1.056	1.070	1.084	1.099	1.114	1.129	1.144
	7	1.001	1.017	1.033	1.049	1.066	1.082	1.099	1.116	1.134	1.152	1.170
	8	1.002	1.020	1.038	1.056	1.075	1.095	1.114	1.134	1.154	1.175	1.196
	9	1.002	1.022	1.043	1.064	1.085	1.107	1.129	1.152	1.175	1.199	1.223
	10	1.002	1.025	1.048	1.071	1.095	1.120	1.145	1.170	1.197	1.224	1.251
	11	1.002	1.027	1.052	1.078	1.105	1.132	1.160	1.189	1.218	1.248	1.279
	12	1.002	1.030	1.057	1.086	1.115	1.145	1.176	1.208	1.240	1.274	1.308

Matrix C

Distance ft (m)

50 (15.2)	125 (38.1)	200 (61.0)	275 (83.8)	350 (107)	425 (130)	500 (152)	575 (175)	650 (198)	725 (221)	800 (244)
1.048	1.125	1.207	1.295	1.390	1.491	1.600	1.717	1.842	1.977	2.121

Table 21.--*Turn time prediction factors, live, clearcut, uphill*

Matrix A

Distance ft (m)	Lateral distance ft (m): 0	10 (3.0)	20 (6.1)	30 (9.1)	40 (12.2)	50 (15.2)	60 (18.3)	70 (21.3)	80 (24.4)	90 (27.4)	100 (30.5)
10 (3.0)	6.790	6.935	7.084	7.236	7.390	7.549	7.710	7.875	8.044	8.216	8.392
90 (27.4)	7.093	7.245	7.400	7.558	7.720	7.885	8.054	8.226	8.402	8.582	8.766
170 (51.8)	7.409	7.567	7.729	7.895	8.064	8.236	8.413	8.593	8.777	8.965	9.157
250 (76.2)	7.739	7.905	8.074	8.247	8.423	8.604	8.788	8.976	9.168	9.364	9.565
330 (101)	8.084	8.257	8.434	8.614	8.799	8.987	9.179	9.376	9.577	9.781	9.991
410 (125)	8.444	8.625	8.810	8.998	9.191	9.387	9.588	9.794	10.003	10.217	10.436
490 (149)	8.820	9.009	9.202	9.399	9.600	9.806	10.016	10.230	10.449	10.637	10.901
570 (174)	9.214	9.411	9.612	9.818	10.028	10.243	10.462	10.686	10.915	11.148	11.387
650 (198)	9.624	9.830	10.041	10.255	10.475	10.699	10.928	11.162	11.401	11.645	11.894
730 (223)	10.053	10.268	10.488	10.713	10.942	11.176	11.415	11.660	11.908	12.164	12.425
810 (247)	10.501	10.726	10.955	11.190	11.429	11.674	11.924	12.179	12.440	12.706	12.978
890 (271)	10.969	11.204	11.444	11.689	11.939	12.194	12.455	12.722	12.994	13.272	13.557
970 (296)	11.458	11.703	11.954	12.209	12.471	12.738	13.010	13.289	13.573	13.864	14.161

Matrix B

Slope (percent)	Number of logs: 1	2	3	4	5	6	7	8	9	10
45	0.486	0.598	0.641	0.664	0.678	0.687	0.694	0.699	0.703	0.707
50	.470	.578	.620	.642	.655	.664	.671	.676	.680	.683
55	.454	.559	.599	.620	.633	.642	.648	.653	.657	.660
60	.439	.540	.579	.599	.612	.621	.627	.631	.635	.638
65	.424	.522	.560	.579	.592	.600	.606	.610	.614	.617
70	.410	.505	.541	.560	.572	.580	.586	.590	.593	.596

Table 22.--*Total foreign element statistics. (Foreign elements are delays attributed to machines, manpower, material, and environmental factors)*

System	Turns with foreign elements	Av. total foreign element time in turns with foreign elements	Av. foreign element time for all turns
	Percent	*Minutes*	*Percent*
Running Skyline Shelterwood Uphill	30.6	28.0	14.4
Running Skyline Shelterwood Downhill	27.7	3.8	23.7
Running Skyline Group Selection Uphill	40.7	2.5	26.3
Running Skyline Group Selection Downhill	14.7	2.2	6.4
Running Skyline Clearcut Uphill	15.7	3.0	8.2
Live Skyline Group Selection Uphill	20.0	11.0	27.8
Live Skyline Clearcut Uphill	19.6	3.2	10.8

Table [illegible]

[illegible] time (min)	[illegible] load						[illegible]					
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	960	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	750	900	1050	1200	1350	1500	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] (40.0)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	800	[illegible]	[illegible]	1200	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	600	720	840 (23.8)	960	1080 (30.6)	1200	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.	[illegible]	686	800	914	1029	1143 (32.4)	[illegible]	[illegible]	1000	1143	[illegible]	[illegible]
.4	[illegible]	[illegible]	764 (21.6)	(24.7)	[illegible]	1091	[illegible]	818	[illegible]	1091	[illegible]	[illegible]
[illegible]	[illegible]	626 (17.7)	730 (20.7)	[illegible]	[illegible]	1043	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	600	700	800	900	1000	[illegible]	750	[illegible]	1000	[illegible]	[illegible]
[illegible]	480 (13.6)	576 (16.3)	672 (19.0)	768	864 (24.5)	960	[illegible]	[illegible]	[illegible]	960	[illegible]	[illegible]
.	462 (13.1)	554	646	738 (20.9)	831 (23.5)	923	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.4	444 (12.6)	533	622	711 (20.1)	800 (22.6)	889	556	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.6	429 (12.1)	514 (14.6)	600 (17.0)	686 (19.4)	771 (21.8)	857	[illegible]	643 (18.3)	750	[illegible]	[illegible]	[illegible]
.8	414 (11.7)	497 (14.1)	579 (16.4)	662 (18.7)	745 (21.1)	828	517	621 (17.6)	[illegible]	[illegible]	[illegible]	[illegible]
6.0	400 (11.3)	480 (13.6)	560 (15.9)	640 (18.1)	720 (20.4)	800	500	600 (17.0)	700	800	900	1000
.2	387 (11.0)	464 (13.1)	542 (15.3)	619	697	774 (21.9)	484 (13.7)	581 (16.5)	677	774	871 (24.7)	968
.4	375 (10.6)	450 (12.7)	525 (14.9)	600 (17.0)	675 (19.1)	750 (21.2)	469 (13.3)	563	656 (18.6)	750	844	938 (26.6)
.6	364 (10.3)	436 (12.5)	509 (14.4)	582 (16.5)	655	727 (20.6)	455 (12.9)	545	636	727	818	909
.8	353 (10.0)	424 (12.0)	494 (14.0)	565 (16.0)	635	706 (20.0)	441 (12.5)	529 (15.0)	618	706	794	882
7.0	343 (9.7)	411 (11.6)	480 (13.6)	549 (15.5)	617 (17.5)	686 (19.4)	429 (12.1)	514 (14.6)	600 (17.0)	686	771	857
.2	333 (9.4)	400 (11.3)	467 (13.2)	533 (15.1)	600 (17.0)	667 (18.9)	417 (11.8)	500 (14.2)	583	667	[illegible]	[illegible]
.4	324 (9.2)	389 (11.0)	454 (12.9)	519 (14.7)	584 (16.5)	649 (18.4)	405 (11.5)	486 (13.8)	568 (16.1)	649	[illegible]	811
.6	316 (8.9)	379 (10.7)	442 (12.5)	505 (14.3)	568 (16.1)	632 (17.9)	395 (11.2)	474 (13.4)	553 (15.7)	632	711	789
.8	308 (8.7)	369 (10.5)	431 (12.2)	492 (13.9)	554 (15.7)	615 (17.4)	385 (10.9)	461 (13.1)	538	615	[illegible]	[illegible]
8.0	300 (8.5)	360 (10.2)	420 (11.9)	480 (13.6)	540 (15.3)	600 (17.0)	375 (10.6)	450 (12.7)	525	600	675 (19.1)	750

Gardner, Rulon B.
1980. Skyline logging productivity under alternative harvesting prescriptions and levels of utilization in larch-fir stands. USDA For. Serv. Res. Pap. INT-247, 35 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

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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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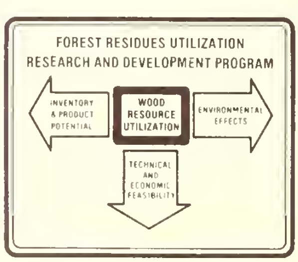

NEW FREEZING TECHNIQUE
OR SAMPLING SALMONID REDDS

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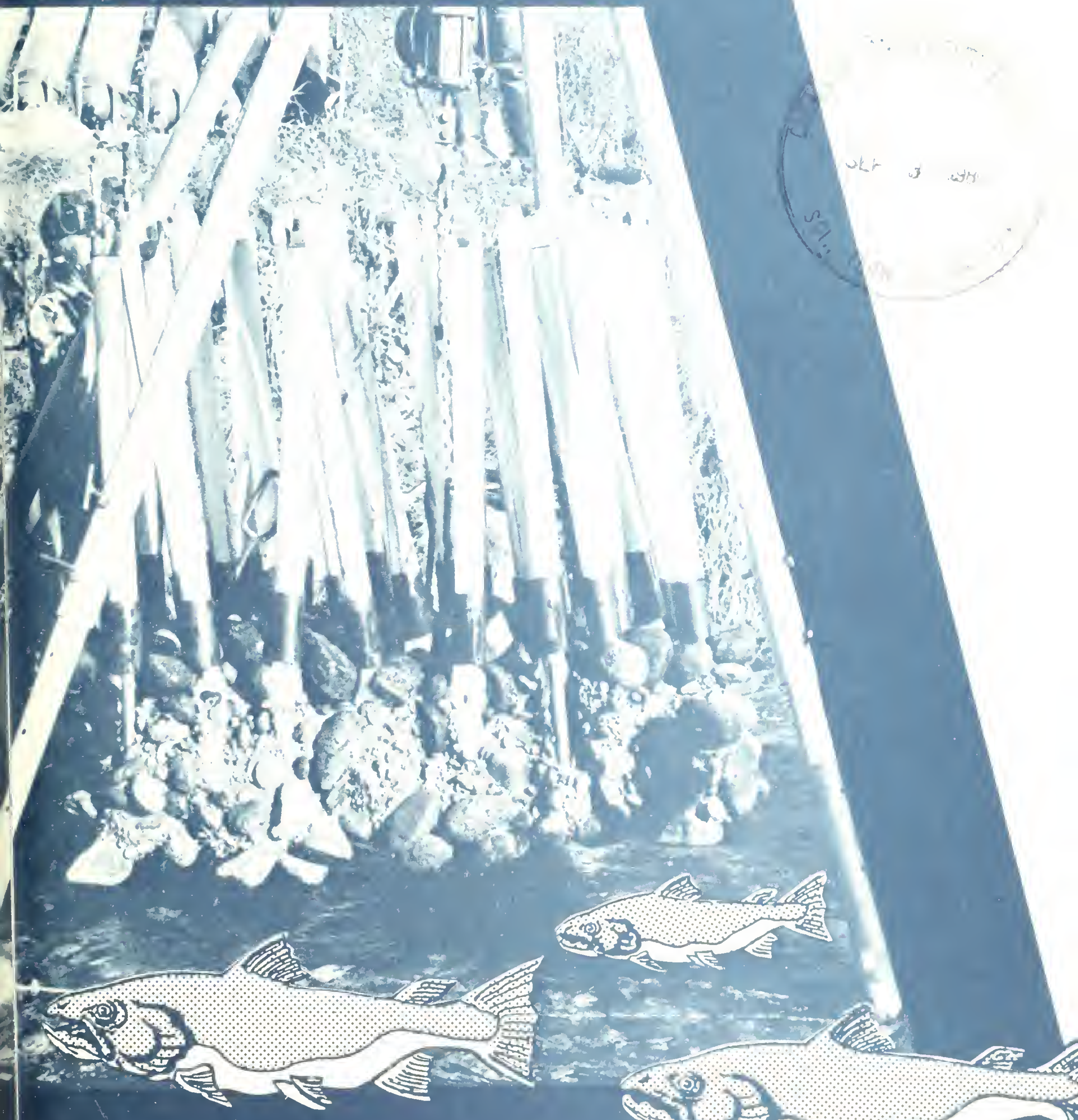

SDA FOREST SERVICE RESEARCH PAPER INT-248
TERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
OREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE

A NEW FREEZING TECHNIQUE FOR SAMPLING SALMONID REDDS

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RESEARCH SUMMARY

This report describes a new multiprobe freeze method for determining salmonid redd sediment particle size distribution. This method will collect salmonid eggs and alevins in the redd at any stage of development, any air or water temperature, any stream depth, and determine their horizontal and vertical location. This method allows larger size samples to be collected which can help improve our understanding of embryo and alevin survival rates and causes of their mortality.

This substrate freeze method differs from the past freeze methods that expanded CO_2 liquid to atmospheric pressure. This method expands CO_2 to a pressure of 78 psia (a boiling liquid - gas medium) which provides a higher heat transfer because of the better control of gas use, higher cooling efficiency, and fewer clogging problems. A field test is described where the ratio of CO_2 consumed to redd materials lifted was 0.34 lb CO_2 per 1 lb of redd material. A complete step-by-step description of the methodology is given with a listing of parts, materials, and suppliers.

CONTENTS

INTRODUCTION

Large increases in sediment loads in stream channels can create intolerable changes to material size composition of salmonid spawning areas (Platts and Megahan 1975). The more commonly used methods to detect and determine the magnitude of these intolerable changes are, however, often inadequate.

The metal core tube (McNeil 1964), which is primarily used in Idaho and other areas in the Pacific Northwest, does not determine the vertical and horizontal stratification of the redd sediment particle size distribution. Therefore, this method could be biased in determining the true effects of sediments on embryo and alevin survival. Salmonid embryo and alevin survival rates have usually been estimated by sampling stream channel materials with 6- to 12-inch (152 to 305 mm) tube core samplers. The substrate particle size distribution of the samples collected is then used to estimate potential survival rates. These estimates may not be accurate because the sediment particle size is (1) limited to the size the coring tube can encase, (2) the sample is completely mixed so no interpretation can be made of vertical and horizontal differences in particle size distribution, (3) the sampling depth is limited by both water depth and the length of the collector's arm, (4) the core tube can push larger particle sizes out of the collecting area, (5) suspended sediments in the core can be lost, and (6) the individual sample size is limited to the core tube diameter. Therefore, the core samples collected may be biased to certain particle sizes.

This report describes a new freeze sampling method similar to those developed by Walkotten (1976) and Lotspeich and Reid (in press). Walkotten (1976) originally developed the freeze core method to lessen the biases previously discussed in sampling channel sediments. Our recent unpublished work, as well as Ringler's (1970), comparing the tube core sampler with the freeze core sampler, suggests, however, that the single probe method may be biased toward larger size sediment particles. We believe one of the main reasons for this bias is that the freeze probe collects larger size particles on the core perimeter more readily than it collects smaller size particles. The smaller size particles may fall off in a higher weight ratio during core extraction. Lotspeich and Reid (in press) have attempted to solve some of these problems by using three freeze probes instead of one. Our new method helps eliminate the perimeter bias by allowing a much larger sample to be taken. The previous methods also have a tendency to take uneven amounts of substrate in the vertical direction, thus collecting more sediment at one depth than another. The new system takes a uniform sample.

The new method, as does the methods used by Walkotten (1976) and Lotspeich and Reid (in press) allows collection of the eggs and alevins in the redd at any stage of development, will function at any air or water temperature or stream depth, and will determine the horizontal and vertical location of the eggs and alevins. The new system uses CO_2 more efficiently and alleviates problems of clogging from dry ice. The method will take a sample of any size that can be lifted and transported and will allow the complete redd or selected parts of the redd to be analyzed in the laboratory in a near natural condition. The method has the potential for improving our estimates of embryo and alevin survival rates and identifying causes of their mortality.

WATER-SUBSTRATE COOLING REQUIREMENTS

The actual cooling requirements were estimated for freezing a 24 by 48 by 18-inch (0.61 by 1.22 by 0.46 m) substrate sample. The following assumptions were made in calculating the requirements:

a. There is no appreciable water circulation in the sample.

b. The water temperature remains constant at 40°F (4.5°C).

c. The average temperature of the frozen sample is 0°F (-18°C).

d. The average dry sample density is 115 lb/ft^3 (1.85 g/cm^3) (Terzaphi and Peck 1948).

e. The unit density of the solids is 165 lb/ft^3 (2.65 g/cm^3) (Terzaphi and Peck 1948).

f. Two inches (5 cm) of the periphery of the sample is rock with very little ice or fine sediment because the rock may be frozen to the sample on one side only.

The constants used in calculating the cooling requirements were taken from Baumester (1967).

<u>Specific heat (Cp)</u>

C_p water = 1 Btu/lb (4.18 J/g°K)

C_p ice = 0.48 Btu/lb (2.01 J/g°K)

C_p rock = 0.20 Btu/lb (0.84 J/g°K)

<u>Heat of fusion</u>

Water = 144 Btu/lb (355 J/g)

The approximate percent voids in the sample which are filled with water are determined by the following equation (Terzaphi and Peck 1948):

$$n = 1 - \frac{yd}{ys}$$

where

n = percent porosity

yd = unit dry weight

ys = unit solid weight

n = 1 - (1.85/2.65) = 0.30 or 30 percent voids.

Sample weight is calculated as follows:

weight of rock (W_r) = (volume of sample) (dry density)

W_r = (2) (4) (1.5) (115)

W_r = 1,380 lb or 626 kg

weight of water (W_w) = (volume of sample w/ice) (porosity) (water density)

W_w = (24-4) (48-4) (18-2) (0.3) (62.4)/1,728

W_w = 152 lb or 69 kg

Calculations for the cooling requirements are shown below:

Cooling water and rock to 0°C plus ice:

Water 40° to 32°F (4.5° to 0°C)

ΔH = (W_w) (C_{pw}) (Δt)

= (152) (1) (8)

= 1,216 Btu or 1.28 MJ

Water to ice ΔH = (W_w) (heat of fusion)

= (152) (144)

= 21,888 Btu or 23.1 MJ

Rock 40° to 32°F (4.5° to 0°C)

ΔH = (W_r) (C_{pr}) (Δt)

= (1,380) (0.2) (8)

= 2,208 Btu or 2.33 MJ

Total to freeze = 25,312 Btu or 26.7 MJ

Cooling ice and rock to 0°F (-18°C):

Ice 32° to 0°F (0° to -18°C)

ΔH = (W_w) (C_{pi}) (Δt)

= (152) (0.48) (32)

= 2,335 Btu or 2.46 MJ

Rock 32° to 0°F (0° to -18°C)

ΔH = (W_r) (C_{pr}) $(\Delta t)/1,000$

= (1,380) (0.2) (32)

= 8,832 Btu or 9.3 MJ

Total 32° to 0°F (0° to -18°C) = 11,167 Btu or 11.76 MJ

TOTAL COOLING REQUIREMENT

40° to 0°F (4.5° to -18°C) 36,479 Btu or 38.47 MJ

The cooling available from liquid CO_2 is approximately 80 Btu/lb (0.186 MJ/kg) from heat of vaporization and 22 Btu/lb (0.051 MJ/kg) from heat absorbed between -11°F and -0°F (-79°C and -18°C) for a total of 102 Btu/lb (0.237 MJ/kg) (Ashrae 1972). The amount of liquid CO_2 was calculated, assuming 70 percent efficiency, as follows:

kg of CO_2 = (36,479) (102) (0.7) = 510 lb or 232 kg

If the conditions described in the paragraph above could be maintained, then the CO_2 consumption per kg of dry sample would be approximately 0.368 lb CO_2/lb sample (0.368 kg CO_2/kg) or about 25 percent of the CO_2 necessary in Walkotten's (1976) system.

Three variables can cause large discrepancies in the cooling values calculated above. The first is water temperature. If the water temperature was 59°F (15°C) instead of 40°F (4.5°C), the CO_2 required for cooling would increase 22 percent. The second variable affecting the CO_2 requirement is the amount of water circulated through the sample area. As an example, a volume flow rate of 1.05 ft^3/min (494 cm^3/s), which would be equivalent to a velocity of 0.02 ft/s (0.61 cm/s) through the void area in the sample, could add 28,156 Btu (29.7 MJ) of heat to the sample with a 7.2°F (4°K) temperature change in 1 hour. The above velocity would be about 1/100 of normal stream velocity. If very rapid cooling cannot be achieved within 10 minutes, the surface water circulation needs to be reduced to near zero--if possible. The third variable is the cooling efficiency of the CO_2. At least 70 percent of the CO_2 cooling capacity should be released into the sample.

DESCRIPTION OF NEW METHOD

CO_2 Liquid-Gas Phase

The freeze methods used today (Walkotten 1976; Lotspeich and Reid, in press) expand CO_2 liquid to atmospheric pressure producing a gas of -110°F (-78°C). This causes large amounts of solid CO_2 (dry ice) to form. Dry ice is a poor heat transfer medium and as it builds up in the probe it decreases the cooling capacity of the expanding CO_2. Our new method expands CO_2 to a pressure of 78 psia (540 kPa) producing a temperature of -68°F (-55°C). At this temperature CO_2 is a boiling liquid-gas medium which provides a much higher rate of heat transfer than dry ice. Initially, the heat transfer rate is less because of the higher temperature (-68°F or -55°C) of the liquid-gas rather than gas at atmospheric pressure (-110°F or -78°C). Liquid CO_2 allows for better gas control, higher cooling efficiency, and fewer clogged probes and lines by dry ice.

CO_2 in the System

A schematic of the system and probe layout is provided in figures 1 and 2. The tanks containing the CO_2 are stationed on the bank. The CO_2 in these tanks is maintained under a pressure of 500 to 850 psia (3.45 to 5.85 MPa) depending on ambient temperature. The tanks release CO_2 through high pressure hoses to a distribution manifold where it is filtered. The CO_2 then flows through opened throttle valves attached to each of the four rows of probes and enters the first probe in each row. These probes rapidly fill with CO_2 liquid and the overflow travels into the next probe in each row. This procedure is repeated until all probes are filled. The excess CO_2 leaves the last probe through an adjustable relief valve. The liquid is then throttled to a pressure of 79 to 84 psia (540 to 580 kPa) providing a temperature of -68°F (-55°C). By maintaining CO_2 in liquid form all the available heat of vaporization for cooling the sample is used. This represents nearly 80 percent of the cooling capacity of the CO_2.

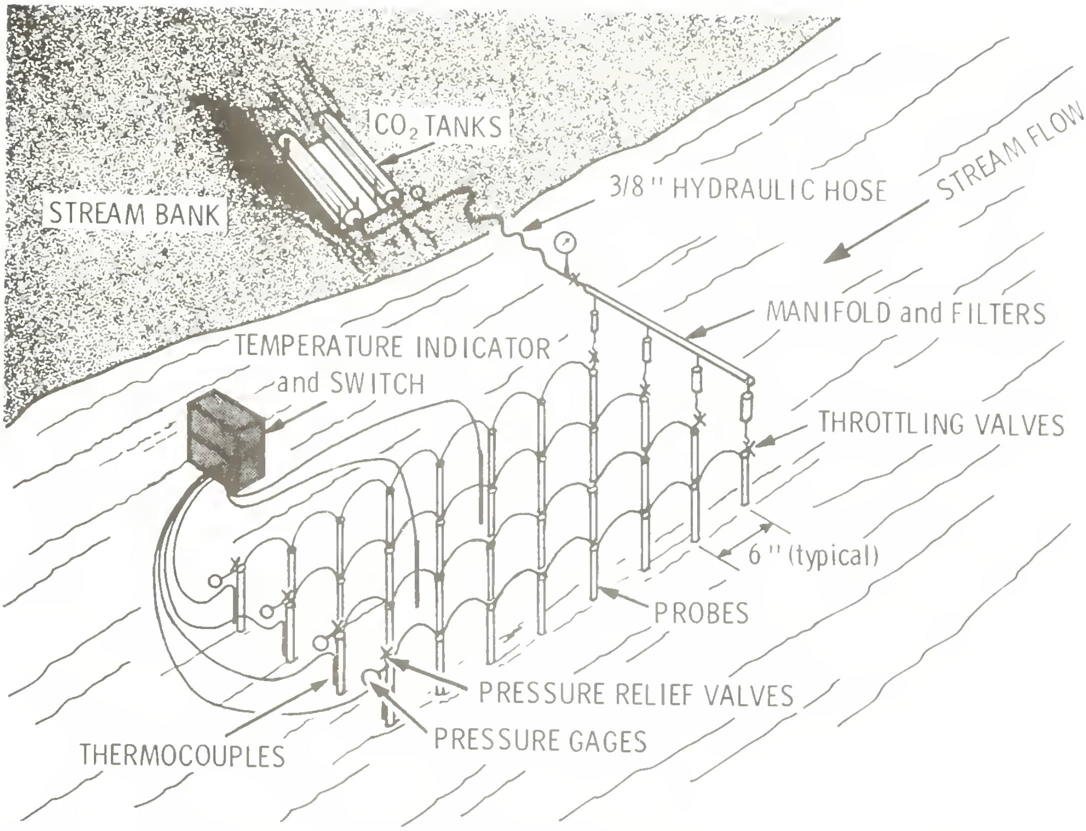


Figure 1.--Layout of sediment freeze probes and CO_2 gas line distribution.

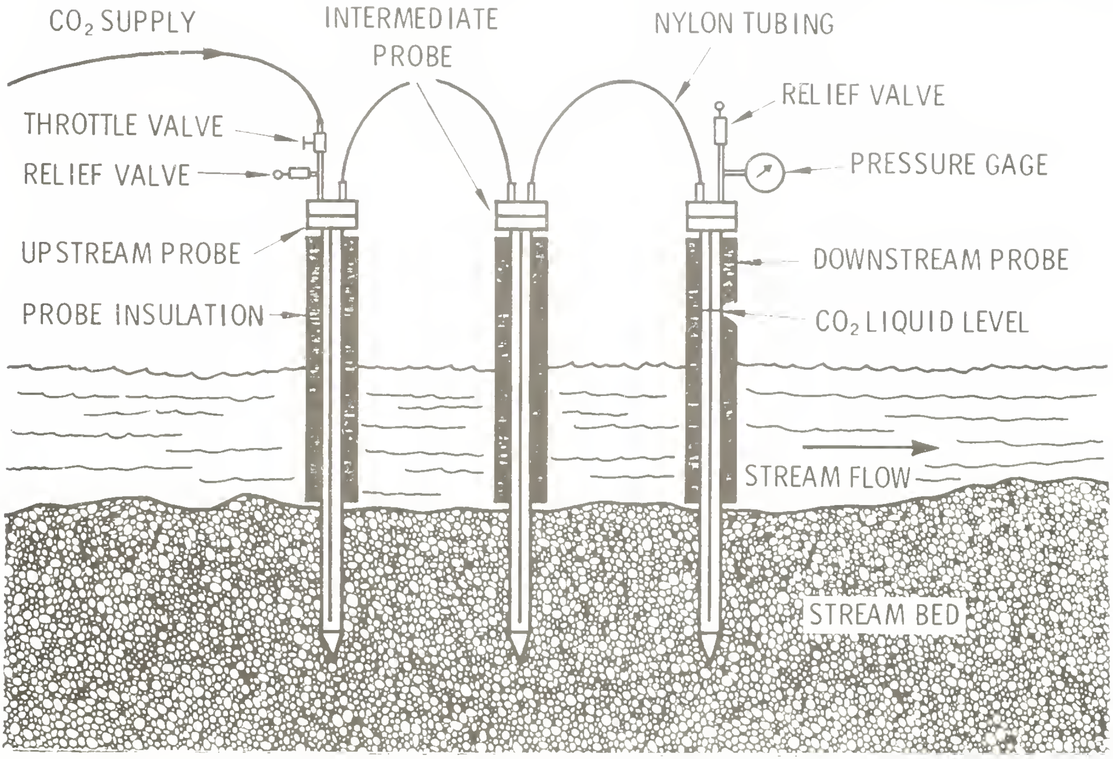


Figure 2.--Drawing of freezing probe schematic under operation.

A pressure gage located on the last probe in each row monitors the CO_2 pressure. The throttle and relief valves are adjusted to maintain the desired pressure in the system and minimize the loss of CO_2 through the relief valve. A second relief valve is positioned on the first probe to relieve excessive pressure (over 100 psi) if blockage should occur in intermediate probes. Such a blockage could allow full tank pressure to be applied to the probes ahead of the blockage.

Maximum efficiency in this system requires the liquid and gas CO_2 to be held at a uniform pressure and therefore, temperature, while it continually circulates in the tubes and probes providing the turbulence necessary for efficient heat transfer. Also, the probes are insulated above the stream channel to reduce cooling losses to water and air. A uniform probe wall temperature is maintained because the CO_2 is at a constant temperature for a given operating pressure.

Probe and Water Flow Shield

The probes are driven into the riverbed to the desired freezing depth exposing the CO_2 cooled probe wall directly to the substrate. The probes are arranged in four rows of eight probes each and spaced 6 inches (15.2 cm) apart so that an area 2 by 4 ft (0.61 by 1.22 m) will be frozen. This provides good control of CO_2 consumption but requires 1 to 1-1/2 hours freezing time. The water circulation must be reduced to low flows for complete freezing to take place. To reduce water circulation, a metal shield and canvas was worked into the streambed around the probes. If high water temperatures become a problem they can be overcome by using more CO_2 and extending the time of CO_2 circulation.

DESCRIPTION OF EQUIPMENT

Probes and Caps

The probe and cap construction is shown in figures 3 and 4. The brass flanges were wetted over the entire joint area while being soldered to the top of the probe. This required pretinning the inside of the flange and the outside of the probe. The probe parts not used directly for freezing were insulated with Cell-O-Flex pipe and insulation. DWV pipe was installed loosely over the probe and held in place with spacers. With the bottom cap removed, insulation was poured between the pipe and probe.

Three different probe cap configurations were used depending on the location of the probes (fig. 5). The basic cap consists of a piece of brass hex machined to the dimensions shown in figure 4. The copper tube is on the inlet side of the cap. The caps for the upstream probe in each row have a 1/4-inch (6.35 mm) hydraulic swivel fitting, a throttle valve, and a relief valve connected to the inlet side of the cap. The downstream cap in each row has 100 psia (0.689 MPa) gage and a relief valve on the outlet side of the cap. All other cap connections have tube fittings as indicated. The probes are connected with flexible nylon tubing rated for 700 psia (4.83 MPa). The downstream probe in each row has a 1/8-inch (3.3 mm) stainless steel clad thermocouple mounted on it to record probe wall temperatures. The thermocouple is equipped with a standard plug near the top of the probe.

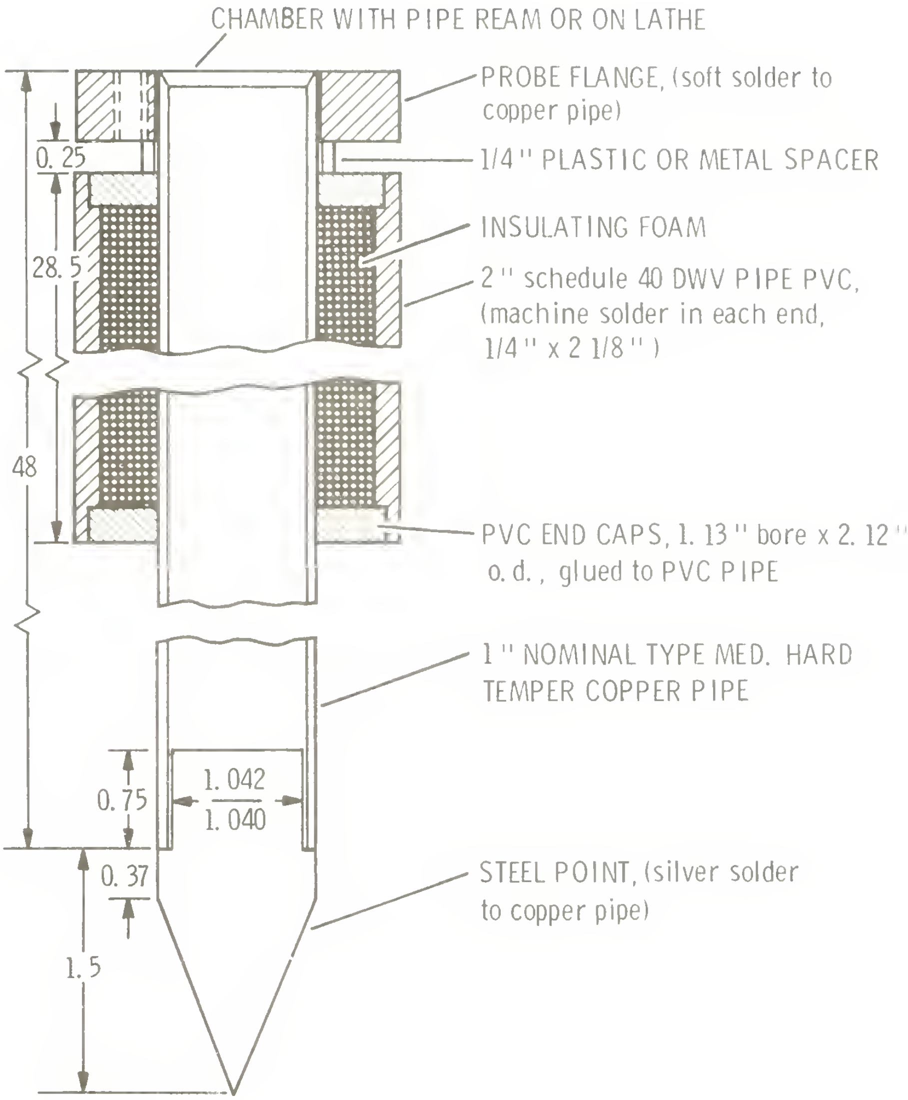
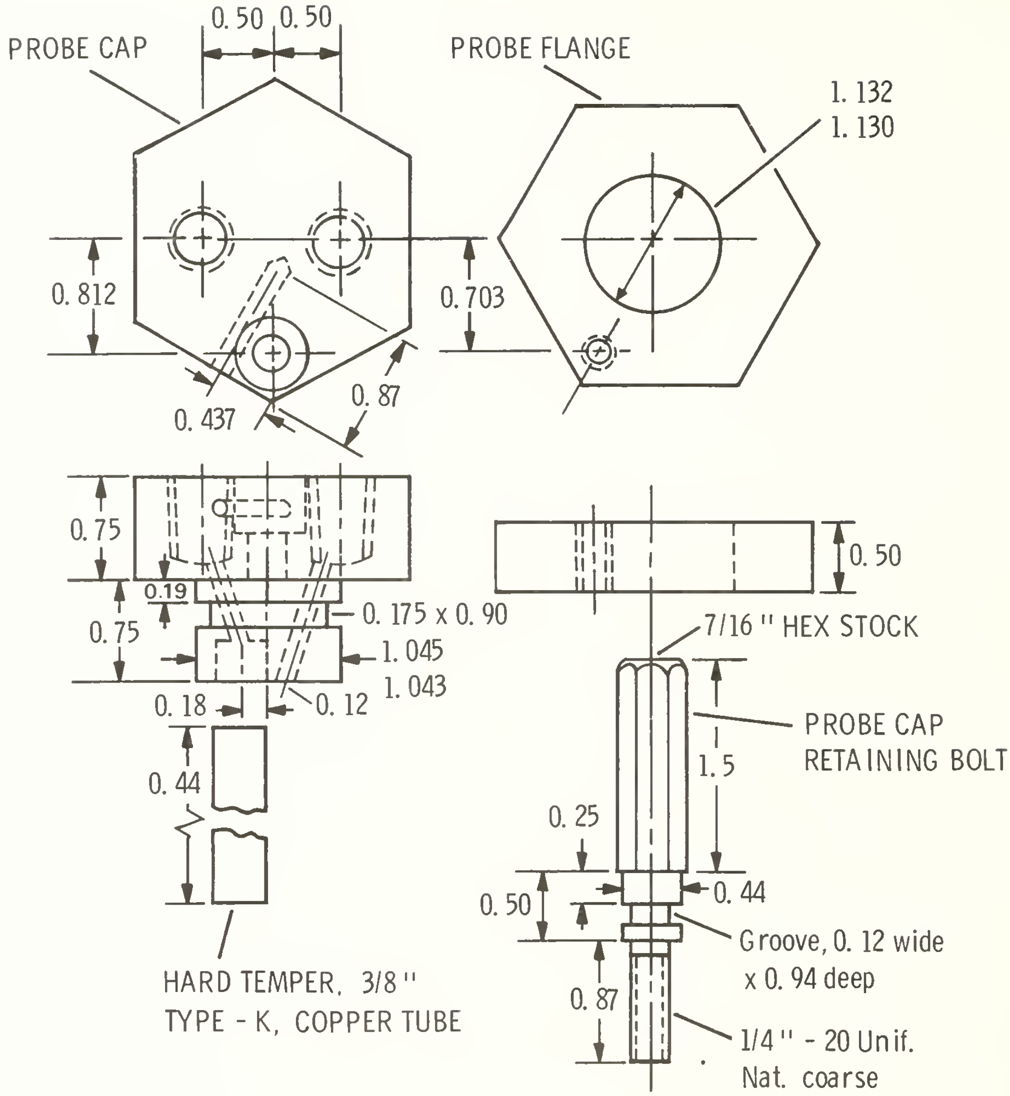


Figure 3.--Details of freezing probe.



Full Scale : (measurements in inches)

Note : Copper tube is soldered to probe cap.
Probe cap and flange are made from brass
and retaining bolt is made from mild steel.

Figure 4.--Details of probe cap and flange.

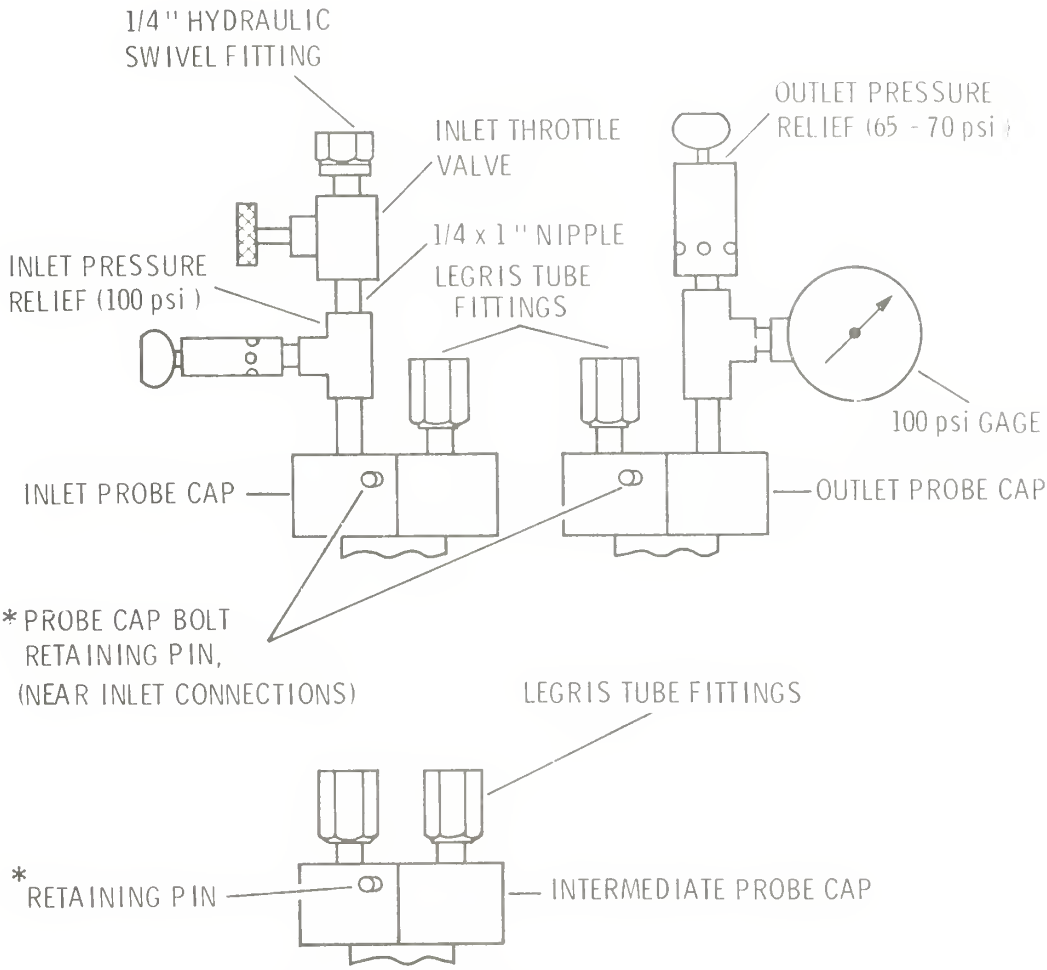


Figure 5.--Probe cap fittings.

CO_2 Supply System

The CO_2 tanks are held in tilting frames so the outlet is lower than the rest of the tank, thus eliminating the need for siphons. The tanks are connected with T-fittings and 12-inch (30.5 cm) lengths of 1/4-inch (6.3 mm) hydraulic hose. A gage measuring at least 1,000 psia (6.89 MPa) is mounted between the tanks and the main supply hose. The main supply hose is SAE 100R3 3/8-inch I.D. hydraulic hose. A shut-off valve and the measuring gage are mounted on the end of the hose. The hose and valve connect to a manifold which distributes the CO_2 through four wire screen filters to an 18-inch (45 cm) SAE 100R3 hydraulic hose connected to the probe throttle valves. All hoses and fittings are exposed to full tank pressure during operation. The gage readings determine if the CO_2 is flowing normally.

Lifting Apparatus

Figure 6 describes the ice anchors used to lift the sample. Figure 7 shows the aluminum tripod lifting frame extracting the sample. The telescoping legs are adjustable to fit variation in streambed contour (fig. 7 and 8). The frame lifting capacity is 5,000 lb (2 268 kg).

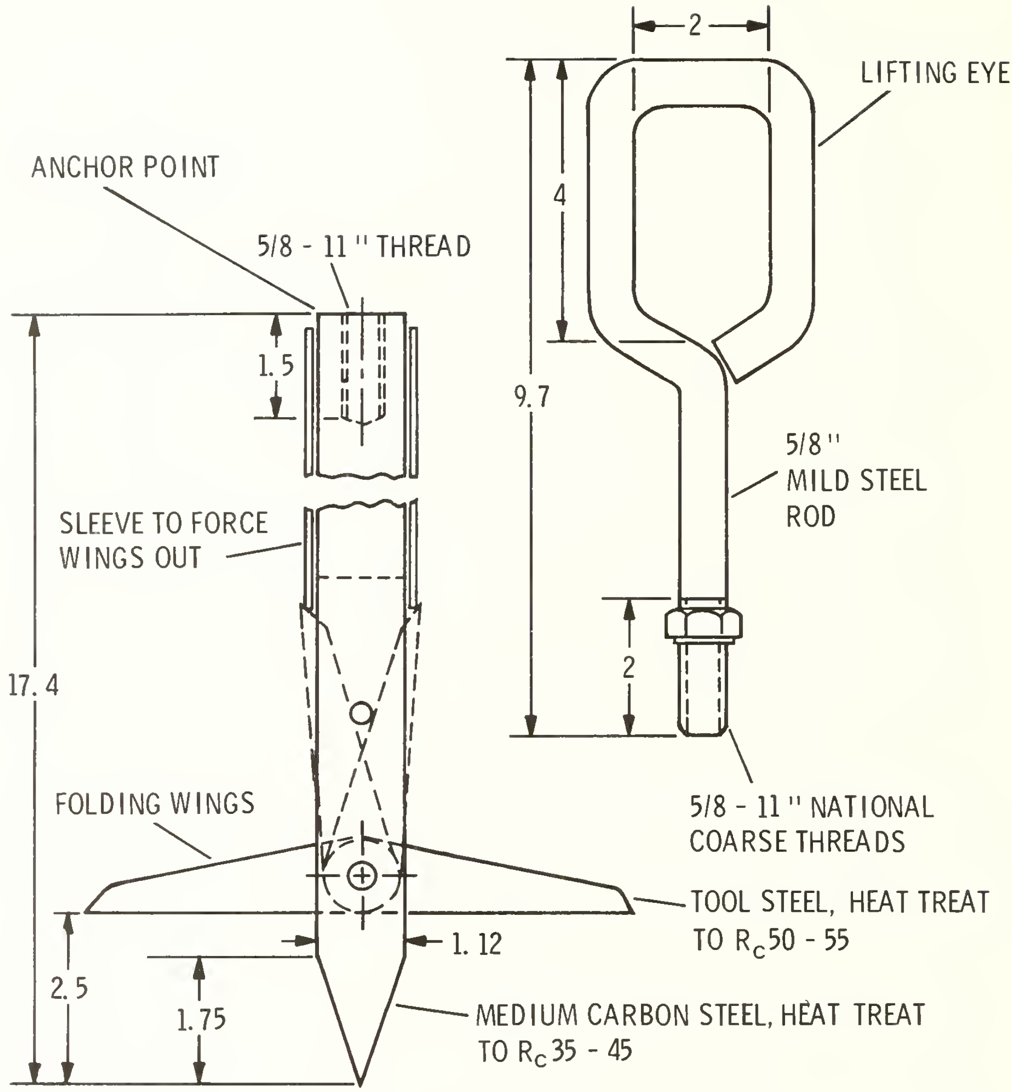


Figure 6.--Details of anchors.

Figure 7.--Hoist used to lift substrate sample.

Figure 8.--Test setup showing hose connections and A-frame.

Temperature Equipment

A Digitec model 5900 digital thermometer and a six position Omega thermocouple switch are used to measure the temperature of the downstream probe in each row and of the two thermocouples placed in the substrate sample. The temperature of the downstream probes is needed to insure the CO_2 was in liquid form.

Sample Transportation

An insulated boat was built to transport the sample. The floating capacity of the boat is 1,400 lb (635 kg) with a 4-inch (10 cm) freeboard. An improvement needs to be made in transporting the sample by boat because of difficulties in supporting the sample in its original form and transporting it to the loading area.

OPERATION OF EQUIPMENT

Three basic cooling mediums were considered for freezing the sample: liquid nitrogen which is difficult to handle, mechanical refrigeration which is expensive, and liquid CO_2 which was accepted as the medium for this method. The liquid CO_2 method was tested twice in an artificial stream channel with good results and twice in a salmon spawning area. The first test in the spawning area showed we needed to stop most of the surface flow for good results. The second test showed freezing was easily accomplished by reducing the surface flows.

The system was final tested by lifting a chinook salmon redd egg pocket in the Poverty Flat spawning area of the South Fork Salmon River in October 1978. A sample 30 by 54 by 17 inches deep (0.76 by 1.37 by 0.43 m), weighing about 1,990 lb (900 kg), was lifted from the redd. Twelve tanks containing 600 lb (272 kg) of CO_2 were used to provide 75 minutes of freezing time which completely froze the sample at a river temperature of 37°F (3°C). The ratio of CO_2 consumed to substrate lifted was about 0.35 lb to 1 lb (0.34 kg to 1 kg) dry sample. This value is better than the estimate of 0.37 lb/lb (0.37 kg CO_2/kg).

The four corners of the sample area were marked with the outer corner probes (fig. 9 and 10). The ice anchors were driven into the sample and the wings spread so they were at least 9 inches (23 cm) below the channel surface. They were also angled inward to eliminate bending force during lifting of the sample.

Figure 9.--Probes being driven into the chinook salmon redd.

Probes and Caps

The probes were driven into the streambed with a slide hammer (fig. 9) and two suffered minor damage. To avoid damage a hardened steel shaft can first be driven to the desired depth, withdrawn, and the probe placed in the remaining hole. The corner probes defined the 18 by 32-inch (0.45 by 0.81 m) sample. The remaining probes were placed within the rectangle at 6-inch (15.2 cm) intervals to a depth of 12 inches (30.4 mm). During probe installation the CO_2 tank frames were set up and the tanks connected together. Aluminum tanks were used which weighed 50 lb (23 kg) empty instead of steel tanks that weigh 100 lb (45 kg) empty. The tanks, hoses, and connections were checked for leaks by closing the valve on the end of the hose and opening one tank valve to apply pressure. The tank valve was then closed until ready to operate. Before installation of the probe caps, probes were checked with a dry dipstick for water that may have leaked in through cracks or tears.

The caps with throttle valves were placed on the four upstream probes and the caps with pressure gages and relief valves were placed on the four downstream probes. After the caps were in place, the plastic tubing was connected between the probes. The nylon tubing was pushed straight in the receiving couplet as far as it would go, carefully avoiding any kinks. The tubing connected the outlet on one probe to the inlet of the next downstream probe. The inlet connection was always next to the cap bolt retaining pin.

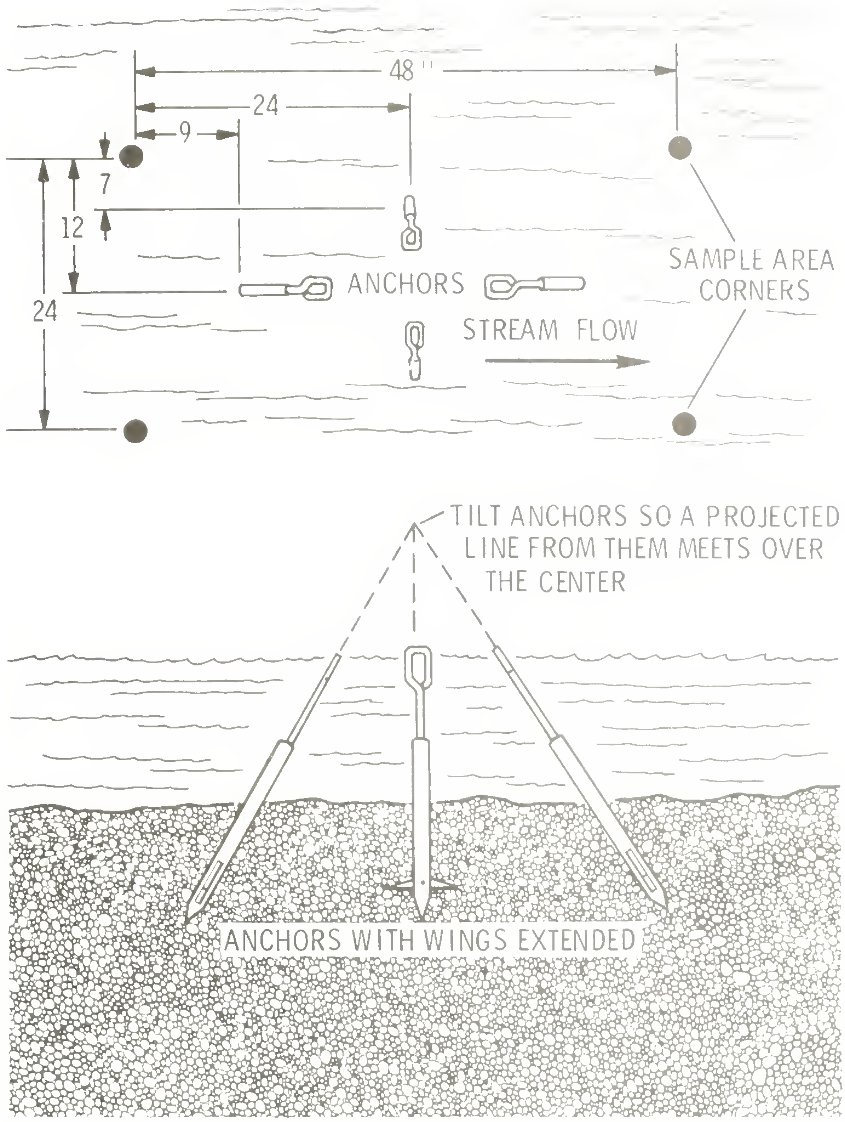


Figure 10. Drawing of anchor location.

Water Flow Shield, Lifting Hoist, and Instrumentation

The water flow shield was placed around the probes to stop surface water circulation (fig. 11). Leaks into the sample area were indicated by water currents near the inside edge of the shield. A canvas was used to cover the upstream side of the shield for a tighter seal. The lifting hoist was then placed over the sample area.

The CO_2 distribution manifold was connected to the probes and then to the CO_2 tanks. CO_2 was turned into each row of probes and leaks were located by looking for bubbles in the water around the probes. If leaks were found, the leaking probe was replaced. Small leaks will not cause the test to fail, but it slows ice formation around the probe.

The thermocouple meter was wrapped in a plastic bag to protect it from water. The thermocouple switch can be taped to the lifting frame near the throttle valves for easy access. The four downstream probe thermocouple probes were inserted in the stream bed in one of the larger spaces between the probes and connected to the thermocouple

Figure 11.--Probes with cofferdam and canvas in place.

switch. The thermocouple temperatures should all record the same ambient stream temperature prior to the freezing operation. The boat for transporting the sample was anchored near the site.

FREEZING PROCEDURE

Gloves and goggles were worn by persons working in the immediate area during operation. The CO_2 tanks were fully turned on with the main valve and throttle valves closed. The time was recorded upon opening each of the throttle valves. The first throttle valve was opened 2-1/2 to 3 turns with immediate adjusting of the corresponding relief valve to maintain 65 to 70 psig (0.448 to 0.483 MPa) in the system. Above 5,000 ft (1 524 m) mean sea level the gage pressure should read at least 70 psig (0.483 MPa). This operation was repeated on each of the rows.

The pressure gages and probe temperatures were checked to determine when the probes were full of liquid CO_2. When the temperature registered -26°F (-15°C), or less, the last probe had filled. The throttle valve was then turned to within 1/2 to 1 turn from closed. If the temperature reached -40°F (-40°C), or the gage started fluctuating rapidly, or dry ice escaped from the relief valve, the valve was turned off until the gage stopped fluctuating and then reopened 1/2 to 1 turn while observing the probe temperature.

The last probe in each row was kept between -26° and -40°F (-15° to -40°C). We initially set the valve at 1 turn and then gradually closed it to 1/2 turn near the end of the test. This generally provided the proper CO_2 flow. The gages were watched closely and when rapid gage fluctuations occurred, the CO_2 was reduced or turned off temporarily. The relief valves generally required periodic adjustment to maintain the operating pressure at 65 to 70 psig (0.448 to 0.483 MPa). The freezing rate of the sample was checked by the amount of ice forming around the probes where they enter the streambed and by monitoring the temperature probes in the substrate.

Problems

Two minor problems occurred [illegible] tests. [illegible] flow of CO_2 through that row of [illegible] detected in two ways. The relief [illegible] ing dry ice, or frost will melt [illegible] of CO_2 to the blocked row of probes [illegible] holding the relief valves open. [illegible] ice blockage removed. The cap was [illegible]

The second problem was an apparent [illegible] empty supply tanks. This was easily [illegible] ends of the hose. Both should register [illegible] to the sample recording a slightly [illegible] test ranged from 500 to 700 psig [illegible]

Shut Down Procedure

Six hundred pounds (272 kg) of CO liquid provided [illegible] When the CO_2 tanks became empty, there was [illegible] substrate temperature at the probes began to [illegible] valve setting. The system was then shut [illegible] connected and removed. The water shield was [illegible] four ice anchors, and the sample lifted [illegible] (1 814 to 2 268 kg) of lift force to [illegible] high enough to get the boat under it [illegible] port to the shore (fig. 13). Tank valves [illegible] drain the lines prior to disassembling the equipment.

Figure 13. [illegible]

The sample can be kept frozen by placing dry ice [illegible] We had difficulties getting our egg packet from the [illegible] Therefore, the top of the redd became unfrozen prior [illegible] the sample 145 miles to the lab and without the [illegible] remained frozen in the insulated carrying box [illegible] morning when it was dissected. Dry ice [illegible] to get it to the place of analysis in its original [illegible]

Figure 13.--Test sample loaded in boat.

MAINTENANCE AND SAFETY

The probes should be inspected before and after use for bends, cracks, and possible leaks. Each probe flange should be inspected to be sure it is still soldered to the probe. Each probe cap should be inspected before and after use for torn O-rings and other visible damage. After each use all filters should be cleaned. The throttle valves should be cleared by blowing air through the valve in a reverse direction.

All hoses should be checked for cracks in the outer cover, damaged coupling threads, and any inside obstructions before each use. Thermocouples need to be checked before and after each use for physical damage. The temperature indicator may need recalibration once each year. The batteries should be charged before each use. Prior to each use the relief valves next to the throttle valves should be checked with air pressure to be certain they open at 100 psig (0.689 MPa). The lifting frame and winch should be inspected for loose bolts, kinks in tubes or plates, and fraying in the wire winch rope.

DISCUSSION

The method described is capable of freezing a complete redd, the redd egg pocket, or any portion of the redd. The individual sample size can be adjusted to provide a more optimum determination of egg location, of the number of embryos and alevins in the redd, of the timing of embryo development and fry emergence, the embryo and alevin survival rate, and sediment particle size distribution by both vertical and horizontal stratification. It will allow this type of analysis because the redd sample can be dissected in its original state using a dissecting grid system. The equipment will work under the conditions we have observed in salmon spawning areas if sufficient access is available.

The method has some of the same disadvantages that other freeze methods have. It can smash embryos and alevins as the probes are being placed in the redd making it difficult to separate natural from artificial mortality, and it kills all the embryos and alevins in the sample. This can be very significant in streams having low runs of salmonids and could preclude the use of taking the complete redd pocket. When you analyze the number of samples required with the commonly used small core sampler, to meet statistical requirements it could also preclude their use in streams with low salmonid runs.

This method also has disadvantages that other methods do not. It required the stoppage of most of the surface flows. However, this should probably be done in all freeze core sampling to prevent the bulbous samples that are often collected. The time required to take a sample is longer than the other methods. The equipment is more expensive (about $5,000 to construct) and more difficult to transport to the study site (appendix B). All the equipment is hand-portable but there is more of it and the equipment takes more experience and expertise to operate.

Regardless of these disadvantages, there may be times when this method may provide the best results because it can reduce sample bias, it takes a more uniform sample, will collect more sample per unit of CO_2 used, the individual sample size can be varied to meet analysis needs, and it offers an excellent opportunity to lift redds in their natural condition. Thus, these redds could be taken to the laboratory or artificial stream channel for additional study and analysis. The method can be reduced in complexity and size to meet small sample needs.

This method can help us better our understanding of the salmonid life cycle from the egg to the emergent embryo. It is a unique experience and an education to be able to dissect a redd egg pocket in its natural state.

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APPENDIX A

Equipment List and Suppliers

Probe Cap Parts

Quantity	Description	Supplier
8	Inlet and outlet pressure relief valves (Nupro 6R-4M-50)	Automation Products
4	Inlet throttle valves (Whitney brass screwed bonnet, regulating type with 0.093-inch orifice 2RF4 1/4-inch national pipe taper female threads)	Automation Products
56	Tube fittings (Legris LF 3000 part No. 3115-60-14)	Buchanan Fluid
4	Outlet pressure gage (2 or 2.5 inch brass case 0 to 100 psig)	Matheson
100 ft	Nylon tubing between probes (Nylo-Hi-flexible pressure tubing 3/8 inch O.D. 0.295 I.D. 700 psi rating, stock No. 5173K15)	McMaster Carr
32+	O-rings for probe caps (1/8 by 13/16 inch I.D. by 1-1/6 inches O.D., Buna-N or hytrile)	Auto parts or bearing supplier

Carbon Dioxide Tank Connections and Supply Hose

Quantity	Description	Supplier
12	Cylinder connections (CGA-320 to 1/4-inch national pipe taper for CO_2)	Matheson
4	Line filters (75 to 100 microns, screen type, pressure rating 1500 psi)	Bottled gas suppliers
2	Main supply hose (50 ft 3/8-inch I.D. SAE 100R3 hydraulic hose 1,125 psi pressure rating, 3/8-inch national pipe taper male fittings each end)	Farm or heavy equipment supplier
4	Manifold to probe inlet hose (18 inches long 1/4-inch I.D. SAE 100R3, 1/4-inch national pipe taper male fittings each end)	Farm or heavy equipment supplier
12	Tank to tank hose (12 inches long, otherwise same as above)	Farm or heavy equipment supplier
1	Main shut-off valve (Whitney 1VM6-screwed bonnet valve V-stem 0.250-inch orifice 3/8-inch national pipe taper male)	Automation Products
	Miscellaneous hydraulic swivel fitting, pipe fittings, etc.	Farm or heavy equipment supplier

Quantity	Description	Supplier
Probes		
	Lower removable insulating hose (Cell-O-Flex cold pipe covering 3/4-inch thick, catalog No. 4463K68). This could be used for insulating the entire probe in place of the cast foam and PVC pipe.	McMaster Carr
Temperature Indicator and Thermocouple Assemblies		
1	Digitec model 5900-1 TC temperature indicator for type T thermocouples -152° to +400° C plus Digitec model 7010 carrying case[1]	Topp. Engineer Sales
4	Downstream probe thermocouple assemblies (Omega model CPSS-18G 32 inches long)	Omega Engineering Inc.
2	Streambed thermocouple assemblies (Omega model CPSS-14G 32 inches long)	Omega Engineering Inc.
1	Switch 6 position and 6 position jack panel same panel (Omega No. STR 3-6 and Omega SJP1-06-6T)	Omega Engineering Inc.
6	Type T thermocouple wire, connectors and clamps to make up cable assemblies (wire, Omega No. PVC-COCO-032; connector Omega No. P-COCO-MF; clamps, Omega No. PCLM)	Omega Engineering Inc.

[1]There are several suppliers who make items equivalent to the above temperature indicators and thermocouples. Some can supply the indicators with channel switching built into the meter.

APPENDIX B

Cost of Equipment and CO_2

Item Cost of Probe Components[1]

Quantity	Description	Total Cost
8	Relief valves Nupro 6R-4M-50	$ 86.00
4	Regulating valves Whitney 2RF4	100.00
1	Main shut-off valve Whitney 1VM6	12.00
4	Pressure gages 0-100 psig	56.00
4	Line filters	56.00
56	Tube fittings Legris LF 3000 part No. 3115-60-14	110.00
16	Cell-O-Flex cold pipe insulation 6 ft lengths	122.00
32	O-rings for probes	6.10
7 ft	2-inch brass hexagon rod	171.00
140 ft	0.375-inch O.D. by 25-inch I.D. type K rigid copper tube	52.00
140 ft	1-inch nominal type M rigid copper water pipe	126.00
	Miscellaneous steel for retainer bolts and probe points	10.00
		$ 864.00
	Estimated labor for 32 probes, 64 h @ $20.00	1280.00
		$2144.00
	Estimated cost per probe $67.00	

Item Cost of Hoses, Fittings, Tank Supports, Etc.

Quantity	Description	Total Cost
2	50 ft high pressure hoses 0.375 inch I.D.	$ 116.00
4	18-inch high pressure hoses 0.25 inch I.D.	20.00
12	12-inch high pressure hoses 0.25 inch I.D.	63.00
12	CO_2 tank connectors	54.00
	Miscellaneous swivel, tee elbows and nipples	40.00
	Labor and materials to build two CO_2 tank support frames	150.00
	Total	$ 443.00

[1]The above prices are figured using Cell-O-Flex insulation for the whole probe in place of PVC pipe and insulating foam. The PVC insulating foam would add about $7.00 to each probe.

Item Cost of Temperature Measuring Equipment

Quantity	Description	Cost
1	Thermocouple meter and case	$ 385.00
4	0.125-inch by 32-inch type T thermocouples	140.00
2	0.25-inch by 32-inch type T thermocouples	66.00
1	Thermocouple switch and jack panel	119.00
	Thermocouple lead cables	90.00
	Total	$ 764.00
2	Probe drivers	$ 100.00
1	Flow shield materials and labor	200.00
4	Anchors materials and labor	200.00
1	A-frame materials	620.00
	A-frame labor	700.00
	Total misc. items	$1820.00

Totals[2]

	Probes	$2144.00
	Hoses and fittings	443.00
	Temperature measuring equipment	764.00
	Miscellaneous equipment	1820.00
	TOTAL	$5173.00

[2] Extra probes, O-rings, fittings, tools, etc., should be considered when putting together a system. These would add about $300.00 to the total cost. CO_2 would be about $17.00 per 50 pound tank or $204.00 per test.

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Platts, William S., and Vance E. Penton.
1980. A new freezing technique for sampling salmonid redds. USDA For. Serv. Res. Pap. INT-248, 22 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

This report describes a new multiprobe freeze method for determining salmonid redd sediment particle size distribution. This method will collect salmonid eggs and alevins in the redd at any stage of development, any air or water temperature, any stream depth, and determine their horizontal and vertical location. This method allows larger size samples to be collected which can help improve understanding of embryo and alevin survival rates and causes of their mortality. A complete step by step description of the methodology is given with a listing of parts, materials, and suppliers.

KEYWORDS: Salmonid, salmon, sediments, freeze method, redd, channel, stream, carbon dioxide, freeze core sampling.

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