Timber Yield and Financial Return Performance of the 1974 Forestry Incentives Program

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Abstract

Analysis of the timber production performance of the 1974 Forestry Incentives Program (FIP) showed that the average "real" rate of return on timber-associated inputs and outputs of the 1974 investments was 10-1/4% on the direct treatment costs. Seventy-five percent of the cases earn a 6-3/8% return. The first rotation yield increase is estimated at 1.04 billion cubic feet, mostly softwoods, occurring within 50 years of the initial treatment. The program overall had high average returns, but some major segments had low returns. Five recommendations, aimed at eliminating low return segments by developing silvicultural guidelines for the screening of cases, development of maximum cost standards, and insuring the follow-up treatments are taken, are proposed.

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[1]*Central headquarters maintained at Fort Collins, in cooperation with Colorado State University.*

Contents

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Introduction

The enabling legislation for the Forestry Incentives Program (FIP), P.L. 93-86, authorizes the Secretary of Agriculture to share the cost of forestry practices with nonindustrial, private forest landowners. The legislative history (Sikes 1973) and the wording of the act (U.S. Congress 1973) list several resource management goals, but increased timber production appears as the primary goal. Similarly, the President's (1973) directive upon signing the bill into law called for development of a cost-effective timber production program.

Early administrative decisions concerning FIP addressed other program goals such as soil conservation and enhancement of recreation opportunities and wildlife habitat. Increased timber production, however, predominated as the major program goal. (USDA Secr. Agric. 1973, USDA-FS 1947a, USDA-ASCS 1974, Mills et al. 1974).

The enabling legislation restricted participation to owners of less than 500 acres of forestland unless a special waiver is approved by the Secretary. The federal cost-share rate could vary from 50% to 75% of the direct practice cost. In 1974, Secretary of Agriculture administrative regulations further restricted participation to tracts with a production potential of more than 50 cubic feet of timber per acre per year. In tree planting practices, owners were not eligible for cost-sharing assistance if they had commercially harvested timber in the previous 5 years on the tract to be cost-shared. Other major changes in program regulations have been instituted since 1974.

The program is jointly administered by three cooperating agencies. The USDA Forest Service (FS) provides technical input such as forestry practice specifications and recommendations for funding apportionment procedures. The USDA Agricultural Stabilization and Conservation Service (ASCS) has the major program administration responsibilities of owner eligibility, waiver applications, and cost-share payments to participants. State forestry agencies and private forestry consultants provide on-site technical assistance to eligible landowners. State forestry personnel also check the installed practice before payment is issued to be sure it complies with practice guidelines.

Study Justification

The law required periodic reports to Congress on FIP performance. An interagency Program Development Committee, established in USDA in 1974, also requested a rigorous evaluation of the performance of FIP. Performance evaluations and cost-effectiveness were central issues. There is also a standing USDA policy which requires an early performance evaluation of new programs (USDA Secr. Agric. 1972).

The FIP evaluation plan, prepared in response to the Program Development Committee's request, outlined a three stage evaluation of the 1974 program performance (USDA-FS 1974b). The first stage described the program composition and rated performance by a number of cost-effectiveness indicators. The results of the first stage evaluation of 1974 performance indicated that program performance was generally favorable with respect to cost effective timber production but improvement was possible (Mills 1976, Mills and Cain 1976). The second stage evaluation, reported in this paper, estimates the potential financial return and timber yield increase from FIP investments. The future third-stage evaluation is designed to evaluate the treatment follow-up and retention of the FIP investment cases.

Study Objectives

Two objectives were sought in this study:

primary objective: estimate the timber yield increase likely from the FIP assistance cases administered in 1974 and estimate the financial return associated with that timber yield increase, and

secondary objective: determine the performance of major segments of the 1974 program with respect to timber output in order to develop recommendations on how future program performance might be improved.

Both objectives concentrate on only the timber aspect of FIP performance on the investments actually installed in 1974. The analysis questions whether the timber yield and value increase likely to result from the FIP treatment can justify the increase in management cost. A marginal analysis format is used which implicitly assumes that the land would be growing trees, with or without the FIP practice.

The 1974 Evaluation Year

FIP assists from 1974 were analyzed in this study. Questions have been raised about how well the first year represents the program. Program delivery started late the first year due to a Presidential appropriation recision request which Congress subsequently overrode. Also, it took time before smooth operating procedures were developed to deliver the program through a delivery system including ASCS, the Forest Service, and State forestry agencies. The initial concern was development of an operational program while the question of program composition was secondary.

The 1974 cases on the other hand, were prescribed and checked by professional foresters in the State forestry agencies. These same foresters had delivered forestry assistance under the Agricultural Conservation Program (ACP) and the Cooperative Forest Management (CFM) Program for years.

In 1974, there was also a backlog of high potential cases and very receptive landowners in some states which may not be common in later program years. The President issued appropriation recision requests again in 1975 and 1976. It might be difficult to select a "typical" year for evaluation, but this earliest possible evaluation will provide program guidance.

In spite of these pros and cons about selection of 1974 as a sample year, there is ample evidence that program guidelines have been progressively focused to enhance timber production performance. For example, most states have set increasingly higher tract size minimums than the nationwide guideline for a 10-acre tract size minimum (USDA-ASCS 1977b). Average tract sizes have risen significantly since 1974, almost doubling for both reforestation and timber stand improvement practices (table 1).

High cost practices have drawn increasing attention since 1974. No formal guidelines have been established at the national level, however, except for the minor component of fencing. Average direct costs (federal plus private share) have risen 27% on site preparation and planting (FP-1). This cost increase on planting is slightly more than the 21% increase in the All Commodity Wholesale Price Index (WPI) over the same period. This is consistent with the findings of Moak et al. (1977) that silvicultural treatment costs in the South, between 1967 and 1976, rose faster than the All Commodity WPI. The average direct cost of timber stand improvements (FP-2) has not risen at all between 1974 and 1977.

The 5-year period harvest rule was removed in 1978. This will probably lead to earlier and less costly site preparation than under the earlier regulations. The State service forester can now specify the federal cost-share rate on a case-by-case basis as long as the cost does not exceed the State maximum and the cost-share percentage is not less than 50%. This too should lead to lower average costs since the State level cost-share maximums were used on almost all cases before. These program changes should be kept in mind when interpreting study results.

Study Procedures

The complete population listing of assistance cases administered in 1974 was stratified into 77 separate sample "cells" and sample cases were randomly drawn from each cell. Investments were analyzed within a marginal analysis format which compared the probable costs and returns without the FIP investment with those likely once the FIP investment was installed. Several types of data were required in the marginal analysis approach, including ground measurements on pre- and post-treatment stand conditions, treatment costs, stumpage prices, management regimes, and yield estimates. These inputs were estimated as closely as possible for case-specific conditions. Then the financial return to timber production and timber yield increase was estimated for each sample case. Sample case results were expanded to total population estimates and aggregate program results were compiled. High and low performance

Table 1. Average direct treatment cost and average tract size in FIP from 1974 to 1977, by practice

Program year	Average direct cost[1]		Average tract size	
	Reforestation[2]	Timber stand improvement[3]	Reforestation	Timber stand improvement
	(dollars/acre)		*(acres)*	
1974	52	29	15.3	17.9
1975-76[4]	68	25	18.6	32.7
1977	66	29	29.1	31.7

Source: USDA-ASCS report EL-11-R which includes all cases completed and paid during the specific period. Wash. D.C.

[1]*Included the federal and private cost-shares*

[2]*Practice FP-1.*

[3]*Practice FP-2.*

[4]*Includes the short 1975 year when funds were received late, the full FY 1976, and the transition quarter when the FY was changed from July to October.*

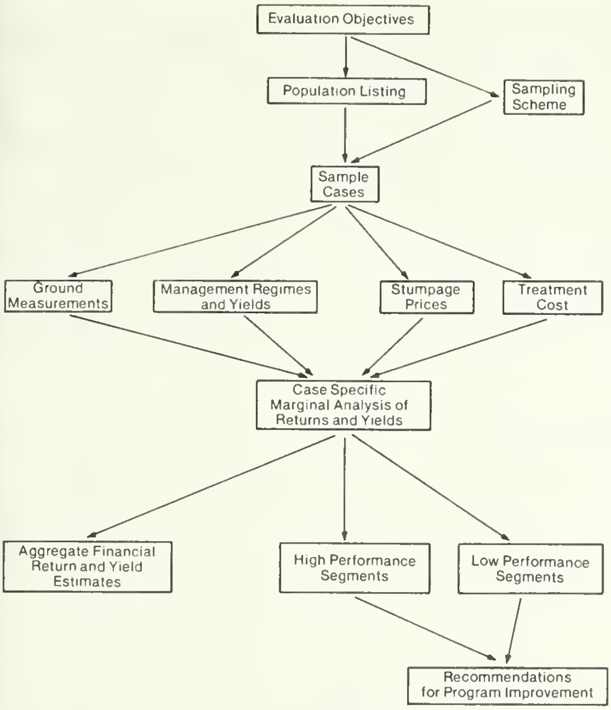

Figure 1.—Schematic representation of major study sections.

segments were then identified which led to recommendations for improved performance. Figure 1 presents a schematic representation of these steps and shows the order in which procedures and results will be described in detail.

Sampling Scheme

A complete population listing of the 15,849 FIP cost-share assists administered in 1974 was developed for the first-stage FIP evaluation. Information on tract size, percentage cost-share rate, and federal cost-share expenditures was available for each case. Site class, pre- and post-treatment forest type, broad practice class, and state identifications were also available. Miscellaneous practices such as fire roads and fencing — some of which can no longer be cost-shared with FIP funds — were excluded from the population list because of their unique evaluation problems. The excluded miscellaneous practices accounted for only 1.5% of the federal cost-share expenditures in 1974 and have had a similarly small role in subsequent program years.

Based on the two evaluation objectives, the population list was stratified by broad practice and forest type groupings. The population was further stratified by state because of the important role that State forestry agencies have in the technical direction of the program.

Separate sample cells were identified if cases within that cell totalled more than 1,500 acres. States were separated for individual sampling if more than 1.5% of the 1974 treated acreage was within the state and if more than 75% of the treated acres occurred in one of the broad practice-forest type strata. If a state was not separately identified or if one of the broad practice-forest type strata was small in an identified state, the cases were placed in an "Other North," "Other South," and "Rocky Mountain" or "Pacific Coast" strata. Practices that were not individually identified in any of the major broad practice-forest type strata were placed in an "Eastern Residual" or "Rocky Mountain Residual" cell for sampling purposes.

This stratification approach identified 77 separate sampling cells, with 38 in the South, 33 in the North, 4 in the West, and 2 residual cells. Thirteen separate practice-forest type strata were employed and 20 states were individually recognized for sampling purposes (table 2). Population cases were then separated into nine subcell stratifications by three federal cost-per-acre classes and three site classes.

With no prior information on the variance of financial return and increased yield within sample cells, sample size was a function of intuition and time and cost constraints. Twenty sample cases were drawn from each sample cell with a minimum sampling intensity of 3% and a maximum sampling intensity of 50%. Samples were proportionally allocated among the nine subcell strata and systematically drawn after a random start.

A total of 1,439 sample cases were drawn under this approach in the East and 90 were drawn in the West. In July 1975, a few sample cases still identified as only "substantially completed" were replaced by "completed" cases drawn in the same manner as the original samples. Later, 96 cases were discarded due to incomplete or widely conflicting ground measurements.

This left a final sample of 1,354 cases in the East and 79 in the West. The resulting sampling intensity was 10% in the South, 9% in the North, and 16% in the West. The sampling intensity generally ranged between 6% and 18% for the states that were individually sampled.

All study results are in the form of population estimates. Sample results were expanded to population estimates by the following factor:

$$\text{expansion factor} = \frac{\text{no. population cases in sample cell}}{\text{no. sample cases in sample cell}}$$

This same expansion factor was applied to a sample case regardless of any post-stratification of the sample. All estimates of population means, such as average internal rate of return, were calculated as weighted averages where the tract size as well as the expansion factor were used as weights.

Table 2. Sampling cell, sample size, population size, and sampli

Species group and practice	State: Missouri	Alabama	Arkansas	Florida	Georgia	Louisiana	Mississi
Southern pine, plant bare land	—	(1) 17 186	(2) 18 75	(3) 20 110	(4) 19 89	(5) 15 166	(6)
Southern pine, site preparation and planting	—	(11) 23 481	(12) 21 77	(13) 20 197	(14) 22 652	(15) 25 122	(16)
Southern pine and oak-pine, precommercial thin, and release	(22) 13 71	—	(23) 15 153	—	(24) 10 36	(25) 19 70	(26)
Southern pine, and oak-pine, cull tree removal	(30) 10 35	—	(31) 8 56	—	(32) 16 29	(33) 10 26	
Northern pine, site preparation and planting	—	—	—	—	—	—	
Eastern residual	—	—	—	—	—	—	
Total[2]	[3]87 507	44 714	64 449	42 327	67 822	69 413	
Percent sampled	17.16	6.16	14.25	12.84	8.15	16.71	(

Species group and practice	State: Michigan	Minnesota and Wisconsin	Vermont	Maine	New Hampshi
Northern pine, and spruce-fir, plant bare land	(39) 25 388	(40) 25 810	—	(41) 19 255	
Northern pine, and spruce-fir, site preparation and planting	(43) 12 137	(44) 16 225	—	—	
Northern pine, and spruce-fir, precommercial thin, and release	—	—	—	(46) 20 191	(47) 2
Northern pine, and spruce-fir, prune	(48) 19 108	(49) 20 59	—	—	
Oak-hickory, precommercial thin, and release	—	—	—	—	
Oak-hickory, cull tree removal	—	—	—	—	
Maple-beech-birch, precommercial thin, and release	(55) 21 191	—	(56) 23 109	(57) 16 59	(58) 1
Maple-beech-birch, cull tree removal	(61) 15 88	—	—	—	
Total	99 1025	68 1296	29 180	63 601	4
Percent sampled	9.66	5.25	16.11	10.48	10

centages[1] by geographic region, species, and practice group.

			State					
orth olina	Oklahoma	South Carolina	Texas	Virginia	Other South	Eastern residual	Total[4]	Percent sampled
14 139	—	(8) 16 80	(9) 23 154	(10) 13 116	(35) 20 60	—	199 1468	13.56
39 1114	(18) 19 34	(19) 24 229	(20) 18 167	(21) 27 498	(36) 19 191	—	274 4177	6.56
—	(27) 17 51	—	(28) 19 51	(29) 17 56	(37) 17 233	—	141 783	18.01
—	—	—	—	—	(38) 8 84	—	52 230	22.61
21 191	—	—	—	—	—	—	—	—
—	—	—	—	—	—	(71) 29 949 (72) 5 235	—	2.87
83 1605	39 96	41 336	60 389	57 683	64 568	34 1184	[5]666 6658	10.00
5.17	40.63	12.20	15.42	8.35	—	2.87	10.00	

		State				
ew ork	Pennsyl- vania	Indiana	Missouri	Other North	Total	Percent sampled
—	(42) 21 210	—	—	(63) 27 679	117 2342	5.00
—	(45) 14 195	—	—	(64) 13 468	76 1216	6.25
—	—	—	—	(65) 30 389	75 830	9.04
—	—	—	—	(66) 21 191	60 358	16.76
—	(50) 9 95	(51) 19 58	(52) 26 109	(67) 18 596	72 858	8.39
—	—	(53) 19 80	(54) 26 116	(68) 28 391	73 587	12.44
20 340	(60) 25 90	—	—	(69) 15 171	137 1066	12.85
20 86	—	—	—	(70) 9 65	44 239	18.41
47 573	80 775	44 225	87 507	161 2950	654 7496	8.72
8.20	10.32	19.56	17.16	—	8.72	—

Table 2. Continued

Species group and practice	Region: Pacific coast	Rocky mountains	Total	Percent sampled
Douglas-fir and ponderosa pine, plant	*(73)* 20 201	—	20 201	9.95
Douglas-fir and ponderosa pine, precommercial thin and release	*(74)* 20 81	—	20 81	24.69
All types, plant	—	*(75)* 7 59	7 59	11.86
Douglas-fir and ponderosa pine, precommercial thin and release	—	*(76)* 18 106	18 106	16.98
Rocky Mountains residual	—	*(77)* 14 51	14 51	27.45
Total	40 282	39 216	79 498	15.86
Percent sampled	14.18	18.06	15.86	—

[1]*The three numbers in each block are the sample cell number (in italics), the number of samples, and the number of cases in the population.*
[2]*The state total includes the "other" and the "residual" samples in the state.*
[3]*The Missouri total includes the "North" and "South" samples.*
[4]*The total column adds down, but does not add across.*
[5]*The South total and the North total do not include the Eastern residual.*

Marginal Analysis Format

The study objectives call for comparisons of the financial return and yield increase associated with the FIP investment against what would be expected in the absence of FIP on that tract. Since no immediate yield increases occurred as the result of the initial FIP practice, assumptions about two complete management regimes were required:

intense regime: a set of actions starting with one FIP practice and followed by a sequence of relatively intense but practical practices and harvest, and

current regime: a sequence of actions characteristic of what typical nonindustrial private landowners are now applying.

All yield and mean annual increment (MAI) increases are estimated from the difference or the interval between these two regimes (figure 2). Both regimes are carried to a second rotation which is then repeated in perpetuity in order to standardize the time horizons of competing investments. The financial returns are estimated from the interval between these two perpetual series. Any costs or returns that are of the same magnitude and occur at the same time in both the intense and current regimes cancel each other out. For this reason land costs can be ignored. Annual management costs were also excluded, although they may be slightly higher in the intense regime. Taxes were excluded because they have no impact upon the productivity of the investments.

This study estimates the return and yield increase likely from sample FIP investments as they were actually installed, assuming they are followed by a sequence of practices of an intensity commensurate with the initial treatment. This estimates whether the marginal FIP investment which was actually installed will be "productive." The study does not attempt to determine whether the treated acreage should be used for timber production or not, nor whether the level of management intensity reflected by the FIP practice is the optimum intensity for that site and stand condition.

Assumptions about the practices and harvests which follow the initial FIP treatment and the se-

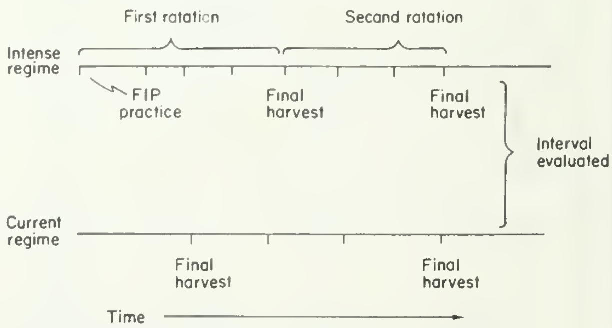

Figure 2.—The basic marginal analysis format.

quence which is assumed for the current regime have a great impact upon the study results. Several alternative sets of assumptions are possible and each has its advantages. The selection of alternative assumptions was judgmental.

One important assumption in the regimes concerns the retention of the practices through final harvest. The ground measurements were made from 1 to 1-1/2 years after the FIP practice was installed, which covers the most crucial plantation survival period. Some plantations were absent at that time because of poor survival, fire, land use changes, or any one of a host of other reasons. For the plantations still intact, however, it was assumed that all will be carried to maturity, i.e., that subsequent retention is 100%. Kurtz et al. (1978) estimates of the retention of ACP tree planting practices in five Eastern states generally run above 90%. Shackelford's (1976) estimates of Soil Bank plantation retention in selected southeastern states are very similar. Williston (1972) found similar retention in Civilian Conservation Corps (CCC) plantations in north Mississippi. Since these studies include losses from the time of planting, the results are quite consistent with the 100% subsequent retention rate assumption beyond age 1-1/2 years.

Williston and Dell (1974) found a lower retention among Yazoo-Little Tallahatchie (Y-LT) plantations in north Mississippi. The lower retention rates in this study may be related to the stronger soil conservation goal of the Y-LT program.

Another important assumption was that complete practice follow-up will occur if sample case conditions indicate that they are needed. This assumption is less certain than the one on 100% subsequent retention. Studies on the current condition of plantations (Kingsley and Mayer 1972, Kurtz et al. 1978, Williston 1972) indicate that follow-up practices are applied less frequently than can be justified silviculturally and financially. Because of these prior studies, special attention was given to identifying 1974 FIP cases that require follow-up treatment, specifying where they are generally located, and indicating what follow-up is required.

The intense regimes were all carried through a "sawtimber" rotation, for example, 30 years for slash pine, 45 years for loblolly pine, and 50 years for longleaf and shortleaf pine. Commercial thinnings were included in all regimes but care was taken to include them only when sufficient thinning volume had accumulated to yield a merchantable harvest. An alternative would have been to carry the plantings to shorter rotations which included no commercial thinnings and was more heavily weighted toward pulpwood production at the expense of sawtimber production. This alternative would generally be consistent with a wider initial seedling spacing than occurred in the 1974 plantings though.

The occurrence of the commercial thinnings is crucial in the financial return calculations. The sensitivity of their presence was tested by assuming that no commercial thinnings will occur. All commercial thinning yields were simply collapsed into the final harvest yield and the financial returns were reestimated.

Ground Measurements

On-the-ground measurements were taken on each of the sample cases 1 to 1-1/2 years after initial treatment to determine the pre- and post-treatment stand conditions. Pretreatment estimates were taken from initial management plans and/or were reconstructed from stump counts or standing dead trees. Standard mensurational procedures were employed using variable radius plots to tally all trees 1 inch in diameter and larger. Fixed radius plots of 6.8 feet were used to tally all trees less than 1 inch.

Plots were systematically located over the entire tract. The number of tally plots varied with tract size as follows:

Tract size (*acres*)	Minimum no. tally plots
less than 10	5 (1 per acre)
10-15	12
16-25	14
more than 25	18

Average pre- and post-treatment stand estimates were derived from the individual tree tally information including the species and respective basal area of the predominant crop species, additional crop tree basal area, and noncrop basal area. The average age, diameter, and height of dominant and codominant trees were estimated, again for both the pre- and post-treatment stand. Site index and site index species were recorded. In plantation cases, the number of surviving planted, volunteer, and free-to-grow seedlings were estimated by species. The type and method of practice application were recorded along with practice intensity for some practices. Sample case reporting forms for a planting and a timber stand improvement case are shown in appendix tables A1 and A2.

The majority of the ground measurements in the East were made by State personnel who measured cases in other states rather than their own to avoid possible bias. For example, the sample plots in Virginia were measured by State personnel from North Carolina. States were seldom handled on a direct reciprocal relationship, but were close enough to insure that the foresters were familiar with the forest types and practices measured. All service forester personnel were trained by a small group of USDA Forest Service personnel and used the same instructions and measurement procedures to insure consistency. Most of the western plots and some of the eastern plots were measured by USDA Forest Service personnel.

Management Regimes and Yield Estimates

A three-step process was employed to get the management regime and yield estimates for the sample cases. First, the cases were matched up with "stylized" intense and current regimes which covered a relatively broad range of case conditions. Second, information in the cases was compared against a set of "silvicultural thresholds" which defined conditions where the yield increase resulting from the practice will be negligible. If the case failed to pass the threshold test, the yield increase was set to zero. Third, if the case passed the silvicultural threshold test, the regime and yields were adjusted as closely as possible to case-specific conditions. Analysis of 1,433 separate sample cases prohibited the construction of management regimes and yields from scratch for each individual case. A full scope of computerized yield simulators were not available and hand compilations were impractical.

"Stylized" management regimes and yields were developed for both intense and current regimes. The stylized regimes, which covered a relatively broad range of case conditions, were distinguished by species groups, site index ranges, initial treatment categories, and regions. Additional distinguishing labels were used as needed, e.g., for classes of stand age at time of treatment or ranges of stand stocking. Twenty-two separate species groups were identified and are defined in appendix table A3. This approach resulted in 92 separate stylized intense regimes and 48 separate stylized current regimes in the East. A similar approach was used for Douglas-fir and a less structured approach was used for other Western species.

Each stylized regime contains the entire transaction list of subsequent practices that might be needed for cases in the broad area as well as commercial thinnings and final harvests, each recorded by stand age. All regimes follow a clearcut final harvest format, except northern hardwoods in the Lake States which were structured as a selection system on a 12-year cutting cycle. Both the first rotation and the second rotation, repeated in perpetuity, are contained in the same stylized regime. "Optimum" stocking and practice application are assumed in the second rotation of the intense regime. All timber yields are recorded in thousand cubic feet for up to four product groups: softwood timber, softwood pulpwood, hardwood sawtimber, and hardwood pulpwood.

Stylized regimes were developed for four broad practice groups: (1) tree planting, with internal adjustments for plantings on bare land and planting following site preparation; (2) understory release for the removal of overstory trees to release established seedlings in the understory; (3) precommercial thinning restricted to treatments in Southern pine stands younger than 10 years old; and (4) intermediate treatments which covered any treatments of stands between 10 years of age and the maximum age in the silvicultural thresholds. Distinctions between cleanings, cull tree removals, and precommercial thinnings in hardwoods became too fuzzy to retain as separate practice categories and were collapsed into the intermediate treatment class.

These four practice groups are later collapsed into two practice categories for aggregate presentation. The first category is planting, both bare land and site preparation. The second category is timber stand improvement which includes all the nonplanting practices.

Appendix table A4 displays stylized yield examples for both the intense and current regimes, each listed by species group, initial practice, and site index range. The yields are expressed in terms of mean annual increment (MAI) in cubic feet per acre per year. The rotation age and number of commercial thinnings are also shown.

One of the crucial assumptions in the management regimes for conifer plantings is that most of the areas would not have produced a merchantable stand in the absence of the planting. The current regime yields were set to zero. If some minimum number of established volunteer seedlings were counted when the ground measurements were taken, a small yield was assigned to the current rotation. Since the vast majority of the existing Southern pine stands resulted from natural seeding of abandoned farmland, this assumption may seem unduly optimistic for program performance, and harsh toward current yields. This criticism may be true for Southern pine bare land plantings which have an adequate seed source. Measurement of the number of volunteer seedings 1½ years after treatment may not give an accurate picture of seed source adequacy. If a bias does exist, however, bare land plantings of the Southern pines only composed 16% of the total 1974 conifer plantings. Bare-land plantings of red pine and white pine seldom have an adjacent pine seed source and composed only 22% of the 1974 conifer plantings.

In the case of Southern pine site preparation and planting practices, the pretreatment stand usually was an oak-pine or oak-hickory type that was converted to a pine plantation. Although the current management stand would contain volume, it was assumed to be unmerchantable as most of the existing oak-hickory stands on pine sites in the South currently are. Forty-five percent of the 1974 conifer plantings were such site preparation and plantings of Southern pine.

Once a sample case was matched with appropriate intense and current regimes using the regime labels, certain basic case characteristics were compared against "silvicultural thresholds." The silvicultural thresholds defined situations where yield increase due to the practice is expected to be negligible, either because of the stand that was treated, or the way in which it was treated. The thresholds can be grouped as follows:

1. minimum number of surviving planted seedlings, below which stocking is insufficient to justify carrying the stand to maturity,
2. maximum stand age at time of treatment, beyond which the stand is too close to harvest age to accumulate sufficient growth increase and/or beyond which the trees are not physiologically capable of sufficient response,
3. minimum basal area reduction, below which the stocking level was not reduced enough to induce sufficient growth increase,
4. minimum pretreatment stocking, below which the stand is stocked sparsely enough that removal of additional trees will not significantly affect growing space, and
5. several miscellaneous thresholds, such as removal of suppressed understory trees in northern hardwood stands.

The actual silvicultural thresholds developed for these five groups are shown in table 3. These thresholds were derived from available silvicultural guides and augmented by professional judgment.

Some cases that fail the silvicultural threshold tests will produce a positive yield increase. For example, intermediate treatments of oak-hickory stand over 45 years old may result in a yield increase, especially on high sites. In such hardwood types as oak-hickory or maple-beech-birch, a positive financial return may result because the growth of the post-treatment stand can be concentrated on higher value tree species. Cases that pass the threshold test, however, will yield higher returns, and use of the thresholds forces concentration upon higher return cases.

If a case failed to pass any of these thresholds, it was assigned a net yield increase of zero and a net cost equal to the initial treatment cost. Alternatively, if only part of a sample case exceeded the silvicultural thresholds, the case was split accordingly. For example, if 3 acres of a 10-acre plantation were lost to fire, the 3 acres were thereafter treated as an inadequately stocked parcel while the 7 acres were treated as adequately stocked, each parcel carrying one half of the expansion factor due the whole case. A detailed list of the threshold tests which 1974 cases failed to pass is presented later in this report.

If a sample case passed the threshold tests, basic case characteristics were again examined, this time to adjust the stylized regime and yield as closely as possible to the situation described in that case. The adjustment factors can be grouped into 5 classes: stocking adjustments, stand age adjustments, situations which remove follow-up practices, site index adjustments, and miscellaneous adjustments. Examples of adjustments for each of these classes are shown in table 4.

The management regimes and yield estimates were drawn primarily by knowledgable USDA Forest Service FIP program personnel from a wide variety of published and unpublished sources. The regime and yield sources consulted are listed by species group in the appendix bibliography. Professional opinion was often required to interpret and extrapolate the published results, especially in the development of the yield adjustment factors. Computerization of the entire case-by-case regime and yield estimating process helped greatly in insuring consistency among these judgments.

A surprisingly small amount of yield data was found for some species groups and practices. The lack of yield response data for intermediate treatments in 10 to 30 year old southern pine, oak-pine stands, and various northern conifer stands was particularly unfortunate since these are the short horizon-low investment practices to which nonindustrial private landowners are often most receptive (Anderson 1975). It was also difficult to find data on which to base the adjustment factors.

Because of the inevitable concern over the accuracy of the yield estimates, the sensitivity of each case's internal rate of return (IROR) to changes in yields was measured. The sensitivity to commercial thinning yields was measured separately from final harvest yields. The results measure how much of a percentage change in yields is necessary to change the case's IROR by 1% point of interest, e.g., from an IROR of 7.5% to 6.5%. Similar sensitivity results were derived for the estimates of stumpage price and the subsequent treatment costs. Sensitivity results were averaged by sample cell for all cases with nonzero IROR's and are tabulated in appendix table A10. Sample regimes for a planting and timber stand improvement case are shown in appendix tables A5 and A6.

Stumpage Price Estimates

The same philosophy used in developing regimes and yields was used in estimating the necessary stumpage price estimates. This started with "stylized" current stumpage prices by region and species. The

Table 3. Silvicultural thresholds used to identify stand and practice conditions that are likely to result in negligible growth increase

I. Timber stand improvement

Species	Practice	Maximum age	Minimum basal area reduction	Minimum pretreatment basal area
		(years)		
1. Southern pine[1]	Intermediate treatment	40	10 sq. ft.	0-3" DBH, 300 trees 4-6" 20 sq. ft. 7-10" 30 sq. ft. 11+" 40 sq. ft.
2. Oak-pine	Intermediate treatment	45	15%	B-level stocking[2]
3. Oak-hickory	Intermediate treatment	45	15%	B-level stocking[2]
4. Cove hardwood	Intermediate treatment	60	15%	B-level stocking for oak-hickory[2]
5. Black walnut	Intermediate treatment	60	—	—
6. Black walnut	Prune	60	—	—
7. Northern hardwood (Northeast)	Intermediate treatment	60	10 sq. ft.	B-level stocking[2]
8. White birch	Intermediate treatment	45	10 sq. ft.	B-level stocking[2]
9. Northern pine	Intermediate treatment	60	15%	B-level stocking[2]
10. White pine	Prune	60	—	—
11. Red pine	Prune	60	—	—
12. Spruce-fir	Intermediate treatment	50	20 sq. ft.	B-level stocking[2]
13. Hemlock	Intermediate treatment	60	15%	B-level stocking for white pine[2]
14. Douglas-fir	Intermediate treatment	60[3]		
15. Ponderosa pine	Intermediate treatment	60[3]		

II. Planting and understory release

Species	Minimum surviving planted or established seedlings
	(No./acre)
1. Southern pine[4]	200
2. White pine	200
3. Red pine	150
4. Jack pine	200
5. Spruce	200
6. Douglas-fir	150-300[5]
7. Ponderosa pine	250-300[5]

III. Miscellaneous practices

1. Removal of understory trees only in oak-hickory, cove hardwood, northern hardwood, or white birch intermediate treatments.
2. Removal of grape vines only in oak-hickory or cove hardwood stands more than 7 years before final harvest.

[1] *Except for slash pine which has a maximum age of 20 years and Virginia pine which has a 10 year maximum age.*
[2] *The B-level stocking in the respective stocking guide which indicates the minimum basal area required, by diameter class, to achieve full stocking.*
[3] *The maximum age threshold was augmented with field observer comments on other stand characteristics.*
[4] *Except for Virginia pine which has a 250 tree threshold.*
[5] *Varied by region.*

stumpage prices for each case were estimated by weighting the species prices together with case-specific information to reflect the species composition and region where that case occurred. Assumptions about future rates of real price increase were then applied to these current stumpage price estimates in order to estimate prices at the time the timber would be harvested.

Because of the significant impact of species upon stumpage price, separate stylized prices were compiled for 17 softwood, 23 hardwood, and 3 special pruned species in the East, and for 10 softwood species in the West. Since final product suitability has a major impact upon stumpage prices, separate prices were also compiled for sawtimber and pulpwood stumpage by the separate species.

Table 4. Examples of adjustment factors used to move the stylized regimes closer to case-specific situations

Adjustment class	Example
1. Stocking adjustments:	a. slash pine, plantation: if number of surviving planted seedlings is 200-299, remove first commercial thin and reduce yield of second by 10 percent.
	b. oak-hickory, intermediate treatment: if post-treatment basal area is 10-29 sq. ft. and stand age is 0-24 yr., reduce all yields 10 percent.
	c. loblolly pine, understory release: if residual basal area is 20-29 sq. ft., reduce final harvest yields 8 percent.
2. Age adjustments:	a. oak-hickory, intermediate treatments, if the post-treatment stand age is 40-45 yr., reduce the first commercial thinning yields 53 percent, the second 43 percent, the third 28 percent, and the final harvest 11 percent.
3. Practice removal:	a. loblolly pine, plantation: if the number of surviving planted is 300-399 and the number of free-to-grow hardwood seedlings is less than 300, remove the hardwood control treatment.
4. Site index adjustments:	a. northern hardwoods, intermediate treatments: if the site index is 65-74, rather than 55-64 as the stylized is, increase final harvest yields 15 percent.
5. Miscellaneous adjustments:	a. planting genetically improved slash pine: increase all yields 15 percent.
	b. "less intense" site preparation or planting on bare land: reduce all yields on loblolly cases 20 percent and on slash pine cases 10 percent.

Prices also differ by region because of correlation with factors such as competition, terrain, accessibility, and tree quality. Therefore, the stylized stumpage prices were developed for 13 regions in the East (fig. 3) and for 5 regions in the West. The western regions correspond to USDA Forest Service administrative regions 1, 2, 3, 5, and 6. These stylized stumpage prices, computed in dollars per thousand cubic feet to match the timber yield estimates, are arranged in appendix table A7.

The stylized prices were drawn from the published and unpublished sources listed in the appendix bibliography. Just as with the yield data, some empty data cells were filled by linkage to and extrapolation from prices in neighboring regions. The price estimates were set equal to the midpoint of the published stumpage price range or the median price if it was reported.

Special product potentials were considered in setting the prices. For example, 50% of the longleaf pine sawtimber and pulpwood volume was priced at a medium pole grade.[2] This accounts for the price differences between longleaf and the other major pines. Similarly, 4% of the white oak, 15 to 25% of the yellow birch, and 4% of the sugar maple sawtimber stumpage[3] was priced as median grade veneer. Twenty percent of the walnut sawtimber volume in natural stands and 90% of the walnut in plantations was priced as veneer. The median sawtimber prices and the special product prices were weighted together by their respective volume percentages.

[2]*Personal communications with Richard Welch, Southeastern Forest Experiment Station, Asheville, N.C., and William Balmer, Southeastern Area, Atlanta, Ga., USDA Forest Service.*

[3]*Personal communication with James Bones, Northeastern Forest Experiment Station, Upper Darby, Pa., Burton Essex, North Central Forest Experiment Station, St. Paul, Minn., and Burl Ashley, Northeastern Area, Morgantown, W. Va., USDA Forest Service*

The stylized prices per unit were the same for both pre- and post-treatment yields in all situations except hardwood sawtimber. One impact of intermediate treatments in hardwoods is upon the average tree grade. Removing lower quality trees raises the average grade of the residual stand, and the residual stems put on more diameter growth following treatment which is closely related to tree grade. These grade differences influence product potential which in turn is reflected in higher stumpage prices that the discerning landowner can capture. The post-treatment hardwood sawtimber prices are therefore generally higher than the pretreatment prices by 15% to 25%, the actual amount varying by species and region (appendix table A8). These percentages were calculated from the reported price ranges and they raise the prices to a point halfway between the midpoint and top end of the price range.

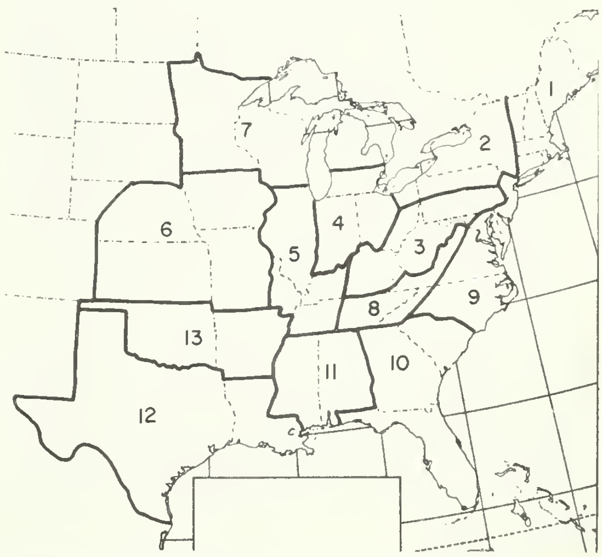

Figure 3.—Stylized stumpage price regions in the East.

The stylized stumpage prices were calculated as the simple average of prices for 1971-72-73 when the data was available. The average price for the base period was updated to 1974 by the All Commodity WPI.

Case-specific stumpage prices for the four product groups shown in the management regimes — softwood sawtimber, softwood pulpwood, hardwood sawtimber, and hardwood pulpwood — were derived by weighting stylized prices by information available in each sample case. The prices for cases that start with an intermediate treatment are derived through a weighting of the prices for crop species listed as present on each case by the basal area of the species, respectively:

$$PR_j = \frac{\Sigma(SPR_{ij} * BA_i)}{\Sigma BA_i}$$

where:

PR_j = the price per thousand cubic feet for product group j

SPR_{ij} = the stylized price for product j of species $_i$

BA_i = the crop tree basal area for species $_i$ for that case.

The price for the current regime yields are derived from the pretreatment prices by species and pretreatment crop tree basal areas. The intense regime prices weight the post-treatment prices by species by the post-treatment crop species basal area. Therefore, changes in the species composition of the stand brought about by the treatment are reflected in the stumpage prices. This species weighting of prices is very important in hardwood stands where one of the most important impacts of the treatment is in changing the species composition toward higher valued species.

The same approach was used to derive the stumpage prices for plantation yields except that the stylized species prices were weighted by the number of surviving planted seedlings by species rather than crop tree basal area. In precommercial thinning and understory release cases, the price is set equal to the price of the predominant species listed for the case. These same case-specific stumpage price estimates were used in the second rotation in most cases, therefore assuming that the second rotation species composition would be the same.

Only crop species are considered in estimating the price for sample cases and crop species generally have higher prices than the average price of all species present in the stand. The same approach is used in both the intense and current regimes, however, so any bias this presents is small when the incremental yield change is evaluated under the marginal analysis format.

The calculations and price data described to this point provide case-specific stumpage price estimates for 1974. When applied in the financial return calculations, prices are required for the year in which the harvest occurs. There is some evidence that real stumpage prices have risen over time and may continue to do so in the future. Therefore, it was necessary to make assumptions about the future annual rate of real stumpage price changes.

Row (1973) developed regressions equations that estimated the historical rate of real price increases in southern pine sawtimber stumpage using annual data between 1910-70 and between 1947-70. Three of his four estimates were quite close and averaged 1.6% per year. The historical rate of real pulpwood price increases in the East from the 1950-73 data reported by Phelps (1973) are much lower except for softwood pulpwood in the Southeast, which was only slightly lower than Row's 1.6%.

As for future increases, the USDA Forest Service's (1973) timber supply and demand analysis predicts a doubling of real softwood sawtimber prices between 1970 and 2000. This gives an average annual rate of increase of 2.1% per year. Adams[4] prepared "trend level" estimates of future real stumpage prices between 1976 and 2030. The rates of increase between the 1976-78 and 2027-30 mean prices of those trend series ranged from 1.5% to 2.6%, depending on regions and species group.

Based upon this accumulated evidence, the annual rates of real stumpage price increase for both sawtimber and pulpwood assumed in the evaluation of the FIP sample cases were:

Stumpage category	Annual increase *(percent)*
Eastern softwoods	1.5
Eastern hardwoods	2.5
Western softwoods	2.5

These rates were employed in the financial return calculation as described by Goforth and Mills (1976).

These historical East and West differentials in real stumpage price increase cannot continue indefinitely. The lower eastern stumpage prices will eventually draw more primary product production capacity into the East, especially the southern portion, which will raise the eastern stumpage prices. The differential increases may roughly continue for 30 to 45 years, however, which covers the first rotation of the Southern pine practices. Sensitivity analysis on the second and subsequent rotations indicates that they have little impact upon the estimated financial return anyway. There is a direct and simple relationship between the IROR and the rate of real price increase assumed in the calculation of the IROR, which should ease major concern about this assumption. There is essentially a direct additive relationship. For

[4]*Personal communication with Darius Adams, Oregon State University, Corvallis.*

example, if a case has an IROR of 4.5% when the annual rate of real price increase is assumed to be 1.5%, the same case will have an IROR of approximately 5.0% if the real price increase assumption is changed to 2.0%. Therefore, the impact upon study results to changes in this assumption are quite easy to estimate.

Treatment Cost Estimates

Two groups of treatment cost data were needed to estimate the financial return of each sample case, one for initial treatment cost and one for the cost of any subsequent treatments in the regime. The cost of the initial FIP practice which starts the schedule of transactions in the intense regime is the largest and most important cost from the point of influencing financial returns. Since the FIP practice had already been applied, the federal funds expended and the cost-share percentage were a matter of record. The direct treatment cost of the FIP practice, both the private and federal share, were calculated from this data.

A program delivery or "overhead" cost per case was also calculated. The delivery cost includes all chargeable ASCS county office costs as estimated from an analysis of 1976 program year costs (USDA-ASCS 1977). The service forester's assistance time was included as estimated from time spent in Cooperative Forest Management (CFM) assists (USDA-FS 1976). Program delivery must also absorb a certain amount of "slippage" cost from cases that were assisted under FIP but for a host of reasons were never cost-shared. In 1976-77 the slippage rate was about 30%.[5] The resulting program delivery cost was $223 per case. Washington Office and Regional Office program delivery costs that amount to roughly $300,000 per year for the Forest Service and Agricultural Stabilization and Conservation Service were not included in this $223 figure.

Four constructs of the initial FIP practice cost were developed from this information which include:

1. direct cost: federal plus private direct cost-share.
2. total cost: direct cost plus per case program delivery cost.
3. public cost: federal direct cost plus per case program delivery cost.
4. private cost: private direct cost only.

The financial return of each case was estimated under each of these four versions of initial cost. Most of the results are displayed under the direct cost option, since it puts the initial cost on the same footing with subsequent treatment costs. The financial results under the public and private cost options provide some insight on the incidence of costs and returns. Investment efficiency is the major focus of this study rather than the distribution question, however. Taxes in the intense and current regimes largely cancel each other out.

The second group of cost data is for the treatments in the regimes which follow the initial FIP practice. For example, an estimate of the cost of precommercial thinning in an overstocked stand was required.

Adjusting "stylized" data for case-specific situations was also attempted here to get subsequent treatment costs, but failed. Equations that predict silvicultural treatment costs as a function of treatment area characteristics such as those developed by Row (1973) are simply not available for the scope of practices encountered in this study.

An effort was made to use the sample FIP cases as a data base for development of treatment cost equations. No significant relationships could be developed between the direct treatment cost and characteristics of the treated area or the treatment itself. Contacts with selected state and federal personnel revealed that the FIP cost-share for each case is often the maximum federal share permitted in the county for that practice irrespective of the cost of treating that particular case. As a result, some cases may receive more cost-share funds and some may receive less funds than are actually needed to achieve the 50 to 75% cost-share rate permitted by law. The method of allocating cost-share to individual cases in 1974 then may have an impact upon financial returns.

Average direct costs were therefore compiled from a number of sources for the subsequent treatments (append. table A9). Costs were varied by regions and species groups where appropriate. Four cost regions were used in the East and separate costs were compiled for each National Forest administrative region in the West. Subsequent treatment costs were unchanged regardless of which initial cost option was used.

The real cost of subsequent treatments was held constant at their 1974 level. All subsequent treatments in the first rotation are small and the second rotation costs are far in the future. The cost of subsequent treatments only has a minor impact upon the estimated financial returns, even if a small real cost increase were assumed. The sensitivity analysis results on data errors shown in table 11 bear this out.

The subsequent treatment cost data was collected from a number of sources. Costs for site preparation and planting, intermediate treatments in hardwoods, and pruning in the East were compiled from 1976 FIP costs and adjusted to 1974 by the All Commodity WPI. Costs for hardwood control by mist blower, prescribed burning, and precommercial thinning[6] in

[5]*Personal communication with Robert Shackelford, Cooperative Forestry, USDA Forest Service, Washington, D.C.*

[6]*Personal communication with James Moak, Mississippi State University, Mississippi State.*

the East were compiled from Moak et al. (1977), Callahan and Smith (1974), and professional judgment of state and federal personnel involved in the delivery of FIP. Costs in the West were derived from Zach (1977) and adjustments of National Forest costs.

Discount Rates

The financial returns of the program are displayed in terms of internal rate of return (IROR), present net worth (PNW), and benefit/cost ratio (B/C). Use of IROR requires some alternative return for comparison and the alternative rate is included in PNW and B/C calculations as the discount rate.

All PNW and B/C calculations were made at each of four different discount rates, in part to test the sensitivity of the study conclusions to the discount rate assumption. First, the Federal Office of Management and Budget (OMB) (1972) requires that public programs, with a few exceptions, be evaluated against a 10% discount rate. OMB estimated that this rate equals the "real . . . rate of return on private investment, before taxes and after inflation." Second, a discount rate of 7-1/2% was used. This is the current "nominal" rate of return, as distinguished from the real rate once inflation has been removed, on longterm government bonds. Third is the 1977 Water Resources Council rate of 6-3/8% (USDA-SCS 1976). The rate for federal water projects is related by law to the nominal rate on longterm government bonds. Fourth, a discount rate of 3% was used. This rate is much lower than the nominal rate on government bonds but it is closer to the real rate on government bonds, given current inflationary expectations, than the three higher discount rates.

Recall that the costs and prices used in the financial return calculations in this study are "real" costs and prices that include real or relative price changes but exclude any inflationary impact of a change in the value of the dollar. The resulting IROR estimates are therefore real rates of return. The FIP investments should then be rated against a "real" alternative rate of return rather than a "nominal" return (Gregersen 1975). The 3% rate might be valid under this approach if the nominal government borrowing rate of 7-1/2% or 6-3/8% were used and an inflationary rate of 4-1/2% or 3-3/8% were assumed, respectively. On the other hand, FIP must compete with other federal programs for dollars, and other natural resource programs are most commonly ranked against a nominal rate of 6-1/2 to 7-1/2%. The most detailed results are presented against the 1977 Water Resources Council rate of 6-3/8%.

Study Results

All results are population estimates for the 1974 program, excluding the small number of miscellaneous practices. Many of the detailed results are presented for both the original sampling scheme stratification shown in table 2 and the detailed practice and species group stratification developed for the stylized management regimes shown in table 5. Sample cases carried the expansion factor based upon the sample strata in which they originated, regardless of any post-stratification.

Practice and Species Composition of the Program

There were 6,230 southern pine cases in the plant bare land, site preparation and planting, and understory release practice categories (table 5). This was 39% of the 1974 program. The vast majority of these southern pine cases (78%) were loblolly pine and a much smaller percentage (17%) were slash pine. Almost all of the slash pine planting occurred in Florida and Georgia. This is indicative of the trend toward loblolly pine planting and away from slash pine planting because of offsite plantings of slash pine in the past. Of these southern pine cases 3% were shortleaf and 1% were Virginia pine, both of which typically have lower returns than loblolly and slash pine.

A large number of southern pine and oak-pine assists were reported as precommercial thinning cases in the first stage evaluation. Data in this study revealed that only 18 cases were treatments in stands less than 10 years old — the class that might be called "true precommercial thinning" cases. Conversely, 511 cases were in stands over 10 years old and were classed as "intermediate treatments" in this study. It was the intermediate treatment practice which was highlighted as largely lacking yield data.

There were 3,767 northern conifer cases in the plant bare land, site preparation and plant, and understory release practices or 24% of all the 1974 cases. There were 60% as many northern conifer cases as there were corresponding southern pine cases and the southern pine cases on the average had larger tract sizes. Red pine contributed 45% of the cases in this class, white pine had 40%, and white spruce contributed 12%.

Intermediate and pruning cases in northern conifer species totalled 1,175 cases or 7% of the 1974 cases. Sixty-four percent of these cases were white pine. Twenty-two percent of the cases were exclusively pruning and 26% had both pruning and an intermediate treatment. Recall that pruned cases had a separate pruned price (appendix table A5) which implies that log grade will have the same relative importance when these stands mature as it does now.

Table 5. Number of sample (italic) and estimated number of population cases in the 1974 program by detailed species and practice categories

Species	Practice: Plant bare land	Site preparation and planting	Understory release	Precommercial thin	Intermediate	Prune and intermediate	Prune	Total
Slash pine	*34* 202	*47* 850	*4* 25	*1* 2	*14* 34	—	—	*100* 1113
Longleaf pine	*3* 21	*4* 87	—	—	*6* 18	—	—	*13* 126
Loblolly pine	*158* 1232	*221* 3205	*76* 394	*3* 16	*23* 148	—	—	*481* 4995
Shortleaf pine	*6* 18	*7* 64	*21* 88	—	*23* 168	—	—	*57* 338
Virginia pine	*3* 9	*1* 35	—	—	*4* 50	—	—	*8* 94
Oak-pine	—	—	—	—	*17* 93	—	—	*17* 93
Red pine	*61* 1275	*31* 432	—	—	*3* 39	*8* 69	*36* 180	*139* 1995
White pine	*38* 811	*38* 649	*2* 48	—	*40* 436	*23* 232	*11* 81	*152* 2257
Jack pine	—	*3* 89	—	—	*1* 13	—	—	*4* 102
Spruce-fir	*24* 362	*7* 77	—	—	*8* 86	—	—	*39* 525
Hemlock	—	—	—	—	*5* 39	—	—	*5* 39
Larch	*1* 10	*1* 14	—	—	—	—	—	*2* 24
Oak-hickory	*2* 70	*2* 52	—	—	*128* 1183	*1* 9	—	*133* 1314
Cove hardwood	—	*3* 105	—	—	*21* 346	*1* 4	—	*25* 455
Black walnut	*3* 87	*10* 233	—	—	*19* 190	*6* 155	*4* 78	*42* 743
Northern hardwood	—	—	—	—	*151* 1164	—	—	*151* 1164
White birch	—	—	—	—	*9* 39	—	—	*9* 39
Douglas-fir	*3* 30	*11* 110	—	—	*23* 100	—	—	*37* 240
Ponderosa pine	—	*10* 92	—	—	*22* 116	—	—	*32* 208
Lodgepole pine	—	—	—	—	*6* 24	—	—	*6* 24
Total	*336* 4127	*396* 6094	*103* 555	*4* 18	*523* 4286	*39* 469	*51* 339	*1452* 15888[1]

[1] *The total does not add to the population total in table 1 due to rounding errors in the expansion factors.*

There were 547 hardwood planting cases or 3% of the 1974 program. Over half of these were black walnut plantings and the rest were about evenly split between cove hardwood and oak-hickory species.

Intermediate and pruning cases in the oak-hickory type contributed 1,965 cases to the 1974 program or 12% of the total cases. Of the 1,965 cases, 61% were predominantly oak-hickory, 18% were cove hardwoods, and 21% were predominantly black walnut stands or would be managed as such given a very liberal definition of what constitutes a black walnut stand (append. table A3).

There were 1,164 intermediate treatments in northern hardwoods and 39 in white birch. These constituted 8% of the 1974 cases and 61% as many as there were similar treatments in the oak-hickory type.

Douglas-fir planting contributed 140 cases and intermediate treatments in Douglas-fir and ponderosa pine totalled 216 cases. In total, the West had 472 cases or 3% of the 1974 cases.

In summary, the largest segments of the 1974 program include the planting and release of loblolly pine (30%), planting red pine (11%) and white pine (9%), and planting slash pine (7%). Intermediate treatments in oak-hickory (7%) and northern hardwoods (7%) were also significant. Together these six species-practice groups accounted for 71% of the cases in the 1974 program.

Aggregate Study Results

The aggregate results for the 1974 population include all cases, except the small group of miscellaneous practices, as they were actually installed in 1974. Failure cases as well as successful cases are included. The results also reflect the particular mix of practices, species, sites, and treatment costs actually installed in 1974. It is very important to remember this if any attempt is made to extrapolate 1974 results to other program years.

Under the direct cost option of the initial FIP treatment, the weighted average real IROR was 10.2% (table 6). The average PNW per acre using a 6-3/8% discount rate was $213 and the total B/C ratio, calculated by the sum of the expanded benefits divided by the sum of the expanded costs, was 5.6 at the 6-3/8% rate. Seventy-five percent of the cases were capable of earning the 6-3/8% rate and 67% were capable of earning the 7-1/2% rate. The total PNW of the 1974 program was $54 million at 6-3/8%. The cost of the initial FIP practices was $8.3 million for the direct federal cost-share plus an estimated private cost-share of $3.0 million, plus program delivery cost of approximately $3.8 million dollars. The cost of subsequent treatments must be added to this $15.1 million initial cost to get a total cost estimate.

The average IROR was 9.4% under the total cost option which adds the $223 per case program delivery charge to the direct cost (table 7). The IROR under the total cost option is only 0.8% less than the IROR under the direct cost option. On the other hand, the percentage of cases capable of earning the 6-3/8% rate declines by 16% to 63%. Fifty-three percent of the cases can earn 7-1/2%.

The $223 per case program delivery cost is only one factor that influences the economics of scale of silvicultural treatments. Row (1973), for example, also includes direct treatment cost and stumpage price variations by tract size. Even with the program delivery cost alone, however, the IROR under the total cost option is significantly lower than under the direct cost option for small tract size cases. The average IROR for all timber stand improvement treatments 1 to 9 acres in size declines by 30% when the program delivery cost is added to the direct cost (figure 4). The IROR impact is smaller on planting cases because direct planting costs are higher but even there the IROR for 1 to 9 acre tracts declines 18%. The majority of the delivery cost impact upon IROR is dissipated once tract sizes reach 20 acres.

The average IROR under the federal cost option is 10.2% (table 8) and under the private cost option which includes only the private share of the direct cost is 14.9 percent (table 9).

The total yield increase expected during the first rotation is estimated to be 1.04 billion cubic feet

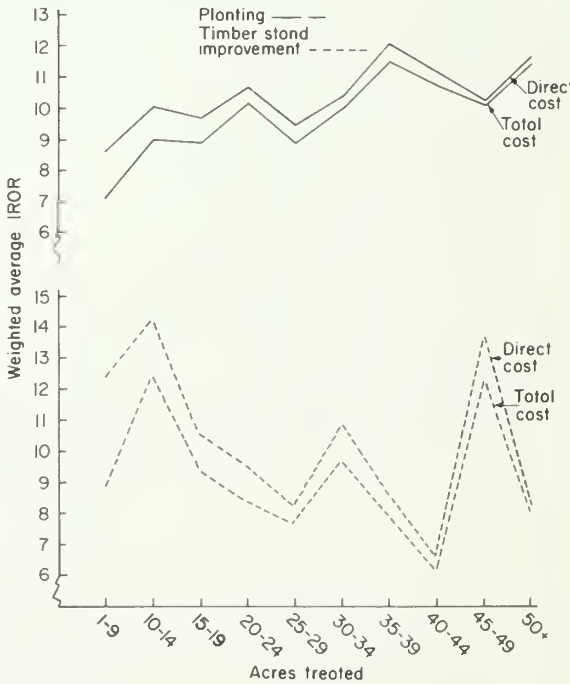

Figure 4.—Weighted average internal rate of return tract size for planting and timber stand improvement cases, by cost option and tract size.

Table 6. Aggregate financial return results under the direct cost option of the FIP treatment

Discount rate	Total PNW	Average PNW	Total B/C ratio	Cases earning discount rate
(percent)	*(mil. dollars)*	*($/acre)*		*(percent)*
10	7.94	31.40	1.9	45
7-1/2	30.96	122.41	3.6	67
6-3/8	53.96	213.37	5.6	75
3	605.81	2,395.45	54.2	83
(weighted average IROR = 10.2)				

Table 7. Aggregate financial return results under the total cost option of the FIP treatment

Discount rate	Total PNW	Average PNW	Total B/C ratio	Cases earning discount rate
(percent)	*(mil. dollars)*	*($/acre)*		*(percent)*
10	4.42	17.47	0.9	32
7-1/2	27.43	108.48	1.9	53
6-3/8	50.44	199.45	3.0	63
3	602.29	2,381.70	31.8	82
(weighted average IROR = 9.4)				

Table 8. Aggregate financial return results under the public cost option of the FIP treatment

Discount rate	Total PNW	Average PNW	Total B/C ratio	Cases earning discount rate
(percent)	*(mil. dollars)*	*($/acre)*		*(percent)*
10	7.56	29.89	1.0	39
7-1/2	30.58	120.90	2.2	57
6-3/8	53.58	211.86	3.5	65
3	605.43	2,393.94	36.0	82
(weighted average IROR = 10.2)				

Table 9. Aggregate financial return results under the private cost option of the FIP treatment

Discount rate	Total PNW	Average PNW	Total B/C ratio	Cases earning discount rate
(percent)	*(mil. dollars)*	*($/acre)*		*(percent)*
10	16.09	63.62	5.3	69
7-1/2	39.10	154.62	10.9	79
6-3/8	62.11	245.58	16.0	82
3	613.96	2,427.66	114.9	83
(weighted average IROR = 14.9)				

Table 10. Estimated first rotation yield increase, in million cubic feet, by product and year

Year	Softwoods Sawtimber	Softwoods Pulpwood	Hardwoods Sawtimber	Hardwoods Pulpwood	Total
		(million cubic feet)			
1974-2000	3.3	98.1	8.3	10.4	120.1
2001-2025	368.8	199.2	14.6	8.4	590.9
2026-2050	81.4	1.0	33.4	-10.1	105.8
2051-2075	71.8	-1.7	1.3	0.9	72.3
2076-2100	154.4	0.0	-0.1	0.5	154.8
Total	679.7	296.7	57.4	10.1	1043.9

(table 10). The majority of this yield is softwood sawtimber (65%) and softwood pulpwood accounts for most of the rest (28%). Hardwoods account for a much smaller yield increase. This is in keeping with the observation that intermediate treatments in hardwoods primarily affect tree quality and species composition, not total yield. Hardwood treatments were also a relatively small component of the program. The average increases in mean annual increment (MAI) in cubic feet/acre/year are:

Product	MAI increase
softwood sawtimber	44.01
softwood pulpwood	26.93
hardwood sawtimber	2.44
hardwood pulpwood	0.44
total	73.82

The first rotation yield increases are spread over a 125-year period, from 1974 to 2100. A very large share (40%) of the softwood sawtimber yield increase is expected to occur between 2020 and 2025 when the loblolly pine plantations mature. Over half (55%) of the softwood sawtimber yield increase occurs within 50 years of the initial investment. Twelve percent occurs between 51 and 75 years after 1974 and 11% occurs in the final 25-year period. Twenty-three percent occurs 100 to 125 years after initial investment when the northern pine plantations mature. The softwood pulpwood yield increase generally occurs earlier, 33% in the first 25 years and 67% in the next 25 years. Most of the pulpwood yield comes in commercial thinnings while the majority of the sawtimber yields are not achieved until final harvest.

Forty-two percent of the hardwood sawtimber yield occurs in the first two 25-year periods. The remaining 58% of the hardwood sawtimber yield occurs between 51 to 75 years following the initial investment.

Roughly 0.1% of the nonindustrial private commercial timberland was treated under the 1974 FIP program. Although the softwood yield increases from the first rotation are spread over a 125-year period, their sum equals 28% of the total nonindustrial private softwood removals from growing stock in 1970 (USDA-FS 1973). The average softwood rotation in the 1974 FIP cases was 54 years. The average first rotation softwood yield increase for all the cases was 3.86 thousand cubic feet per acre.

Assuming that a similar 0.1% could be treated each of the 54 years, and assuming that their total output equals the 1974 level on the average, 28% of the annual softwood growing stock removals in this class could be derived each year from 5.4% of the nonindustrial private acreage. Carried one step further, if enough similar acres could be located, management of 19% of the nonindustrial private acreage would produce an average annual yield increase equal to the total 1970 removals from this owner class. This small percentage is not surprising given that the majority of the softwood yield on nonindustrial private lands currently come from natural stands where the pines must compete with hardwoods, while the FIP cases are heavily weighted toward plantations on bare land or those following conversion.

This means that intensive culture on a relatively small percentage of the total acres could produce as much yield increase as is currently being produced from the total commercial timberland base. These conclusions are similar to those reached by Vaux (1973) for California. Intensive culture of a larger percentage of the acreage could produce more output and a significant percentage of the acreage would still be free for nontimber management objectives.

Sensitivity of Aggregate Results to Changes in Data and Assumptions

The sensitivity of the IROR in each sample case to changes in data input was measured. Sensitivity was measured by determining how much of a percentage change in selected groups of data was necessary to change the IROR of each case by 1 percentage point of interest, e.g., from 6.4% return to 5.4% or 7.4%. Sensitivity to changes in each of four data groups was measured independently; subsequent treatment costs, commercial thinning yields, final harvest yields, and stumpage prices. Only data in the first rotation of the intense regime was subjected to the sensitivity analysis. If the sensitivity of the same data items in the intense and current regimes had been tested jointly, the sensitivity would be much lower since the errors tend to compensate for each other. The computer program developed by Goforth and Mills (1975) was used to measure the sensitivity and can be found in more detail in Mills et al. (1976).

The simple average of percentage data changes for individual sample cases with non-zero IROR's was calculated for each of the 77 sample cells or strata (append. table A10). The sensitivity results were further summarized by determining how many cells had average sensitivity levels between certain bounds or percentage data change (table 11).

The sensitivity to errors in the subsequent treatment cost data is very low. The subsequent treatment cost estimates would have to be decreased on the average by 200% in most cells before the IROR is increased by 1% of interest. That is, the cost estimate would actually have to change signs. There is also low sensitivity to errors in the final harvest yield values. In 60 of the sample cells, final harvest yields would have to be increased by more than 100% before the IROR rises 1% of interest.

The financial return results are more sensitive to the commercial thinnings yields, even though they generally produce less yield, largely because they occur earlier in the regime than the final harvests. Even with the commercial thinnings, though, in 57 of the 75 cells that contained thinnings, the yields would have to be increased at least 25% on the average to raise the IROR by 1% of interest.

Table 11. Number of sample cells with data sensitivity levels between certain bounds of percentage data change, by data group

Percentage data change[1]	Subsequent treatment costs[2]	Commercial thinning yields	Final harvest yields	Stumpage prices
0-9	—	3	—	2
10-24	—	15	1	28
25-49	—	26	1	32
50-99	—	24	15	13
100-199	4	6	23	1
200 +	48	1	37	1

[1]*Average percentage change of data within cases in a sample cell necessary to increase IROR by 1 percent of interest. For example, in three of the sample cells, the commercial thinning yield estimates had to be changed by 0-9% in order to raise the IROR by 1% of interest.*

[2]*The percentage changes are negative for the cost class.*

The most sensitive of the data tested is the stumpage price data. In 30 of the cells, a data error of less than 25% would change the IROR by the specified sensitivity level. The highest sensitivity areas are largely intermediate treatment cases (append. table A10). Even with stumpage price data, however, in 47 of the cells the price estimates would have to be raised more than 25% before the IROR would increase 1% of interest. In summary, there appear to be few situations where potential data errors could materially affect the financial return results. Estimated financial return is more sensitive to the initial cost than to any of the other data items (Mills et al. 1976). Sensitivity of the initial cost was not measured, however, since it had already been expended.

The impact of changing three basic assumptions in the analysis procedures was also tested. First, as shown in the yield information in appendix table A4, the softwood plantation regimes contain from 0 to 4 commercial thinnings and the hardwood intermediate treatment regimes contain from 0 to 5 commercial thinnings. Although thinnings were not included unless they contained merchantable volumes, there are widely varying opinions about their desirability.

A simple test of the impact of the thinning assumption was made by accumulating all commercial thinning volumes into the final harvest without reducing the total rotation harvest volume or changing the rotation length. Under the direct cost option, this reduced the weighted average IROR of all cases in the 1974 eastern population from 10.3% to 7.9%, a reduction of approximately one-fourth. Perhaps more significantly, only 58% of the cases could earn 6-3/8% when thinnings were removed versus 76% when the thinnings were retained. Although it is felt that the thinnings included are silviculturally and economically practical, this points up the necessity of follow-up assistance to these owners to insure that the thinning yields are marketed. Although the previously discussed analysis of data sensitivity indicates that the actual thinning volume achieved can fluctuate some without significantly influencing IROR, this assumption test shows that the thinning *must* take place to gain the estimated returns.

Second, the assumed increase in post-treatment stumpage prices to reflect tree quality impacts of the treatment was tested. The increase of post-treatment prices was removed so the pre- and post-treatment prices were the same by species. Price changes reflective of species composition changes were retained. Again using the eastern population as a test, the weighted average IROR only declined from 10.3% to 10.2%. The greatest impact of removing this assumption was on northern hardwood cases where the weighted average IROR declined from 15.0% to 13.3%.

Last, the second and perpetual rotations of both the intense and current regimes were removed, leaving only the first rotation of each. This was tested in five representative sample cells (cells 11, 25, 39, 50, and 55). The weighted average IROR changed by less than 0.1 percentage point of interest.

The perpetual rotations permit a "clean" financial return comparison with similar time horizons but it is an unnecessary refinement for these timber investments.

Regional and Broad Practice Group Results

The estimates of MAI increase and percentage of cases that can earn 6-3/8% and 7-1/2% differ quite a bit by region. The major financial return and yield indicators of performance were higher in the South than in any other region and 66% of the federal cost-share funds were expended in the South in 1974 (table 12). The average IROR was 10.8% and the average per acre MAI increase was 94 cubic feet. Eighty-eight percent of the cases could earn 6-3/8%.

The average IROR in the North was lower, 8.9%, and so was the average per acre MAI increase, 42 cubic feet. The smaller yield increase is related to the larger proportion of hardwood investments. In the North 66% of the cases could earn 6-3/8%, down 22% from the South.

Table 12. Financial return and yield results by region under the direct cost option

Region	Average IROR	Average MAI increase	Cases earning discount rate 6-3/8%	Cases earning discount rate 7-1/2%	Percentage of total funds
	(percent)	*(cubic feet/acre)*	*(percent)*		*(percent)*
South	10.8	94	88	86	66
North	8.9	42	66	52	29
Pacific Coast	9.4	67	61	58	3
Rocky Mountains	2.9	2	12	7	2

The average IROR in the Pacific Coast was 9.4% and the average per acre MAI increase was 67 cubic feet, both of which are between those of the North and South. Although the Pacific Coast average IROR was greater than in the North, 5% less (or 61%) of the cases were capable of earning 6-3/8%.

The average IROR in the Rocky Mountains was 2.9%. The other indicators of timber yield and financial return performance were also relatively lower than for the South, North, and Pacific Coast. Only 2% of the 1976 federal funds were spent in the Rocky Mountains, however, so the total program impact was small.

Of the states sampled individually, New York had the highest average IROR (20.0%) under the direct cost option, followed by Indiana (14.6%), Louisiana (14.1%), Florida (12.6%), and Georgia (12.3%) (append. table A11). Several other Southern states had average IROR's above 10%.

The variations in average IROR by state are largely reflective of the sites treated, the mix of practices applied, and regional stumpage price differentials. The average IROR from the southern pine plantings was 11.3% or almost twice as high as the average IROR on northern conifer plantings (6.9%) and over twice as great as the IROR of western conifer plantings (5.0%) (table 13). The percentage of the cases capable of earning 6-3/8% varied similarly. Ninety-one percent of the southern pine plantings, 63% of the northern conifer plantings, but only 47% of the western conifer plantings, could earn the target rate.

The northern conifer plantings do have a larger MAI increase (122 cubic feet) than the southern pine plantings (108 cubic feet). The northern conifers, especially white and red pine, are capable of maintaining a high periodic growth longer than the southern pines which gives rise to the relatively large first rotation yield in the northern conifer plantings. The financial returns are lower in spite of this growth characteristic because fewer northern conifer plantations had the minimum acceptable stocking levels, the MAI peaks at an older age than for southern pine, and the pine stumpage prices in the regions where northern conifers were planted are not as high as where southern pines were planted.

The hardwood plantings had a high average IROR (10.2%). The management regimes required to achieve this return are quite intense, however, requiring several subsequent cultural operations. If those subsequent practices are not installed, the financial return picture will be much different.

The average IROR for timber stand improvements in southern pine and oak-pine and in northern conifers are essentially the same (9.3 and 9.4%). The returns on timber stand improvements of western conifers are lower (7.3%), largely because fewer cases passed the silvicultural thresholds. The per acre MAI increase for the conifer timber stand improvements are much less than for the plantings — 45 cubic feet for southern pines and oak-pine, 25 cubic feet for northern conifers, and 16 cubic feet for western conifers. The yield increase is smaller because the current regime of timber stand improvement cases contains the unmanaged yield of an existing stand. The current regime in most planting cases has negligible yield or largely unmerchantable species.

Timber stand improvements in the cove hardwood and black walnut cases had the highest average IROR of any of the broad practice groups (21.4%). The northern hardwood cases are also high (15.0%). Only a small amount of this high IROR can be attributed to yield increase. The average MAI increases for the two species groups are only 16 and 10 cubic feet, respectively. Although some can be attributed to the assumption of tree quality increase due to the treatment as reflected through stumpage price, when the assumption was removed the average IROR of the northern hardwood cases only fell to 13.3% and the cove hardwood and black walnut fell even less to 20.8%.

Two main factors contribute to these high returns. First, the stumpage price assumptions for the predominant species are high enough that a small yield increase is sufficient. Second, and most important, is the species composition impact of the treatment. Although the post-treatment yield might only be slightly larger than pretreatment yield, it is generally dominated by higher value species. The species composition impact of hardwood timber stand improvements is often ignored in studies of treatment potentials, which leads to an underestimate of potential returns. On the other hand, the impact of the species

Table 13. Financial return and yield results by broad practice groups under the direct cost option

Species group and practice	Average IROR	Total B/C ratio @ 6-3/8%	Total PNW @ 6-3/8%	Cases earning 6-3/8%	Average MAI increase	Total yield increase: Sawtimber	Total yield increase: Pulpwood
	(percent)		(mil. dollars)	(percent)	(cu. ft./ ac./yr.)	(million cubic feet)	
Southern pine, plantings	11.3	4.6	29.31	91	108.1	320.1	229.8
Southern pine and oak-pine, timber stand improvement	9.3	4.3	4.25	73	45.4	45.2	33.4
Northern conifer, plantings	6.9	1.4	0.66	63	122.5	298.1	27.9
Northern conifer, timber stand improvement	9.4	1.8	0.57	76	24.6	13.5	3.7
Hardwood, planting	10.2	26.8	6.13	70	44.0	6.1	2.0
Oak-hickory, timber stand improvement	4.7	1.6	0.72	42	9.5	25.6	2.4
Black walnut & cove hardwood, timber stand improvement	21.4	25.7	7.98	80	16.3	10.9	0.2
Northern hardwood, timber stand improvement	15.0	5.9	2.75	80	10.4		4.6
Western conifers, planting	5.0	4.6	1.01	47	67.1	2.3	2.4
Western conifers, timber stand improvement	7.3	2.2	0.58	33	15.6	2.6	0.5
Total, all species and practices	10.2	5.6	53.96	74	74.8	737.8	306.8

composition change is a function of differential stumpage prices by species.

The same stumpage price differentials by species which occur now are assumed to occur at the time of harvest in the treated hardwood stands. If this price differential does not continue or if the price differential changes by species, the hardwood timber stand improvements will have much lower returns. The price differentials are largely influenced by consumer preferences for products like furniture. The future hardwood prices, and the estimated returns, are more uncertain than the softwood prices.

The average IROR for oak-hickory timber stand improvements is lower than for any other broad practice group (4.7%). The MAI increase is lowest (10 cubic feet) and so is the percentage of the cases capable of earning 6-3/8% (42%). The lower performance resulted from a large number of cases exceeding the silvicultural thresholds, especially the one for maximum stand age. The average IROR of oak-hickory cases that do pass the silvicultural thresholds, however, is about 10%, again reflecting the low treatment cost and species composition impact of the treatment. The same tabulation of results under the total cost option is contained in appendix table A12.

Relatively High and Low Performance Program Segments

Three indicators of timber production performance were used to determine the performance of program segments: the weighted average IROR with respect to the 6-3/8% return criterion, the percentage of cases capable of earning 6-3/8% return, and the average per acre MAI increase relative to the average for the 1974 program. Only large program segments were rated against these indicators unless the segment was isolated enough to permit easy program modification. Financial return criteria were generally given more weight than physical timber yield increase in this ranking. Study results are shown in table 5, and appendix tables A13, A14, and A3.

Loblolly pine plantings ranked highest with respect to these three characteristics. These plantings had an above average IROR and MAI increase. Ninety-three percent of the cases can earn 6-3/8%. Slash pine plantings also ranked high. Their average IROR is higher but the MAI increase and percentage of cases earning 6-3/8% are lower than for loblolly pine plantings. Loblolly pine understory release cases (release of an established understory from overstory competition) constitute a smaller part of the program but their returns are high. The percentage of cases capable of earning 6-3/8% is higher than for any other program segment (97%).

Some of these southern pine planting cases have enough hardwood invasion to require a subsequent hardwood control treatment. Similarly, many of the understory release cases are overstocked such that the management regimes include a subsequent precommercial thinning. If these follow-up treatments are not installed, the actual returns realized will be lower than the estimates (table 14).

Intermediate treatments in northern hardwoods had a high average IROR (15.0%), higher than for southern pine treatments. The major reason is change in species composition brought about by the practice, coupled with high stumpage prices. Eighty percent of the cases can earn the 6-3/8% return.

Intermediate treatments in cove hardwoods had an even higher average IROR (16.0%) and so did black walnut intermediate treatments (16.9%). Both of these "fine hardwood" treatments had below-average percentages of cases earning 6-3/8%, though, just over 70% for both practices.

Intermediate treatments in Douglas-fir had a higher average IROR (14.8%) than similar treatments of eastern conifers. Less than half of the Douglas-fir intermediate treatment practices could earn 6-3/8%, however.

The primary reason that individual cases in the high performance program segments could not earn the 6-3/8% return limit was failure to pass one of the silvicultural thresholds, such as minimum plantation stocking (append. table A14). Cases that did pass the silvicultural thresholds, however, could usually earn 6-3/8%. The only two exceptions were intermediate treatments in black walnut and Douglas-fir. In these practices, some cases that passed the silvicultural thresholds failed to earn 6-3/8%. This usually resulted from some combination of low sites and/or high treatment costs. The high cost and low sites of some Pacific Coast investments in 1974 was noted in the first stage evaluation of the 1974 FIP evaluation (Mills 1976).

The low performance program segments were predominantly conifer treatments. Timber stand improvements in slash pine and oak-pine stands were low performance segments (table 15). With a low average IROR, only 12% and 19%, respectively, could earn 6-3/8%.

Treatment of slash pine and oak pine stands above the maximum stand age threshold were the primary reason for the low performance. This finding is contrary to the high returns for southern pine and oak-pine timber stand improvement derived by Anderson (1968). The reason is that some individual trees removed during the practice were sold in Anderson's analysis, which lowered the effective practice cost. No such salvage was assumed in this study. Extensive salvage is not permitted in FIP practices and the ground measurements indicate that little salvage occurred in this practice.

Shortleaf pine plantings had an average IROR of 5.7% with 25% earning 6-3/8%. Most loss is due to low financial returns rather than inadequate stocking. Shortleaf pine rotations are longer than the loblolly and slash pine rotations. Shortleaf pine is also planted in lower stumpage price regions.

White pine plantings had an IROR of 6.1% and 50% can earn 6-3/8%, even though there is a large MAI increase. The reason white pine plantings fail to earn 6-3/8% is split between inadequate stocking and low financial returns even when stocking is above the 200 seedling limit.

Spruce plantings have a lower than average IROR and percentage of cases earning 6-3/8%. Timber stand improvements in spruce-fir and hemlock have an average IROR of 3.0%.

Ponderosa pine plantings and timber stand improvements were both low performance segments

Table 14. Major segments of the 1974 FIP program which exhibited relatively high financial return and timber yield performance

Program segment[1]	Weighted average IROR	Percent of cases earning 6-3/8%	Weighted average MAI increase
	(percent)		*(cu. ft./ac./yr.)*
1. Loblolly pine, planting	10.9	93	110.1
2. Slash pine, planting	12.4	90	104.8
3. Loblolly pine, understory release	12.6	97	91.3
4. Northern hardwood, timber stand improvement	15.0	80	10.4
5. Cove hardwood, timber stand improvement	16.0	72	26.9
6. Black walnut, timber stand improvement	16.9	71	4.1
7. Douglas-fir, timber stand improvement	14.8	48	39.9

[1]*In some situations these "segments" are aggregations of the detailed groups shown in appendix table A. "Timber stand improvement" includes the precommercial thinning, intermediate treatments, prune and intermediate treatment, and prune practices, for example.*

Table 15. Major segments of the 1974 FIP program which exhibited relatively low financial return and timber yield performance

Program segment[1]	Weighted average IROR	Percent of cases earning 6-3/8%	Weighted average MAI increase
	(percent)		*(cu. ft./ac./yr.)*
1. Slash pine, timber stand improvement	3.2	12	4.5
2. Oak-pine, timber stand improvement	4.8	19	3.2
3. Shortleaf pine, planting	5.7	24	62.6
4. White pine, planting	6.1	49	126.9
5. Spruce, planting	6.7	63	106.2
6. Spruce-fir & hemlock, timber stand improvement	3.0	24	1.5
7. Oak-hickory, timber stand improvement	4.7	43	9.5
8. Ponderosa pine, planting	2.0	11	12.4
9. Ponderosa pine, timber stand improvement	3.7	26	1.6

[1]*In some situations these "segments" are aggregations of the detailed groups shown in appendix table A. "Timber stand improvement" includes the precommercial thinning, intermediate treatments, prune and intermediate treatment, and prune practices, for example.*

with an IROR of 2.0% and 3.7% respectively. The MAI increases and percentages that can earn 6-3/8% return are also quite low.

The only major hardwood treatment that ranked low by these indicators was timber stand improvement in oak-hickory stands. The MAI increase was low (9.5 cubic feet), as it was for most hardwood treatments but the average IROR was also low (4.7%). Only 43% of the cases can earn 6-3/8%. The low percentage resulted from cases exceeding the silvicultural thresholds, particularly the one for maximum stand age. Unfortunately, these oak-hickory treatments constitute a major share of the FIP program in several central-region states.

In summary, the average estimated financial return and timber yield increase of the 1974 FIP investments are quite high. There are several major program segments which rate low against the financial return and yield criteria, however. The occurrence of low performance segments is analyzed in the following section and recommendations are made for possible program redirection.

Practices Which Require Timely Follow-up Treatment

The ground measurements from the 1974 sample cases indicate that some of the initial FIP treatments need to be followed by subsequent treatments, specifically: removal of residual basal area, hardwood or brush control in plantations, or precommercial thinning due to overstocked seedlings. Most of the needed follow-up treatments occur in conifer planting cases. In the financial return and yield increase analysis, all subsequent treatments are assumed to take place. A yield penalty was registered for these cases, however, affecting financial return. If the follow-up treatments are not done, actual returns and yield increases will be much lower than the estimated returns.

If plantations exceeded 10 square feet of residual overtopping basal area at the time of the ground measurement 1 to 1½ years following initial treatment, a follow-up treatment to remove the basal area was included. In southern pine plantings, 4.2% or an estimated 239 cases had more than 10 square feet of residual basal area (table 16). The average residual basal area for those cases was 30 square feet. The residual trees were 7 to 12 inch pine trees scattered across all of the measurement points on the sample tracts.

One explanation for this situation is that stumpage markets were soft in 1974 and the residual volume was not merchantable at that time. Another explanation is that the 5-year prior harvest rule was in effect in 1974. These may be very good planting opportunities but the overtopping trees must be removed before seedling survival is significantly affected. Some seedling survival and yield penalty were assessed against these cases. A much safer strategy in the future would be to wait until the overstory is removed before the trees are planted. That way the success of an initially costly practice, is not contingent upon a subsequent and uncertain management decision or variations in stumpage markets.

Residual basal area is much more prevalent in southern pine understory release cases than in the planting cases. Over half or 311 of these cases had excessive residual basal area per acre. The average was 43 square feet for cases that exceed the 10 square feet basal area threshold test. As in the planting cases, the trees were mostly 5 to 12 inch crop trees, some hardwood mixed with the pine, and were usually spread across the entire tract.

A less risky future strategy here too would be to remove all of the overtopping basal area at the time of the first treatment. If insufficient numbers of established seedlings exist, postpone the treatment until enough are present or harvest the stand and plant. The planting and release cases that had overtopping basal area occurred almost exclusively in the south-central states of Oklahoma, Texas, and Louisiana.

Roughly 6.7% or 615 of the eastern conifer planting cases had enough hardwood volunteers in relation to the surviving planted seedlings to signal the need for a follow-up hardwood control treatment. Unlike the residual basal area situation, hardwood volunteers cannot be avoided by changing the nature of the initial practice. Hardwood control is simply a necessary part of the job of growing pines on some sites.

Seedling overstocking occurred in 20.5% or 114 of the southern pine understory release cases. This is also difficult to avoid at the time of initial treatment. A large percentage of the Douglas-fir planting cases also require brush control (79.0%). In total, an estimated 1,390 or 8.7% of the 1974 FIP cases require some immediate follow-up treatment.

Identification of needed follow-up is particularly important for non-industrial private owners that participated in FIP. A large percentage of these owners would not have applied the initial practice without the technical and/or the financial assistance provided by FIP and probably will not apply needed follow-up practices unassisted. Previous studies by Kurtz et al. (1978), Shackelford (1976), and Kingsley and Mayer (1972) support the hypothesis that follow-up treatments are not applied on nonindustrial private lands as frequently as needed.

Follow-up assistance, at least of a technical nature, should be an integral part of the program delivery structure. This may only be accomplished under existing money and manpower constraints at the expense of signing new cases. The follow-up treatments are usually low cost practices, but they "protect" much more costly planting practices. New and costly planting treatments are questionable if the potential of past plantings is not achieved for want of a low cost and financially justifiable follow-up treatment. This is just one more facet on the question of program quality versus quantity. Too much emphasis on program size often results in lower quality and smaller final program effect in turn.

Practices that Failed to Pass Silvicultural Threshold Tests

Four silvicultural threshold categories were used to identify cases likely to produce negligible yield increase: insufficient plantation stocking, treatment of old stands, treatment of understocked stands, and removal of insufficient basal area (table 3). Some cases, particularly plantations, failed threshold tests because of natural factors that were not predictable at the time the practice was installed. These are simply the risks of growing a timber crop. There were cases though, where the prescribing forester could have developed information to indicate that the case probably would fail. These situations are labeled "management controllable" threshold failures.

Eleven percent or 1,165 of all the 1974 plantation cases had insufficient surviving seedling stocking to justify carrying the plantation to maturity. Ground observer comments were studied to determine if the low stocking could have been avoided by proper pre-

Table 16. Specific follow-up treatments needed and scope of each

Follow-up treatment and practice category	Percent of practice category affected	Number of cases	Predominant states
Remove overtopping basal area from southern pine plantings	4.2	239	Louisiana Oklahoma Texas
Remove overtopping basal area from released seedlings, southern pine	56.1	311	Louisiana Mississippi Oklahoma Texas
Hardwood control in southern pine and northern conifer plantings	6.7	615	North Carolina South Carolina Pennsylvania
Precommercial thinning in overstocked southern pine release cases	20.5	114	Texas Mississippi Virginia
Spray for brush control in Douglas-fir plantings	79.0	111	Oregon Washington
Total	8.7	1390	

Table 17. Management controllable situations when silvicultural thresholds were exceeded

Threshold affected	Percent of class affected	Number of cases	Major practice categories
Insufficient plantation stocking	6.4	649	Southern pines Northern conifers Western conifers
Treatment of old stands	21.3	1087	Oak-hickory Southern pines
Removal of insufficient basal area	4.9	235	Oak-hickory
Treatment of understocked stands	2.4	113	
Total	13.1	2084	

scription and treatment. Over half of the plantation failures were management controllable (table 17). The reasons given include inadequate site preparation, poor planting stock, and failure to remove overtopping trees. About half of the southern pine and northern conifer plantation failures were identified as management controllable (table 18). Since this designation was made using remarks from ground observers, it may understate the problem. All of the Douglas-fir and ponderosa pine plantation failures measured at the age of 1 to 1½ years were identified as management controllable.

A closer look at the distribution of plantations by stocking class in figure 5 shows that a large percentage of the slash pine and loblolly pine plantations fell in the "optimum" stocking range of 400 to 599 surviving seedlings per acre. Roughly 20% fell in the 200 to 399 tree range. Even though these latter cases exceed the 200 tree minimum stocking threshold, a yield penalty was assessed, usually by foregoing early thinnings until stand density reached full stocking. The distribution of northern conifer plantations in figure 6 shows a similar relationship although the largest concentration of red pine and spruce-fir plantations are in a higher stocking class—600 to 799 surviving seedlings.

Study of recorded ground measurement indicated that almost all of the timber stand improvement cases which exceeded silvicultural thresholds fell into the management controllable category. Treatment of over-aged stands was the most common threshold exceeded. This occurred in 1,087 cases or 21.3% of the timber stand improvement cases.

Treatment of old stands was especially prevalent in oak-hickory and southern pine and oak-pine timber stand improvements. Half of the oak-hickory timber stand improvements were over the 45-year silvicultural threshold (table 18).

Figure 7 also shows that most cases did not fall just over the threshold. Ten percent of the oak-hickory cases were stands over 80 years old. A small number of the cases over 45 years old may have an acceptable IROR if the species composition is improved significantly by the practice. Some yield increase can also be achieved by treatment of some of these stands, but they are decidedly low priority treatments.

The largest share of the southern pine cases over the age threshold were slash pine cases which were compared against a 20-year threshold (fig. 8). Fourteen percent of the northern hardwood timber stand improvements were over the 60 year threshold and about half as many black walnut and cove hardwood cases were. The black walnut and cove hardwood cases were largely 20 to 45 years old, which is very desirable for timber yield effect.

All of the red pine stands were between 11 to 30 years old at the time of treatment (fig. 9). Treatment of 40 to 50 year old white pine and spruce-fir stands was not uncommon though. Only 10% of the ponderosa pine stands were less than 40 years old at the time of treatment (fig. 10). Forty-five percent were over 70 years old, some going as high as 89 years. Older maximum age thresholds were used on western types than on eastern conifer types.

Removal of insufficient basal area occurred in 235 cases which was less frequent than the excessive age problem. This "light treatment" situation occurred in more than 5% of the timber stand improvements in southern pine and oak-pine, northern conifers, and oak-hickory stands (table 15). Treatment of understocked stands that were understocked before the practice was applied occurred in 113 cases.

In total, 2,084 cases exceeded the silvicultural thresholds used in this study. The thresholds were based upon standard silvicultural information, such as stand age, stocking, and species composition. If this stand information had been collected and properly evaluated, many cases would have been treated differently or would have been rejected for treatment. Over half (51%) of the oak-hickory timber stand improvements and 44% of the southern pine and oak-pine timber stand improvements failed the basic silvicultural threshold tests used in this study.

Conclusions and Recommendations

The average financial returns for the 1974 Forestry Incentives Program (FIP) are quite high. The average real internal rate of return (IROR) was 10.2%. The average and total yield increase resulting from the 1974 cases is also quite high. This is impressive con-

Table 18. Reasons that silvicultural thresholds were exceeded, by species group

Practice and reason	Southern pine and oak-pine	Northern conifers	Oak-hickory	Northern hardwood	Black walnut and cove hardwood	Douglas-fir	Ponderosa pine
	(percent of cases)						
Plantations:							
Management causes[1]	3.2	7.7	—	—	—	21.5	82.1
Natural[2]	1.6	0.9	—	—	—	—	—
Other[3]	0.7	2.4	—	—	—	—	—
No reason	1.8	4.4	—	—	—	—	—
Total	7.2	15.3	—	—	—	21.5	82.1
Intermediate:							
Excessive stand age	30.2	3.3	50.2	14.2	7.7	16.2	36.7
Treatment of understocked stands	4.7	2.4	1.2	1.0	2.8	5.9	—
Removal of insufficient basal area	8.9	6.6	5.2	1.5	4.5	—	—
Other[4]	—	0.8	—	2.4	—	4.1	7.0
Total	43.8	13.1	56.9	19.2	15.0	26.1	43.7

[1] *Management causes include: poor planting stock, inadequate site preparation, incorrect species, grazing of site, planting under an overstory.*
[2] *Natural causes include: fire, drought, flooding.*
[3] *Other includes: land use change, ownership changes*
[4] *Other includes: land use change, removal of understory hardwoods.*

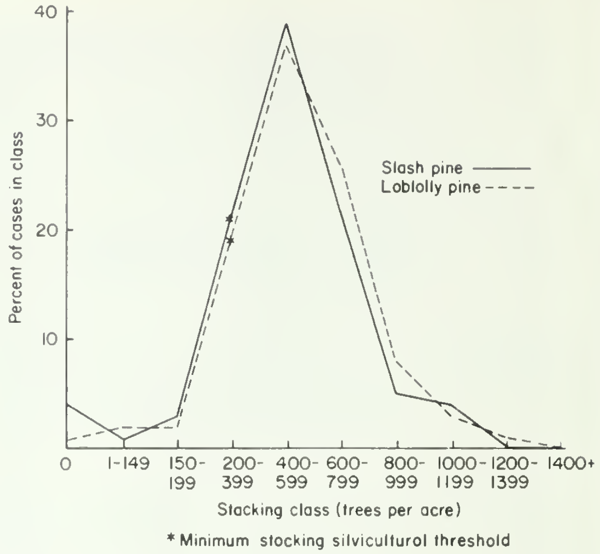

Figure 5.—Distribution of loblolly pine and slash pine plantation by stocking class.

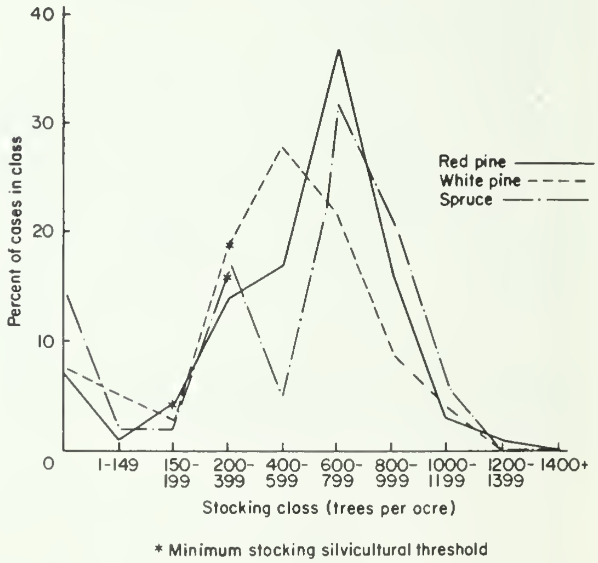

Figure 6.—Distribution of red pine, white pine, and spruce-fir plantation by stocking class.

sidering that it was the first program year and the greatest administrative effort was aimed at development of an operational program rather than upon program composition.

Several major program segments had even higher average financial returns and/or yield increase. The loblolly and slash pine plantings and timber stand improvements in northern hardwoods, cove hardwoods, and black walnut stands are particularly noteworthy.

Some segments of the 1974 program had estimated financial returns below the 6-3/8% target rate and yield increase estimates far below the average for the

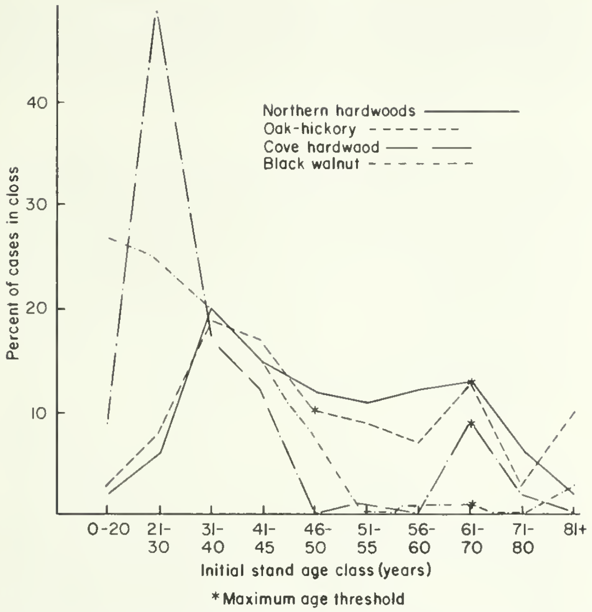

Figure 7.—Distribution of hardwood timber stand improvement cases by initial stand age classes.

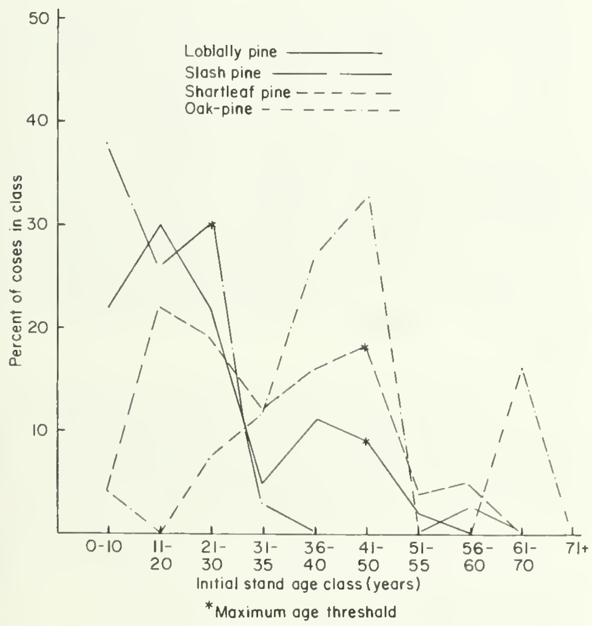

Figure 8.—Distribution of southern pine timber stand improvement cases by initial stand age classes.

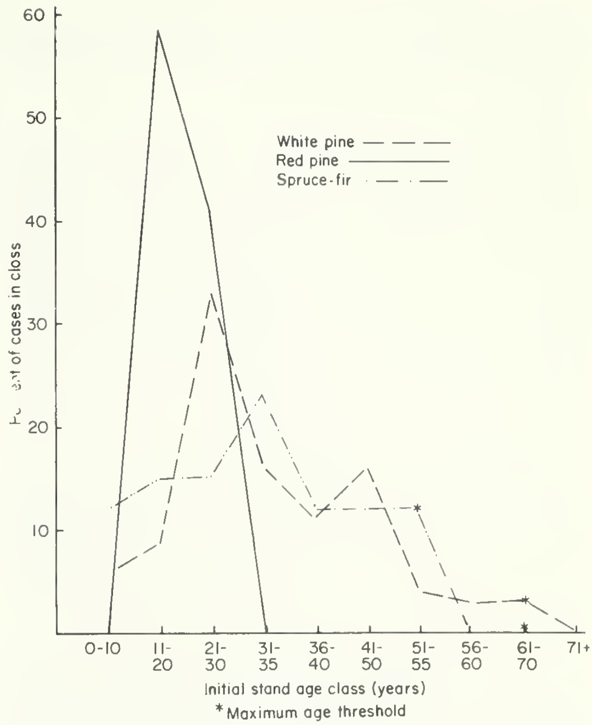

Figure 9.—Distribution of northern conifer timber stand improvement cases by initial stand age classes.

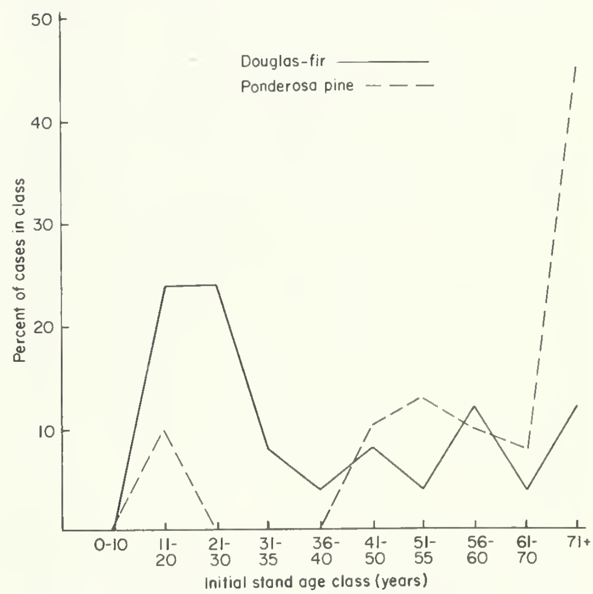

Figure 10.—Distribution of western conifer timber stand improvement cases by initial stand age classes.

1974 investments. A small percentage of these were the result of natural risks, such as drought. Most were the result of management decisions made at the time the practice was prescribed or at the time the treatment was installed.

Five recommendations for program modifications may help improve the performance of FIP in future years. While some aspects of certain recommendations are already included in program regulation changes since 1974, a more consistent and structured approach may be needed in some areas.

Recommendation #1: Develop detailed silvicultural guidelines to identify case and treatment conditions that are likely to produce only a negligible yield increase.

In 1974, an estimated $1.3 million dollars of federal and private cost-shares was spent on cases that exceeded the silvicultural thresholds, $0.9 million of that was federal funds. Additional program delivery funds were also spent. If the silvicultural guidelines embodied in this study's thresholds had been used in 1974, the average IROR would have been 12.1% rather than 10.2%. The average MAI increase would have been 87 cubic feet per acre versus 74 cubic feet and 87% of the cases would have earned 6-3/8% rather than 75% of the cases.

Guidelines may also be developed to identify the top priority investments in addition to developing guidelines that exclude only the low priority ones. Overall performance may be improved most rapidly by excluding the low performance segments first, however.

The silvicultural threshold approach used in this study simply employs some basic timber-growing knowledge that has been available and accepted for some time. The maximum stand age threshold for timber stand improvements in oak-hickory is a good example. A silvicultural guide for oak-hickory recommending a 45-year maximum stand age was published in 1971 (Gingrich) yet almost half of the oak-hickory timber stand improvement cases were over 45 years old and 10% were over 80 years old.

Some information needed for silvicultural guidelines is available in published form. Many more guidelines are required, however, which can only be based on more fragmentary research and professional judgment. Even if published guides were available for all types, it is questionable that simply referring service foresters to a scattering of published sources will lead to their use. The service forester should be given the silvicultural guidelines in one source document. The guidelines should be developed in a relatively consistent format by professionals familiar with the practices and forest types involved.

The first priority for implementation of silvicultural guidelines is timber stand improvements in oak-hickory, southern pines, and oak-pines. Second priority is timber stand improvements in the other softwood species. Third priority is timber stand improvements in other hardwoods and site preparation guidelines for pine plantings.

There is already evidence that steps have been taken by some states down this path. The practice guidelines for hardwood timber stand improvement developed in Tennessee are a good example. A more concerted and consistent nationwide effort is needed, however.

Recommendation #2: Develop maximum cost guidelines for the federal cost-share by practice, species, site index, and region so that all assisted cases can earn at least some minimum financial return.

For example, a site preparation and planting cost of $150 an acre may just yield a 6-3/8% return for a loblolly pine plantation on site 80 land in price region 10. If a 75% cost-share rate is used, the maximum federal cost-share for the practice would be $113. If a particular tract costs more than that to treat, the owner would have the option of paying the added cost, thereby lowering the federal cost percentage. The federal share would remain $113.

The maximum cost guidelines could be developed at a number of levels of geographic aggregation. There are advantages to each level. If a relatively disaggregated approach such as state-by-state, is used, care must be taken to insure that the analytical procedures used are consistent. Financial return is much more sensitive to the initial treatment cost than any of the subsequent costs or returns (Mills et al. 1976) and different analysis formats can give widely different answers.

If the silvicultural thresholds and maximum treatment cost guidelines, set to achieve a minimum 6-3/8% return target, had both been in use in 1974, the average real IROR of all cases would have been 12.5% and 96% of the cases would have earned 6-3/8%. The remaining 4% of the cases were unpredictable plantation failures. In 1974, an estimated $0.8 million dollars in federal plus private cost-shares, $0.6 million of which was federal cost-shares, was spent on cases that passed the silvicultural thresholds but failed to earn 6-3/8% because of a combination of species; site index, and price region effects.

Priority should be given to maximum treatment cost guidelines for shortleaf pine, red and white pine, ponderosa pine, and Douglas-fir plantings. All of these had a significant percentage of cases that passed the silvicultural thresholds but could not earn 6-3/8%. Attention has been given to treatment costs ever since the first program year and since the first stage evaluation was complete. A more structured and complete approach is warranted.

Recommendation #3: Distribute cost-shares among assistance cases in a manner more sensitive to the actual cost of treating each case, constrained by the maximum cost-share guidelines.

Because little site preparation is needed, a particular site 80 loblolly pine plantation in price region 10 may only cost $90 per acre. The prescribing forester should estimate this cost and recommend that the landowner be given $68 per acre in federal cost-shares, if the 75% share level is used. That tract should not be given $113, just because that is the maximum cost-share permitted for that practice.

Recall that the first stage evaluation concluded that there was unexplained cost variation among the states. The attempt to relate FIP treatment costs to major cost determinants such as terrain factors and the amount of basal area removed also failed. These results, and personal communication with federal and state personnel, indicate that maximum treatment cost ceilings were used in many instances in lieu of a cost-share allocation procedure which was more sensitive to the actual treatment cost of individual cases.

The probable result was that many cases received a higher cost-share than was necessary to achieve the 75% cost-share ceiling set by law. It also reduces the financial return on the investments and raises an equity question of why cost-share percentages should vary among participants. Establishment of cost-share maximums by practice, species, site index, and region as called for in Recommendation #2 should help solve this problem. Development of actual treatment cost prediction equations that could be applied case-by-case would be even more efficient, though.

The new 1978 program year regulation that permits the prescribing forester to estimate treatment cost is a step in the right direction. Some states also have varying cost maximums that relate the federal cost-share to the amount of basal area removed by the treatment. Again, a more concerted effort would improve investment efficiency.

Recommendation #4: Avoid installing practices that require immediate follow-up treatments if the practice can be installed in an alternative manner where success is not so sensitive to successful follow-up.

This recommendation is not intended to exclude efficient practices which require rapid follow-up. For example, direct seeding followed by a precommercial thinning may be more financially desirable than planting. Hardwood control may also be an integral part of plantation growth in the South on some sites. This recommendation is directed at the residual basal area cases found in the southern pine planting and southern pine understory release practices. These practices appear to needlessly place the initial investment in jeopardy. The same recommendation applies to similar practices that lead to similar conditions.

Recommendation #5: Insure that follow-up visitations to the site of the initial practice are an integral part of the program delivery structure.

Past studies of assistance programs indicate that follow-up treatment was not applied as frequently as needed. This study identifies several areas where follow-up treatments should be applied. The need for hardwood control in pine plantations is frequent enough in the 1974 cases to warrant special attention, as is the need for brush control in Douglas-fir plantations. Southern pine understory release cases were also frequently overstocked enough to need a precommercial thinning.

Similarly, commercial thinnings occur in many of the intermediate treatments in hardwoods within 10-20 years after initial treatment. Although it is not as time sensitive as subsequent treatments, the presence of the commercial thinning does influence the financial return on investment.

Whether identification of the needed follow-up leads to a subsequent technical and/or cost-sharing assist is a question of program policy. Attention to new case sign-ups at the expense of adequate follow-up practices, however, will have a significant effect upon the financial return to timber output and the timber yield increase.

Most of these recommendations, are guidelines or standards that the service forester can apply on the ground during the case selection and prescription process. The guidelines would inevitably let a few low priority investments through and block some high priority investments from assistance. If properly designed, however, the guidelines would significantly reduce the amount of low priority cases in the program very quickly.

The guidelines could be developed at one or a few central locations by individuals familiar with the analytical techniques involved. The service forester will still have to use a great deal of professional judgment in the application of the guidelines to individual situations. Freed of the detailed analysis, the forester could spend the majority of this time in locating new assists, checking for follow-up practices, making treatment prescriptions, and checking for practice completion; tasks for which the forester is uniquely situated and trained.

It has been suggested that the forester actually do the financial analysis for each case before approving assistance. While this exercise would force the forester to place all the physical and economic information at hand into a helpful format, it would detract from the tasks that only he can do. In many cases it would also result in inconsistent and incomplete analysis.

The guideline approach, where the guidelines are developed in a consistent manner, is a more practical approach that will yield the greatest and quickest improvement. Implementation of the five recommendations drawn from this study, while at the same time maintaining recent gains such as the 10-acre minimum tract size standard, will increase the timber performance of FIP significantly.

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Appendix

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Appendix Table A1. Sample ground measurement reporting form for a site preparation and planting case.

Forestry Incentives Program
Treatment Analysis Record

A. Location Description — Card 1 (80) — (1) … (31)

1. Sample Number	14820	7. Site Index	070
2. State	13	8. Site Species	131
3. County	251	9. Slope	1
4. Farm Number		10. Physiographic Class	3
5. Prior CFM	1	11. Adjacent Available Acres	128
6. Prior Land Use	1	12. Treatment Applied	1

B. Stand Conditions — Card 2 (80), Card 3 (80)

(6) Pretreatment Conditions		Post Treatment Conditions (77)	
13. Crop Species	131	13. Crop Species	
14. Crop BA/AC	040	14. Crop BA/AC	
a. Additional Crop BA/AC		a. Additional Crop BA/AC	
15. Other Trees BA/AC	120	15. Other Trees BA/AC	
(6)		(29)	
16. Dominant/Codom. Average DBH	06	16. Dominant/Codom. Average DBH	
17. Dominant/Codom. Average Height	025	17. Dominant/Codom. Average Height	
18. Dominant/Codom. Average Age	030	18. Dominant/Codom. Average Age	
19. Operability	2	19. Operability	2
20. Acres To Be Treated	052	20. Acres Treated	052

C. Tree Planting — Card 3 (80), Card 4 (80) — (30) … (53)

Prescribed		Observed	
21. Planting Treatment	2	21. Planting Treatment	2
a. Method of Site Preparation	1	a. Method of Site Preparation	1
b. Intensity of Site Preparation	3	b. Intensity of Site Preparation	3
22. Species	131 / — / —	22. Species	131 / 800 / 400 / Other
(6)		(65) No/Acre	
a. No./Acre	0545 / — / —	a. Planted	0381 / 0000 / 0900 / 0000
		b. Volunteer	0000 / 1224 / 0057 / 0081
		c. F.T.G.	0381 / 0892 / 0049 / 0057

D. Timber Stand Improvement Treatment — Card 5 (80)

(6) Prescribed		Observed (43)	
23. Precommercial Thinning Method		23. Precommercial Thinning Method	
24. Pruning Method		24. Pruning Method	
a. Number Trees/Acre Pruned		a. Number Trees/Acre Pruned	
b. Average Pruned Height		b. Average Pruned Height	
25. Crop Tree Release Method		25. Crop Tree Release Method	
a. Number Crop Trees/Acre To Be Released		a. Number Crop Trees/Acre Released	
		b. Average Distance Between Crowns	
26. Understory Release Method		26. Understory Release Method	
a. No. Established Seedlings/Acre		a. No. Established Seedlings/Acre Released	
27. Cull Removal Method		27. Cull Removal Method	
28. Site Prep.--Natural Regeneration Method		28. Site Prep.--Natural Regeneration Method	

E. Professional Observations — (44) … (50)

29. Were Treatments Prescribed Correct?	
30. Were Treatments Applied As Prescribed?	
31. What is Next Likely Treatment?	
32. When? 15 Years	33. Number of Observations 37

34. F -- Remarks Prescribed burning used in site prep. Bulldozing apparently done in strips with hand injection work done on residual cull trees. Despite large number of oak sprouts, I believe the pine seedlings will overtop them in 4 to 7 years.

35. ______________ Observer

36. ______________ Date

Appendix Table A2. Sample ground measurement reporting form for a timber stand improvement case.

Forestry Incentives Program
Treatment Analysis Record

Card 1 (80)

(1) A. Location Description (31)

1. Sample Number	585///	7. Site Index	070
2. State	33	8. Site Species	3/7
3. County	009	9. Slope	/
4. Farm Number		10. Physiographic Class	6
5. Prior CFM	/	11. Adjacent Available Acres	085
6. Prior Land Use	/	12. Treatment Applied	2

Card 2 (80)

B. Stand Conditions

(6) Pretreatment Conditions		Post Treatment Conditions (77)	
13. Crop Species	3//73//854//37/	13. Crop Species	3//73//854//37/
14. Crop BA/AC	0//60//400800 4	14. Crop BA/AC	0//60//400800 4
a. Additional Crop BA/AC		a. Additional Crop BA/AC	
15. Other Trees BA/AC	078	15. Other Trees BA/AC	044

Card 3 (80)

(6)		(29)	
16. Dominant/Codom. Average DBH	09	16. Dominant/Codom. Average DBH	09
17. Dominant/Codom. Average Height	065	17. Dominant/Codom. Average Height	065
18. Dominant/Codom. Average Age	050	18. Dominant/Codom. Average Age	050
19. Operability	2	19. Operability	2
20. Acres To Be Treated	004	20. Acres Treated	004

(30) C. Tree Planting (53)

Prescribed		Observed	
21. Planting Treatment		21. Planting Treatment	
a. Method of Site Preparation		a. Method of Site Preparation	
b. Intensity of Site Preparation		b. Intensity of Site Preparation	
22. Species		22. Species	Other

Card 4 (80)

(6)		(65) No/Acre	
a. No./Acre		a. Planted	
		b. Volunteer	
		c. F.T.G.	

Card 5 (80)

D. Timber Stand Improvement Treatment

(6) Prescribed		Observed (43)	
23. Precommercial Thinning Method	/	23. Precommercial Thinning Method	/
24. Pruning Method		24. Pruning Method	
a. Number Trees/Acre Pruned		a. Number Trees/Acre Pruned	
b. Average Pruned Height		b. Average Pruned Height	
25. Crop Tree Release Method	5	25. Crop Tree Release Method	5
a. Number Crop Trees/Acre To Be Released	/00	a. Number Crop Trees/Acre Released	095
		b. Average Distance Between Crowns	20
26. Understory Release Method		26. Understory Release Method	
a. No. Established Seedlings/Acre		a. No. Established Seedlings/Acre Released	
27. Cull Removal Method		27. Cull Removal Method	
28. Site Prep.--Natural Regeneration Method		28. Site Prep.--Natural Regeneration Method	

(44) E. Professional Observations (50)

29. Were Treatments Prescribed Correct?	/
30. Were Treatments Applied As Prescribed?	/
31. What is Next Likely Treatment?	/
32. When? /0 Years	33. Number of Observations 05

34. F -- Remarks An excellent job of thinning in northern hardwoods. Adjacent commercial operation salvaged much of the small amount of merchantable timber killed to properly effect the release. Trees were killed with a frill and silvisar. Results of this were excellent on all observed species.

35. ______________________ Observer

36. ______________________ Date

Appendix Table A3. Definitions of the species group codes used to distinguish between stylized management regimes

Species group code	Definition
1. Slash pine:	the greatest number of the surviving planted seedlings are slash pine; or in the case of a timber stand improvement where greater than 50% of the crop basal area is longleaf, loblolly, shortleaf, and/or slash pine, slash pine has the greatest amount of basal area.
2. Longleaf pine:	the greatest number of the surviving planted seedlings are longleaf pine; or in the case of a timber stand improvement where greater than 50% of the crop basal area is longleaf, loblolly, shortleaf and/or slash pine, longleaf pine has the greatest amount of basal area.
3. Loblolly pine:	the greatest number of the surviving planted seedlings are loblolly pine; or in the case of a timber stand improvement where greater than 50% of the crop basal area is longleaf, loblolly, shortleaf and/or slash pine, loblolly pine has the greatest amount of basal area.
4. Shortleaf pine:	the greatest number of the surviving planted seedlings are shortleaf pine; or in the case of a timber stand improvement where greater than 50% of the crop basal area is longleaf, loblolly, shortleaf and/or slash pine, shortleaf pine has the greatest amount of basal area.
5. Virginia pine and other southern pine:	the greatest number of the surviving planted seedlings are Virginia pine or other southern pine; or in the case of a timber stand improvement where greater than 50% of the crop basal area is Virginia pine and/or other southern pine.
6. Oak-pine:	greater than 50% of the crop basal area is northern red oak, southern red oak, white oak, other oaks, hickory, gums, and/or sweetgum, and 15% to 50% of the crop basal area is longleaf, loblolly, shortleaf and/or slash pine.
7. Red pine:	the greatest amount of the surviving planted seedlings are red pine; or in the case of pruning the greatest amount of the crop basal area is red pine.
8. White pine:	the greatest amount of the surviving planted seedlings are white pine; or in the case of pruning the greatest amount of the crop basal area is white pine.
9. Spruce/Spruce-fir:	the greatest amount of surviving planted seedlings are black spruce, red spruce, white spruce, balsam fir, and/or other true firs; or in the case of a timber stand improvement, greater than 50% of the crop basal area is black spruce, red spruce, white spruce, balsam fir, and/or other true firs.
10. Northern pine:	greater than 45% of the crop basal is eastern white pine, red pine, jack pine, and/or hemlock, but less than 47% of the crop basal area is hemlock, and/or less than 45% is hard maple, soft maple, beech, yellow birch, black cherry, and/or basswood.
11. Jack pine:	the greatest amount of the surviving planted seedlings are jack pine.
12. Oak-hickory:	greater than 49% of the crop basal area is hickory, northern red oak, southern red oak, white oak, other oaks, yellow poplar, elm, and/or white ash but less than 8% of the crop basal area is black walnut, less than 15% of the crop basal area is loblolly, longleaf, slash, shortleaf, less than 60% is yellow poplar, and/or less than 41% is white ash.
13. Cove hardwood:	greater than 60% of the crop basal area is yellow poplar or greater than 41% of the crop basal area is white ash, but less than 8% of the crop basal area is black walnut.
14. Black walnut:	black walnut seedlings have been planted or in the case of a timber stand improvement greater than 7% of the crop basal area is black walnut.
15. Northern hardwood:	greater than 45% of the crop basal area is hard maple, soft maple, beech, yellow birch, black cherry, basswood and/or white ash, but less than 8% of the crop basal area is black walnut, and/or less than 41% of the crop basal area is white ash.
16. Hemlock:	greater than 47% of the crop basal area is hemlock, but less than 45% is hard maple, soft maple, beech, yellow birch, black cherry and/or basswood.
17. White birch:	greater than 40% of the crop basal area is white birch and/or yellow birch, but less than 45% is hard maple, soft maple, beech, yellow birch, black cherry, and/or basswood, and/or less than 45% of the crop basal area is eastern white pine, red pine, jack pine, and/or hemlock.
18. Larch:	greater than 90% of the surviving planted seedlings are larch.
19. Ponderosa pine:	ponderosa pine was the planted species, or the crop trees were predominantly ponderosa pine.
20. Douglas-fir:	Douglas-fir was the planted species, or the crop trees were predominantly Douglas-fir.
21. Lodgepole pine:	the crop trees were predominantly lodgepole pine.

Practice	Species	Site index range	Number of thins[1]	Rotation age	Intense: Sawtimber	Intense: Pulpwood	Intense: Total	Current: Sawtimber	Current: Pulpwood	Current: Total	Net Change: Sawtimber	Net Change: Pulpwood	Net Change: Total
Plant[2]	Slash pine	[3]66-75	2	30	15.27	61.67	76.93	0.00	[4]0.00	0.00	15.27	61.67	76.93
		76-85	2	30	22.60	91.27	113.86	0.00	[4]0.00	0.00	22.60	91.27	113.86
		86-95	2	30	30.99	125.18	156.17	0.00	[4]0.00	0.00	30.99	125.18	156.17
Plant[5]	Longleaf pine	66-75	3	55	24.55	38.02	62.57	0.00	[4]0.00	0.00	24.55	38.02	62.57
		[3]76-85	3	55	32.73	50.69	83.42	0.00	[4]0.00	0.00	32.73	50.69	83.42
		86.95	3	55	39.27	60.83	100.10	0.00	[4]0.00	0.00	39.27	60.83	100.10
Plant[6]	Longleaf pine	66-75	3	50	36.00	55.80	91.80	0.00	[4]0.00	0.00	36.00	55.80	91.80
		[3]76-85	3	50	48.00	74.40	122.40	0.00	[4]0.00	0.00	48.00	74.40	122.40
		86-95	3	50	57.60	89.28	146.88	0.00	[4]0.00	0.00	57.60	89.28	146.88
Plant[7]	Loblolly pine	66-75	3	45	59.20	33.12	92.32	0.00	[4]0.00	0.00	59.20	33.12	92.32
		[3]76-85	3	45	82.22	46.00	128.22	0.00	[4]0.00	0.00	82.22	46.00	128.22
		86-95	3	45	105.24	58.88	164.12	0.00	[4]0.00	0.00	105.24	58.88	164.12
Plant[8]	Shortleaf pine	[3]66-75	3	50	42.34	49.48	91.82	0.00	[4]0.00	0.00	42.34	49.48	91.82
		76-85	3	50	55.04	64.32	119.37	0.00	[4]0.00	0.00	55.04	64.32	119.37
		86-95	3	50	67.74	79.17	146.91	0.00	[4]0.00	0.00	67.74	79.17	146.91
Plant	Virginia pine	56-65	0	30	0.00	71.23	71.23	0.00	[9]0.00	0.00	0.00	71.23	71.23
		[3]66-75	0	30	0.00	94.97	94.97	0.00	[9]0.00	0.00	0.00	94.97	94.97
		76-85	0	30	0.00	118.71	118.71	0.00	[9]0.00	0.00	0.00	118.71	118.71
Understory[10] release	Slash pine	[3]66-75	2	30	13.67	55.33	69.00	0.00	0.00	0.00	13.67	55.33	69.00
		76-85	2	30	20.23	81.89	102.12	0.00	0.00	0.00	20.23	81.89	102.12
		86-95	2	30	27.74	112.33	140.07	0.00	0.00	0.00	27.74	112.33	140.07
Understory[10] release	Loblolly pine	66-75	3	45	47.36	27.36	74.72	0.00	0.00	0.00	47.36	27.36	74.72
		[3]76-85	3	45	65.78	38.00	103.78	0.00	0.00	0.00	65.78	38.00	103.78
		86-95	3	45	84.20	48.64	132.84	0.00	0.00	0.00	84.20	48.64	132.84
Understory[10] release	Shortleaf pine	[3]66-75	3	50	33.98	39.50	73.48	0.00	0.00	0.00	33.98	39.50	73.48
		76-85	3	50	44.17	51.35	95.52	0.00	0.00	0.00	44.17	51.35	95.52
		86-95	3	50	54.37	63.20	117.57	0.00	0.00	0.00	54.37	63.20	117.57
Precommercial thin	Slash pine	[3]66-75	2	40	30.95	30.63	61.58	28.18	11.96	40.14	2.77	18.67	21.44
		76-85	2	40	45.81	45.33	91.14	35.23	14.95	50.18	10.58	30.38	40.96
		86-95	2	40	62.83	62.17	125.01	42.27	17.94	60.22	20.56	44.23	64.79
Precommercial thin	Loblolly pine	66-75	3	50	41.06	41.04	82.10	28.22	12.05	40.27	12.84	28.99	41.83
		[3]76-85	3	50	51.32	51.30	102.62	35.28	15.06	50.34	16.04	36.24	52.28
		86-95	3	50	61.58	61.56	123.14	42.34	18.07	60.41	19.24	43.49	62.73
Intermediate[11]	Virginia pine	56-65	0	30	0.00	65.45	65.45	0.00	43.05	43.05	0.00	22.40	22.40
		[3]66-75	0	30	0.00	87.27	87.27	0.00	61.50	61.50	0.00	25.77	25.77
		76-85	0	30	0.00	109.09	109.09	0.00	79.95	79.95	0.00	29.13	29.13
Intermediate[12]	Slash pine	66-75	2	40	42.40	25.92	68.32	28.18	11.96	40.14	14.22	13.96	28.18
		[3]76-85	2	40	53.00	32.40	85.40	35.23	14.95	50.18	17.77	17.45	35.22
		86-95	2	40	76.32	46.66	122.98	48.61	20.63	69.25	27.71	26.03	53.73
Intermediate[12]	Longleaf pine	66-75	3	60	34.53	15.53	50.06	18.21	7.83	26.04	16.32	7.70	24.02
		[3]76-85	3	60	43.17	19.42	62.58	22.77	9.78	32.55	20.40	9.64	30.03
		86-95	3	60	54.39	24.47	78.85	27.32	11.74	39.06	27.07	12.73	39.79
Intermediate[12]	Loblolly pine	66-75	3	50	47.84	29.01	76.85	28.22	12.05	40.27	19.62	16.96	36.58
		[3]76-85	3	50	59.80	36.26	96.06	35.28	15.06	50.34	24.52	21.20	45.72
		86-95	3	50	75.35	45.69	121.04	42.34	18.07	60.41	33.01	27.62	60.63
Intermediate[12]	Shortleaf pine	66-75	4	60	45.99	25.63	71.62	26.27	11.13	37.40	19.72	14.50	34.22
		[3]76-85	4	60	57.48	32.03	89.52	32.83	13.92	46.75	24.65	18.11	42.77
		86-95	4	60	72.43	40.36	112.80	39.40	16.70	56.10	33.03	23.66	56.70
Intermediate[13]	Longleaf pine	66-75	3	60	25.13	13.08	38.20	18.21	7.83	26.04	6.92	5.25	12.16
		[3]76-85	3	60	33.50	17.43	50.93	22.77	9.78	32.55	10.73	7.65	18.38
		86-95	3	60	41.88	21.79	63.66	27.32	11.74	39.06	14.56	10.05	24.60

Appendix Table A4. Continued

Practice	Species	Site index range	Number of thins[1]	Rotation age	Intense Sawtimber	Intense Pulpwood	Intense Total	Current Sawtimber	Current Pulpwood	Current Total	Net Change Sawtimber	Net Change Pulpwood	Net Change Total
Intermediate[13]	Loblolly pine	66-75	2	50	35.79	21.90	57.70	28.22	12.05	40.27	7.57	9.85	17.43
		[3]76-85	2	50	47.72	29.22	76.94	35.28	15.06	50.34	12.44	14.16	26.60
		86-95	2	50	59.65	36.53	96.18	42.34	18.07	60.41	17.31	18.46	35.77
Intermediate[13]	Shortleaf pine	66-75	3	60	34.98	18.75	53.73	26.27	11.13	37.40	8.71	7.62	16.33
		[3]76-85	3	60	46.65	25.00	71.65	32.83	13.92	46.75	13.82	11.08	24.90
		86-95	3	60	58.31	31.25	89.56	39.40	16.70	56.10	18.91	14.55	33.46
Intermediate[14]	Longleaf pine	66-75	2	60	21.37	8.67	30.04	18.21	7.83	26.04	3.16	0.84	4.00
		[3]76-85	2	60	26.72	10.83	37.55	22.77	9.78	32.55	3.95	1.05	5.00
		86-95	2	60	32.06	13.00	45.06	27.32	11.74	39.06	4.74	1.26	6.00
Intermediate[14]	Loblolly pine	66-75	2	[15]60	32.81	13.31	46.12	28.22	12.05	40.27	4.59	1.26	5.85
		[3]76-85	2	[15]60	41.02	16.63	57.65	35.28	15.06	50.34	5.74	1.57	7.31
		86-95	2	[15]60	49.22	19.96	69.18	42.34	18.07	60.41	6.88	1.89	8.77
Intermediate[14]	Shortleaf pine	66-75	2	60	30.56	12.39	42.95	26.27	11.13	37.40	4.29	1.26	5.55
		[3]76-85	2	60	38.20	15.48	53.68	32.83	13.92	46.75	5.37	1.56	6.93
		86-95	2	60	45.84	18.58	64.42	39.40	16.70	56.10	6.44	1.88	8.32
Intermediate[16]	Longleaf pine	66-75	1	60	18.68	8.01	26.69	18.21	7.83	26.04	0.47	0.18	0.65
		[3]76-85	1	60	23.35	10.02	33.37	22.77	9.78	32.55	0.58	0.24	0.82
		86-95	1	60	28.02	12.02	40.04	27.32	11.74	39.06	0.70	0.28	0.98
Intermediate[16]	Loblolly pine	66-75	1	[15]60	28.73	12.32	41.06	28.22	12.05	40.27	0.51	0.27	0.79
		[3]76-85	1	[15]60	35.92	15.40	51.32	35.28	15.06	50.34	0.64	0.34	0.98
		86-95	1	[15]60	43.10	18.48	61.58	42.34	18.07	60.41	0.76	0.41	1.17
Intermediate[16]	Shortleaf pine	66-75	1	60	26.73	11.47	38.20	26.27	11.13	37.40	0.46	0.34	0.80
		[3]76-85	1	60	33.42	14.33	47.75	32.83	13.92	46.75	0.59	0.41	1.00
		86-95	1	60	40.10	17.20	57.30	39.40	16.70	56.10	0.70	0.50	1.20
Intermediate[17]	Oak-pine	[3]56-65	5	[18]100	[19]51.23	45.94	97.17	37.59	35.45	73.04	13.64	10.49	24.13
		66-75	5	[18]100	74.28	66.61	140.90	54.50	51.40	105.91	19.78	15.21	34.99
		76-85	5	[18]100	92.21	82.69	174.91	67.66	63.81	131.47	24.55	18.88	43.44
Plant	White pine	55-64	3	120	93.33	12.50	105.83	[20]0.00	0.00	0.00	93.33	12.50	105.83
		65-74	3	120	118.33	11.66	130.00	0.00	0.00	0.00	118.33	11.66	130.00
		75-84	4	120	146.66	11.66	158.32	0.00	0.00	0.00	146.66	11.66	158.32
Plant	Red pine	60-64	4	120	102.17	20.67	122.83	0.00	0.00	0.00	102.17	20.67	122.83
		70-74	5	120	129.42	24.75	154.17	0.00	0.00	0.00	129.42	24.75	154.17
		80-84	5	120	158.42	23.92	182.33	0.00	0.00	0.00	158.42	23.92	182.33
Plant	Jack pine	36-45	0	60	28.33	11.67	40.00	0.00	0.00	0.00	28.33	11.67	40.00
		46-55	1	60	42.67	13.33	56.00	0.00	0.00	0.00	42.67	13.33	56.00
		56-85	1	60	53.33	16.67	70.00	0.00	0.00	0.00	53.33	16.67	70.00
Plant	Spruce	46-54	2	80	62.50	9.38	71.88	0.00	0.00	0.00	62.50	9.38	71.88
		55-64	3	80	88.75	11.25	100.00	0.00	0.00	0.00	88.75	11.25	100.00
Prune	White pine	45-54	3	120	[21]74.17	8.33	82.50	74.17	8.33	82.50	0.00	0.00	0.00
		55-64	3	120	93.33	12.50	105.83	93.33	12.50	105.83	0.00	0.00	0.00
		65-74	3	120	118.33	11.66	130.00	118.33	11.66	130.00	0.00	0.00	0.00
Prune	Red pine	50-54	3	120	68.17	21.25	89.42	68.17	21.25	89.42	0.00	0.00	0.00
		60-64	4	120	102.17	20.67	122.83	102.17	20.67	122.83	0.00	0.00	0.00
		70-74	5	120	129.42	24.75	154.17	129.42	24.75	154.17	0.00	0.00	0.00
Intermediate[22]	Northern pines	45-54	3	100	[21]75.20	18.32	93.52	56.00	9.60	65.60	19.20	8.72	27.92
		[3]55-64	3	100	94.00	22.90	116.90	70.00	12.00	82.00	24.00	10.90	34.90
		65-74	3	100	112.80	27.48	140.28	84.00	14.40	98.40	28.80	13.08	41.88
Intermediate[23]	Northern pines	45-54	2	100	[21]74.40	16.00	90.40	56.00	9.60	65.60	18.40	6.40	24.80
		[3]55-64	2	100	93.00	20.00	113.00	70.00	12.00	82.00	23.00	8.00	31.00
		65-74	2	100	111.60	24.00	135.60	84.00	14.40	98.40	27.60	9.60	37.20

Practice	Species	Site index range	Number of thins[1]	Rotation age	Intense			Current			Net Change		
					Sawtimber	Pulpwood	Total	Sawtimber	Pulpwood	Total	Sawtimber	Pulpwood	Total
Intermediate[24]	Spruce-fir	[3]50-60	1	70	51.71	46.86	98.57	20.64	41.29	61.93	31.07	5.57	36.64
		60-70	1	70	57.92	52.48	110.40	24.29	48.57	72.86	33.63	3.91	37.54
Intermediate[25]	Spruce-fir	[3]50-60	1	70	38.29	46.86	85.15	20.64	41.29	61.93	17.65	5.57	23.22
		60-70	1	70	42.88	52.48	95.36	24.29	48.57	72.86	18.59	3.91	22.50
Intermediate	Hemlock	[3]45-54	0	100	[21]78.00	0.00	78.00	70.00	12.00	82.00	8.00	-12.00	-4.00
		55-64	0	100	97.50	0.00	97.50	87.50	15.00	102.50	10.00	-15.00	-5.00
Plant	Black walnut	60-74	2	50	47.29	0.00	47.29	0.00	0.00	0.00	47.29	0.00	47.29
		[3]75-84	2	50	55.64	0.00	55.64	0.00	0.00	0.00	55.64	0.00	55.64
		85-94	2	50	63.99	0.00	63.99	0.00	0.00	0.00	63.99	0.00	63.99
Prune	Black walnut	[3]55-64	0	88	13.09	0.00	13.09	13.09	0.00	13.09	0.00	0.00	0.00
		65-74	0	88	15.06	0.00	15.06	15.06	0.00	15.06	0.00	0.00	0.00
		[3]75-84	2	61	26.89	0.00	26.89	26.89	0.00	26.89	0.00	0.00	0.00
Intermediate[26]	Black walnut	[3]55-64	0	[27]88	13.09	0.00	13.09	5.17	0.00	5.17	7.92	0.00	7.92
		65-74	0	[27]88	15.06	0.00	15.06	5.95	0.00	5.95	9.11	0.00	9.11
		[3]75-84	2	61	26.89	0.00	26.89	19.03	0.00	19.03	10.86	0.00	10.86
Intermediate[28]	Oak-hickory	45-54	3	100	23.04	24.34	47.38	9.02	19.14	28.16	14.02	5.20	19.22
		55-64	4	100	28.79	30.96	59.75	13.66	29.00	42.66	15.13	1.96	17.09
		65-84	5	100	44.95	36.90	81.85	20.76	44.08	64.84	24.19	-7.18	17.01
Intermediate	Cove hardwood	85-94	3	70	73.22	6.85	80.06	34.68	7.27	41.95	38.54	-0.42	68.11
		95-104	3	70	106.37	9.94	116.31	50.38	10.56	60.94	55.99	-0.62	55.37
		[3]105-114	3	70	138.14	12.91	151.05	65.43	13.71	79.14	72.71	-0.80	71.91
Intermediate[29]	Northern hardwood[30]	45-54	2	100	[31]33.15	9.35	42.50	20.40	5.95	26.35	12.75	3.40	16.15
		[3]55-64	2	100	39.00	11.00	50.00	24.00	7.00	31.00	15.00	4.00	19.00
		65-74	2	100	44.85	12.65	57.50	27.60	8.05	35.65	17.25	4.60	21.85
Intermediate[32]	Northern hardwood[30]	45-54	2	100	[31]30.60	9.35	39.95	20.40	5.95	26.35	10.20	3.40	13.60
		[3]55-64	2	100	36.00	11.00	47.00	24.00	7.00	31.00	12.00	4.00	16.00
		65-74	2	100	41.40	12.65	54.05	27.60	8.05	35.65	13.80	4.60	18.40
Intermediate[33]	Northern hardwood[30]	45-54	2	108	[31]28.33	8.66	36.99	20.40	5.95	26.35	7.93	2.71	10.64
		[3]55-64	2	108	33.33	10.19	43.52	24.00	7.00	31.00	9.33	3.19	12.52
		65-74	2	108	38.33	11.71	50.04	27.60	8.05	35.65	10.73	3.66	14.39
Intermediate[34]	Northern hardwood[35]	50-60	0	[36]12	33.33	6.67	40.00	32.00	0.00	32.00	1.33	6.67	8.00
		[3]61-70	0	12	41.67	8.33	50.00	40.00	0.00	40.00	1.67	8.33	10.00
		71-80	0	12	50.00	10.00	60.00	48.00	0.00	48.00	2.00	10.00	12.00
Intermediate[37]	Northern hardwood[35]	50-60	0	[38]12	31.66	6.72	38.38	18.29	0.00	18.29	13.37	6.72	20.09
		[3]61-70	0	12	39.58	7.91	47.49	22.86	0.00	22.86	16.72	7.91	24.63
		71-80	0	12	47.50	9.49	56.99	27.43	0.00	27.43	20.07	9.49	29.56
Intermediate[39]	Northern hardwood[35]	50-60	0	[40]12	30.00	6.00	36.00	12.80	0.00	12.80	17.20	6.00	23.20
		[3]61-70	0	12	37.50	7.50	45.00	16.00	0.00	16.00	21.50	7.50	29.00
		71-80	0	12	45.00	9.00	54.00	19.20	0.00	19.20	25.80	9.00	34.80
Intermediate	White birch	50-69	1	[41]65	98.46	0.00	98.46	35.29	0.00	35.29	63.17	0.00	63.17
		70-90	1	[42]45	142.22	0.00	142.22	50.00	0.00	50.00	92.22	0.00	92.22
Plant[43]	Douglas-fir[44]	130	1	[45]50	157.80	36.60	194.40	48.60	0.00	48.60	109.20	36.60	145.80
		160	1	[45]50	215.20	58.20	273.40	74.20	0.00	74.20	141.00	58.20	199.20
		170	1	[45]50	217.60	74.40	292.00	78.30	0.00	78.30	139.30	74.40	213.70
Intermediate[43]	Douglas-fir[44]	100	1	70	107.10	0.00	107.10	78.60	0.00	78.60	28.50	0.00	28.50
		140	1	50	150.00	32.00	182.00	66.70	0.00	66.70	83.33	32.00	115.30
		170	1	50	213.00	71.00	284.00	78.30	0.00	78.30	134.70	71.00	205.70
Plant[43]	Ponderosa	110	3	120	27.40	0.00	27.40	0.00	0.00	0.00	27.40	0.00	27.40
Intermediate[43]	Douglas-fir[45]	50	1	110	31.00	0.00	31.00	11.00	0.00	11.00	20.00	0.00	20.00
		70	1	110	30.90	0.00	30.90	17.70	0.00	17.70	13.20	0.00	13.20

Appendix Table A4. Continued.

Practice	Species	Site index range	Number of thins[1]	Rotation age	Intense Sawtimber	Intense Pulpwood	Intense Total	Current Sawtimber	Current Pulpwood	Current Total	Net Change Sawtimber	Net Change Pulpwood	Net Change Total
Intermediate[43]	Ponderosa	60	1	120	23.80	0.00	23.80	22.00	0.00	22.00	1.80	0.00	1.80
		80	1	110	25.70	0.00	25.70	15.60	0.00	15.60	10.10	0.00	10.10
Intermediate[43]	Lodgepole	65	1	140	23.50	0.00	23.50	23.40	0.00	23.40	0.10	0.00	0.10

[1] *The number of commercial thins for the first rotation of the intense regime.*

[2] *Planting bare land or planting after an intense site preparation; when planting after a less intense site preparation all yields are reduced by 10%.*

[3] *This is the base regime from which all adjustments are made.*

[4] *This is the MAI when there was an intense site preparation or when there are less than 200 conifer volunteers; for a less intense site preparation or bare land planting and greater than 199 conifer volunteers, the MAI is 20.00 cubic feet/acre/year of pulpwood on a thirty year rotation.*

[5] *Planting after a less intense site preparation.*

[6] *Planting bare land or after an intense site preparation.*

[7] *Planting bare land or after an intense site preparation; when planting after a less intense site preparation all yields are reduced by 20%.*

[8] *Planting bare land or after an intense site preparation; when planting after a less intense site preparation all yields are reduced by 30%.*

[9] *This is the MAI when there was an intense site preparation or when there are less than 250 conifer volunteers; for a less intense site preparation or bare land planting and greater than 249 conifer volunteers the MAI is 14.23 cubic feet/acre/year of pulpwood on a thirty year rotation.*

[10] *MAI's when there are 200-1499 established pine.*

[11] *Practice done in a stand that was 0-10 years old after treatment.*

[12] *Practice done in a stand that was 11-20 years old after treatment.*

[13] *Practice done in a stand that was 21-30 years old after treatment.*

[14] *Practice done in a stand that was 31-35 years old after treatment.*

[15] *Rotation age for the current regime is 50 years.*

[16] *Practice done in a stand that was 36-40 years old.*

[17] *Intermediate treatment in a stand where the hardwood basal area was between 30 and 49 square feet.*

[18] *The rotation age for the current regime is 80 years.*

[19] *The MAI's are for hardwood and softwood yields combined.*

[20] *This is the MAI when there was an intense site preparation or when there are less than 200 conifer volunteers; for a less intense site preparation or bare land planting and greater than 199 conifer volunteers, the MAI is 14.08 cubic feet/acre/year on a 120 year rotation.*

[21] *MAI for the softwood yield only, hardwood not included*

[22] *Practice done in a stand that was 0-34 years old after treatment.*

[23] *Practice done in a stand that was 35-60 years old after treatment.*

[24] *Practice done in a stand that was 10-24 years old after treatment.*

[25] *Practice done in a stand that was 25-50 years old after treatment.*

[26] *MAI's for stands where there are greater than 43 black walnut trees per acre; yield reductions are made for less than 44 black walnut trees.*

[27] *The rotation age of the current regime is 75 years.*

[28] *MAI's when stand was 0-39 years old after treatment.*

[29] *Practice done in a stand that was 0-34 years old.*

[30] *Northern hardwoods in the northeast managed under a clearcut system.*

[31] *MAI for the hardwood yield only, conifer not included.*

[32] *Practice done in a stand that was 45-50 years old after treatment.*

[33] *Practice done in a stand that was 56-60 years old after treatment.*

[34] *Intermediate treatment in stands that were 10-25 inches D.B.H. at time of treatment.*

[35] *Northern hardwoods in the Lake states, managed under a selection cut system.*

[36] *The intense regime has a selection cut every 12 years; the current regime has a rotation age of 20 years.*

[37] *Intermediate treatment in stands that were 6-9 inches D.B.H. at the time of treatment.*

[38] *The intense regime has a selection cut every 12 years; the current regime has a rotation age of 35 years.*

[39] *Intermediate treatment in stands that were 1-5 inches D.B.H. at the time of treatment.*

[40] *The intense regime has a selection cut every 12 years; the current regime has a rotation age of 50 years.*

[41] *The rotation age of the current regime is 85 years.*

[42] *The rotation age of the current regime is 60 years.*

[43] *These MAI's are for specific representative cases instead of stylized regimes.*

Appendix Table A5. Sample case management regime with yields, stumpage prices, and treatments costs for a site preparation and planting case

Basic case identification information:

Sample number: 14,820	County: Screven	Species group: Loblolly pine
State: Georgia	Acres treated: 52	Total surviving planted: 381
Site index: 70	Treatment: Site preparation and plant	Cost option: Total direct
Pre-treatment stand age: 30	Price region: 10	
Cost region: 4		
Regime number (intense): 11,004	Regime number (current): 11,102	

Management regime with yields, costs, and prices:

	Transaction number	Investment year[1]	Cost	Yield	Sensitivity group code[2]	Stumpage price	Sensitivity group code[3]	Perpetuity year[4]	Harvest code[5]	Item description	Stand age at harvest
			($)	*(1,000 cu ft/ac)*		*($/1,000 cu ft)*					*(years)*
Intense regime:											
First rotation—	1	0	64.10	—	—	—	—	—	9	Site preparation and planting	—
	2	4	15.00	—	2	—	—	—	—	Hardwood control	—
	3	10	2.50	—	2	—	—	—	—	Prescribe burn	—
	4	17	—	.47	4	169.46	6	—	2	Commercial thin	—
	5	25	—	.56	4	169.46	6	—	2	Commercial thin	—
	6	35	—	.58	4	529.27	6	—	1	Commercial thin	—
	7	35	—	.25	4	169.46	6	—	2	Commercial thin	—
	8	45	—	2.48	5	529.27	6	—	1	Final harvest	45
	9	45	—	.22	5	169.46	6	—	2	Final harvest	45
Perpetual rotation—	10	45	66.62	—	—	—	—	45	—	Site preparation and planting	—
	11	55	2.50	—	—	—	—	45	—	Prescribe burn	—
	12	62	—	.54	—	169.46	—	45	—	Commercial thin	—
	13	70	—	.54	—	169.46	—	45	—	Commercial thin	—
	14	80	—	.50	—	529.27	—	45	—	Commercial thin	—
	15	80	—	.22	—	169.46	—	45	—	Commercial thin	—
	16	90	—	2.16	—	529.27	—	45	—	Final harvest	—
	17	90	—	.19	—	169.46	—	45	—	Final harvest	—
Current regime[6]:	—	—	—	—	—	—	—	—	—	—	—

Appendix Table A5. Continued

Mean annual increments in cubic feet/acre/year:

	Intense	Current	Net Change
Sawtimber	68.09	0.00	68.09
Pulpwood	33.24	0.00	33.24
Total	101.33	0.00	101.33

Adjustments made to the stylized regime:

	Adjustment parameter	Threshold class	Case value	Adjustment[7] factor	Treatments adjusted
Intense regime:	01 (site index)	60 sq. ft.-75 sq. ft.	70 sq. ft.	.72	3,906 (all harvests, all yields)
	02 (number of surviving planted conifer)	300-399 planted conifer	381 planted conifer	.75	1,713 (first rotation, first commercial thin, softwood pulpwood yield)
	02 (number of surviving planted conifer)	300-399 planted conifer	381 planted conifer	.90	1,723 (first rotation, second commercial thin, softwood pulpwood yield)
	07 (improved seedlings planted)	1 (yes, improved seedlings planted)	1 (yes, improved seedlings planted)	1.15	1,906 (first rotation, all harvests, all yields)
Current regime:	10 (intense method of site preparation)	1 (yes, intense site preparation)	1 (yes, intense site preparation)	.00	3,906 (all harvests, all yields)
	03 (number of volunteer pine)	0-199 volunteer pine	0 volunteer pine	.00	3,906 (all harvests, all yields)

[1]*Investment year is the number of years from the time the FIP treatment was installed.*

[2]*These are the codes assigned to the subsequent treatments costs, commercial thin, and final harvest yields for use in the sensitivity analysis.*

[3]*These are the codes assigned to the stumpage prices for use in the sensitivity analysis.*

[4]*Perpetuity year is the number of years until the treatment is repeated on a continued basis.*

[5]*The harvest codes are: 1 = softwood sawtimber, intense regime; 2 = softwood pulpwood, intense regime; 3 = hardwood sawtimber, intense regime; 4 = hardwood pulpwood, intense regime; 5 = softwood sawtimber, current regime; 6 = softwood pulpwood, current regime; 7 = hardwood sawtimber, current regime; 8 = hardwood pulpwood, current regime; 9 = the FIP treatment.*

[6]*No current regime because of the intense site preparation, even though there was a stand before treatment, it was assumed that the pretreatment stands in southern pine planting cases were of no value.*

[7]*The yield or the treatment under "Treatments adjusted" is increased or decreased, or eliminated by the adjustment factor.*

Appendix Table A6. Sample case management regime with yields, stumpage prices, and treatment costs for a timber stand improvement case

Basic case identification information:

Sample number: 58,511
State: New Hampshire
Site index: 70
Pre-treatment stand age: 50
Cost region: 1
Regime number (intense): 11,004

County: Grafton
Acres treated: 4
Treatment: Intermediate treatment
Price region: 01
Regime number (current): 23,132

Species group: Northern Hardwood
Cost option: Total direct

Management regime with yields, costs, and prices:

	Transaction number	Investment year[1]	Cost	Yield	Sensitivity group code[2]	Stumpage price	Sensitivity group code[3]	Perpetuity year[4]	Harvest code[5]	Item description	Stand age at harvest
			($)	(1,000 cu ft/ac)		($/1,000 cu ft)					(years)
Intense regime:											
First rotation—	1	0	36.00	—	—	—	—	—	9	Intermediate treatment	—
	2	10	—	.50	4	314.43	6	—	3	Commercial thin	—
	3	10	—	.15	4	45.04	6	—	4	Commercial thin	—
	4	30	—	.80	4	314.43	6	—	3	Commercial thin	—
	5	30	—	.25	4	45.04	6	—	4	Commercial thin	—
	6	50	—	2.64	5	314.43	6	—	3	Final harvest	100
	7	50	—	.80	5	45.04	6	—	4	Final harvest	100
Perpetual rotation—	8	60	31.39	—	—	—	—	100	—	Precommercial thin	—
	9	80	31.39	—	—	—	—	100	—	Intermediate treatment	—
	10	100	31.39	—	—	—	—	100	—	Intermediate treatment	—
	11	110	—	.80	—	314.43	—	100	—	Commercial thin	—
	12	110	—	.25	—	45.04	—	100	—	Commercial thin	—
	13	130	—	.90	—	314.43	—	100	—	Commercial thin	—
	14	130	—	.30	—	45.04	—	100	—	Commercial thin	—
	15	150	—	2.64	—	314.43	—	100	—	Final harvest	—
	16	150	—	.80	—	45.04	—	100	—	Final harvest	—
Current regime:											
First rotation—	17	50	—	-2.76	—	271.19	—	—	7	Final harvest	100
	18	50	—	-.80	—	45.04	—	—	8	Final harvest	100
Perpetual rotation—	19	90	—	-1.15	—	271.19	—	40	—	Final harvest	—
	20	90	—	-.34	—	45.04	—	40	—	Final harvest	—

Appendix Table A6. Continued.

Mean annual increments in cubic feet/acre/year:

	Intense	Current	Net change
Sawtimber	39.45	27.60	11.85
Pulpwood	12.05	8.05	4.00
Total	51.50	35.65	15.85

Adjustments made to the stylized regime:

	Adjustment parameter	Threshold class	Case value	Adjustment factor[6]	Treatments adjusted
Intense regime:	01 (site index)	65 sq. ft.-74 sq. ft.	70 sq. ft.	1.15	3,816 (final harvest, all yields)
	37 (percent of post-treatment crop basal area in conifer)	0 percent	0 percent	0.00	1,812 (first rotation, final harvest, softwood sawtimber)
Current regime:	01 (site index)	65 sq. ft.-74 sq. ft.	70 sq. ft.	1.15	3,816 (final harvest, all yields)
	36 (percent of pre-treatment crop basal area in conifer)	0 percent	0 percent	0.00	1,812 (first rotation, final harvest, softwood sawtimber)

[1]*Investment year is the number of years from the time the FIP treatment was installed.*

[2]*These are the codes assigned to the subsequent treatments costs, commercial thin, and final harvest yields for use in the sensitivity analysis.*

[3]*These are the codes assigned to the stumpage prices for use in the sensitivity analysis.*

[4]*Perpetuity year is the number of years until the treatment is repeated on a continued basis.*

[5]*The harvest codes are: 1 = softwood sawtimber, intense regime; 2 = softwood pulpwood, intense regime; 3 = hardwood sawtimber, intense regime; 4 = hardwood pulpwood, intense regime; 5 = softwood sawtimber, current regime; 6 = softwood pulpwood, current regime; 7 = hardwood sawtimber, current regime; 8 = hardwood pulpwood, current regime; 9 = the FIP treatment.*

[6]*The yield or the treatment under "Treatments adjusted" is increased or decreased, or eliminated by the adjustment factor.*

Appendix Table A7. Stylized stumpage prices in dollars per 1,000 cubic feet by species, product and region

Species	Product	Region[1]												
		1	2	3	4	5	6	7	8	9	10	11	12	13
Eastern white pine[2]	sawtimber	227.15	263.70	173.00	193.62	173.00	193.62	193.62	265.47	372.94	433.62	—	—	—
	pulpwood	27.96	27.64	46.66	55.94	46.66	55.94	55.94	65.66	74.93	169.46	—	—	—
Red pine[3]	sawtimber	219.16	254.43	166.92	186.81	—	—	186.81	—	177.40	—	—	—	—
	pulpwood	46.28	45.77	45.77	92.62	—	—	92.62	—	51.60	—	—	—	—
Jack pine	sawtimber	170.74	198.22	130.04	145.54	—	198.22	145.54	—	—	—	—	—	—
	pulpwood	48.31	47.78	47.78	92.62	—	47.78	96.68	—	—	—	—	—	—
Shortleaf pine	sawtimber	—	—	158.77	—	236.46	195.85	—	243.65	434.42	529.27	508.23	600.91	428.75
	pulpwood	—	—	50.04	—	41.00	33.96	—	65.66	74.93	169.46	95.97	81.23	72.69
Slash pine	sawtimber	—	—	158.77	—	236.46	195.85	—	243.65	434.42	529.27	508.23	600.91	428.75
	pulpwood	—	—	50.04	—	41.00	33.96	—	65.66	74.93	169.46	95.97	81.23	72.69
Virginia pine	sawtimber	—	88.95	88.95	—	133.10	110.24	—	136.49	143.39	174.70	167.76	198.35	241.33
	pulpwood	—	50.04	50.04	—	41.00	33.96	—	65.66	74.93	169.46	95.97	81.23	72.69
Loblolly pine	sawtimber	—	—	158.77	—	236.46	195.85	—	243.65	434.42	529.27	508.23	600.91	428.75
	pulpwood	—	—	50.04	—	41.00	33.96	—	65.66	74.93	169.46	95.97	81.23	72.69
Longleaf pine	sawtimber	—	—	158.77	—	236.46	195.85	—	243.65	725.67	773.10	762.58	808.91	722.83
	pulpwood	—	—	50.04	—	41.00	33.96	—	65.66	402.93	450.19	413.45	406.09	401.82
Other southern pines	sawtimber	—	—	88.95	—	133.10	110.24	—	136.49	143.39	174.70	167.76	198.35	241.33
	pulpwood	—	—	50.04	—	41.00	33.96	—	65.66	74.93	169.46	95.97	81.23	72.69
Black spruce	sawtimber	193.53	210.91	137.55	—	—	—	131.79	—	137.55	—	—	—	—
	pulpwood	77.16	63.93	63.93	—	—	—	108.60	—	63.93	—	—	—	—
Red spruce	sawtimber	193.53	210.91	137.55	—	—	—	131.79	—	—	—	—	—	—
	pulpwood	77.16	63.93	63.93	—	—	—	108.60	—	—	—	—	—	—
White spruce	sawtimber	193.53	210.91	137.55	131.79	—	—	131.79	131.79	—	—	—	—	—
	pulpwood	77.16	63.93	63.93	108.60	—	—	108.60	108.60	—	—	—	—	—
Balsam fir	sawtimber	193.53	—	—	—	—	—	131.79	—	—	—	—	—	—
	pulpwood	77.16	—	—	—	—	—	68.38	—	—	—	—	—	—
Other true firs	sawtimber	193.53	—	—	—	—	—	—	—	—	—	—	—	—
	pulpwood	77.16	—	—	—	—	—	—	—	—	—	—	—	—
Tamarack	sawtimber	199.07	234.99	177.40	—	—	—	154.45	—	—	—	—	—	—
	pulpwood	42.65	27.65	51.60	—	—	—	48.73	—	—	—	—	—	—
Eastern hemlock	sawtimber	167.51	210.91	158.77	137.29	209.08	—	137.29	127.54	—	—	—	—	—
	pulpwood	42.65	82.92	50.04	69.95	41.00	—	69.95	65.66	—	—	—	—	—
Other northern conifers	sawtimber	199.07	234.99	177.40	154.45	191.04	154.45	154.45	—	177.40	—	—	—	—
	pulpwood	55.86	27.64	51.60	37.34	43.83	37.34	37.34	—	51.60	—	—	—	—
White oak	sawtimber	243.29	448.03	277.55	514.69	424.16	235.13	243.75	211.91	141.53	164.35	268.54	299.23	299.23
	pulpwood	45.04	37.20	39.96	33.97	24.76	23.19	23.32	13.82	26.51	54.85	59.54	35.65	13.82
Southern red oak	sawtimber	—	—	268.97	451.02	314.40	188.95	—	433.43	255.42	262.12	428.28	477.22	477.22
	pulpwood	—	—	39.96	33.97	24.76	23.19	—	13.82	26.51	54.85	59.54	35.65	13.82
Northern red oak	sawtimber	234.14	495.52	268.97	451.02	314.40	188.95	240.50	433.43	225.42	262.12	—	—	477.22
	pulpwood	45.04	37.20	39.96	33.97	24.76	23.19	23.32	13.82	26.51	54.85	—	—	13.82
Other oaks	sawtimber	173.84	258.46	192.05	234.88	189.49	158.90	219.82	140.38	147.44	118.79	250.96	277.07	250.96
	pulpwood	45.04	37.20	39.96	33.97	24.76	23.19	21.62	13.82	26.51	54.85	59.54	35.65	13.82
Yellow poplar	sawtimber	220.21	431.63	260.72	601.30	340.89	426.65	—	433.98	249.42	118.79	194.90	352.77	352.77
	pulpwood	45.04	37.20	39.96	33.97	24.76	23.19	—	13.82	26.51	54.85	59.54	35.65	13.82

Appendix Table A7. Continued.

Species	Product	Region[1] 1	2	3	4	5	6	7	8	9	10	11	12	13
All hickories	sawtimber	173.44	279.95	192.05	234.88	186.15	158.90	140.56	140.30	147.44	118.79	166.07	166.07	158.03
	pulpwood	45.04	37.20	39.96	33.97	24.76	23.19	21.62	13.82	26.51	54.85	59.54	35.65	13.82
Black walnut[4]	sawtimber	—	4019.08	2595.11	3819.96	3354.91	3927.38	3419.10	2849.25	2595.11	—	—	166.07	—
	pulpwood	—	37.20	39.96	33.97	24.76	23.19	21.62	13.82	26.51	—	—	35.65	—
Butternut	sawtimber	—	395.23	—	—	—	—	321.47	—	—	—	—	—	—
	pulpwood	—	37.20	—	—	—	—	21.62	—	—	—	—	—	—
American elm	sawtimber	—	345.84	191.26	254.11	204.88	158.90	211.63	—	—	—	202.20	—	—
	pulpwood	—	37.20	39.96	33.97	24.76	23.19	21.62	—	—	—	59.54	—	—
Black cherry	sawtimber	335.20	648.97	304.05	548.63	294.62	294.62	294.62	298.68	—	—	—	—	—
	pulpwood	45.04	37.20	39.96	33.97	24.76	23.19	21.62	13.82	—	—	—	—	—
Basswood	sawtimber	166.61	466.79	256.28	446.81	289.58	—	284.61	—	214.78	—	—	—	—
	pulpwood	45.04	37.20	39.96	33.97	24.76	—	42.71	—	26.51	—	—	—	—
White ash	sawtimber	226.46	644.85	367.59	561.07	306.41	234.29	162.18	304.34	367.59	—	202.20	—	158.03
	pulpwood	45.04	37.20	39.96	33.97	24.76	23.19	21.62	13.82	26.51	—	59.54	—	13.82
Beech	sawtimber	145.02	263.57	148.03	241.70	199.78	—	219.82	—	147.44	—	—	166.07	—
	pulpwood	45.04	37.20	39.96	33.97	24.76	—	21.62	—	26.51	—	—	35.65	—
Yellow birch	sawtimber	482.07	678.91	318.07	541.91	256.42	—	519.14	—	285.45	—	—	—	—
	pulpwood	45.04	66.94	39.96	33.97	24.76	—	31.57	—	26.51	—	—	—	—
White birch	sawtimber	284.95	395.23	192.05	291.80	—	—	188.38	—	—	—	—	—	—
	pulpwood	45.04	66.94	39.96	33.97	—	—	31.57	—	—	—	—	—	—
Hard maple	sawtimber	329.40	704.49	376.98	685.29	324.26	407.06	279.82	312.11	334.44	118.79	—	—	—
	pulpwood	45.04	37.20	39.96	33.97	24.76	23.19	21.62	13.82	26.51	54.85	—	—	—
Soft maple	sawtimber	189.90	432.56	288.72	421.43	279.88	351.34	197.42	239.05	288.72	118.79	—	—	—
	pulpwood	45.04	37.20	39.96	33.97	24.76	23.19	21.62	13.82	26.51	54.85	—	—	—
Quaking aspen	sawtimber	152.33	231.39	231.39	118.16	—	—	118.16	—	—	—	—	—	—
	pulpwood	12.29	53.06	53.06	38.38	—	—	38.38	—	—	—	—	—	—
Eastern cottonwood	sawtimber	—	—	174.30	189.45	231.87	162.18	146.46	—	174.30	—	—	166.07	—
	pulpwood	—	—	39.96	38.38	24.76	23.19	38.38	—	26.51	—	—	35.65	—
Sweetgum	sawtimber	—	—	174.30	234.88	228.73	—	—	249.50	174.30	118.79	359.57	359.57	359.57
	pulpwood	—	—	39.96	38.38	24.76	—	—	13.82	26.51	54.85	59.54	35.65	13.82
Other gums	sawtimber	—	258.46	174.30	234.88	239.08	—	—	—	—	359.57	359.57	—	359.57
	pulpwood	—	53.06	39.96	38.38	24.76	—	—	—	—	54.85	59.54	—	13.82
Other hardwood	sawtimber	173.44	258.46	192.05	234.88	220.34	158.90	219.82	140.30	147.44	118.79	202.20	166.07	158.00
	pulpwood	45.04	37.20	39.96	33.97	24.76	23.19	21.62	13.82	26.51	54.85	59.54	35.65	13.82
Eastern white pine, pruned[5]	sawtimber	312.63	377.44	247.62	411.96	—	—	411.96	—	533.00	—	—	—	—
	pulpwood	27.96	27.64	46.66	55.94	—	—	55.94	—	74.93	—	—	—	—
Red pine, pruned[6]	sawtimber	301.63	364.17	238.92	330.93	—	—	330.93	—	—	—	—	—	—
	pulpwood	46.28	45.77	45.77	92.62	—	—	92.62	—	—	—	—	—	—
Black walnut, pruned[7]	sawtimber	—	12497.40	9207.99	12472.51	11526.69	12485.61	10200.97	9239.43	9239.43	—	—	—	—
	pulpwood	—	37.20	39.96	33.97	24.76	23.19	21.62	13.82	13.82	—	—	—	—

Appendix Table A7. Continued.

Species	Product	Region[8] 1	2	3	5	6
Douglas-fir	sawtimber	77.85	—	—	372.00	625.00
	pulpwood	—	—	—	—	417.88
Ponderosa pine	sawtimber	167.55	54.65	251.00	468.30	—
	pulpwood	—	—	—	—	—
Jeffrey pine	sawtimber	—	—	—	468.30	—
	pulpwood	—	—	—	—	—
Sugar pine	sawtimber	—	—	—	487.15	—
	pulpwood	—	—	—	—	—
Lodgepole pine	sawtimber	40.50	108.25	—	69.30	—
	pulpwood	—	—	—	—	—
Engelmann spruce	sawtimber	131.30	—	—	—	—
	pulpwood	—	—	—	—	—
Western red cedar	sawtimber	92.40	—	—	463.80	—
	pulpwood	—	—	—	—	—
True firs	sawtimber	60.90	—	—	219.30	—
	pulpwood	—	—	—	—	—
Western larch	sawtimber	134.00	—	—	—	—
	pulpwood	—	—	—	—	—

[1]*For regional delineations see figure 3 showing the stylized stumpage price regions in the East.*
[2]*Stumpage price for non-pruned eastern white pine.*
[3]*Stumpage price for non-pruned red pine.*
[4]*Stumpage price for non-pruned black walnut.*
[5]*Stumpage price for pruned eastern white pine.*
[6]*Stumpage price for pruned red pine.*
[7]*Stumpage price for pruned black walnut.*
[8]*These regions refer to the Forest Service administrative units.*

Appendix Table A8. Percentages by which the posttreatment stumpage prices differ from the pretreatment prices, by species and region

Species	Region[1] 1	2	3 + 8	4	5	6 + 13	7
White oak	20	20	22	27	25	20	39
Southern red oak	—	18	23	26	22	19	—
Northern red oak	19	18	23	26	22	19	25
Other oaks	16	15	20	23	19	16	22
Yellow poplar	12	12	24	23	22	20	—
All hickories	21	21	21	21	22	21	20
Black walnut	—	26	28	21	27	27	37
Butternut	—	20	—	—	—	—	20
American elm	—	24	26	26	21	15	28
Black cherry	18	20	24	23	22	20	20
Basswood	20	16	24	22	27	—	25
White ash	19	17	22	28	26	26	27
Beech	28	19	24	17	17	—	19
Yellow birch	16	19	18	18	18	—	17
White birch	17	17	17	17	—	—	26
Hard maple	16	21	26	26	20	20	22
Soft maple	14	19	23	23	23	11	37
Aspen	12	12	12	12	—	—	32
Cottonwood	—	—	21	21	21	13	25
Sweetgum	—	—	21	20	19	—	—
Other gums	—	21	21	20	19	—	—
Other hardwoods	17	19	21	27	19	15	20

[1]*For regional delineations see figure 3 showing the stylized stumpage price regions in the East.*

Appendix Table A9. Average subsequent treatment costs in dollars per acre by species group and region

		Region[1]			
Practice	Species group	South	Central	Northeast	Lake
Site preparation and planting	Southern pine[2]	[3]62.18 [4]66.62	59.19	59.19	—
	Oak-pine	66.62	75.00	59.19	—
	Northern pine[5]	84.01	61.14	47.76	57.51
	Other northern conifer[6]	36.86	36.86	36.86	55.16
	Black walnut	62.57	81.53	29.20	50.88
Hardwood control	Southern pine	15.00	15.00	15.00	—
	Northern pine	15.00	15.00	15.00	15.00
	Other northern conifer	15.00	15.00	15.00	15.00
	Black walnut	15.00	15.00	15.00	15.00
Prescribe burn	Southern pine	2.50	2.50	2.50	—
Precommercial thin	Southern pine	22.00	22.00	22.00	—
	Black walnut	15.00	15.00	15.00	15.00
	Northern hardwood	—	40.96	31.39	—
	White birch	—	26.40	26.40	26.40
Intermediate	Southern pine	24.54	24.21	—	—
	Other northern conifer	25.77	25.77	25.77	25.77
	Oak-hickory	29.71	25.29	42.82	49.77
	Black walnut	[7]22.00 [8]29.71	[7]22.00 [8]25.29	[7]22.00 [8]42.82	[7]22.00 [8]49.77
	Cove hardwood	29.71	25.29	42.82	49.77
	Northern hardwood	—	40.96	31.39	30.35
	White birch	—	23.76	23.76	23.76
Prune	Northern pine	36.67	58.14	36.67	24.35
	Black walnut	[7]12.00 [8]16.02	[7]12.00 [8]16.02	[7]12.00 [8]16.02	[7]12.00 [8]17.75

	Region[9]				
Practice	R-1	R-2	R-3	R-5	R-6
Planting	85.00	[10]200.00	150.00	90.00	65.00
Precommercial thin	60.00	60.00	11.50	78.00	40.00
Spray (brush control)	—	—	—	—	25.00
Release	—	—	—	31.00	—

[1]*The regions include the following states: South—Georgia, Florida, Alabama, Mississippi, Louisiana, Texas, Oklahoma, Arkansas, Maryland, Delaware, Virginia, North Carolina, South Carolina; Central—West Virginia, Kentucky, Tennessee, Ohio, Indiana, Illinois, Iowa, Missouri; Northeast—Pennsylvania, New York, Massachusetts, Connecticut, New Jersey, Rhode Island, Maine, New Hampshire, Vermont; Lake—Michigan, Minnesota, Wisconsin.*

[2]*Southern pine includes longleaf, slash, loblolly, shortleaf, Virginia pines.*

[3]*Cost for longleaf and slash pines.*

[4]*Cost for loblolly, shortleaf, Virginia pines.*

[5]*Northern pine includes white, red, and jack pine, and hemlock.*

[6]*Other northern conifer includes spruce and spruce-fir.*

[7]*Cost for black walnut plantations.*

[8]*Cost for natural stands of black walnut.*

[9]*These regions refer to the Forest Service administrative regions.*

[10]*This is the cost for the Rocky Mountain area; the Black Hills cost is $150/acre.*

Appendix Table A10. Average percentage data changes necessary to raise or lower the IROR by 1 percent of interest, by sample cell and three data groups

Sample cell number[1]	Simple average IROR[2]	Upper IROR threshold[3]				Lower IROR threshold[4]			
		Subsequent treatment cost	Commercial thin yield	Final harvest yield	Stumpage price	Subsequent treatment cost	Commercial thin yield	Final harvest yield	Stumpage price
1	14.7	-946	40	118	29	1,089	-36	-73	-23
2	14.0	-907	41	135	30	1,056	-37	-81	-24
3	17.4	-840	32	70	19	886	-30	-50	-17
4	17.4	-844	28	132	21	905	-26	-83	-18
5	14.3	-1,076	51	108	33	1,268	-44	-67	-25
6	14.9	-995	38	135	29	1,145	-34	-82	-23
7	12.6	-1,053	46	151	32	1,250	-41	-90	-25
8	17.0	-766	28	282	24	844	-25	-157	-20
9	13.1	-1,287	56	97	34	1,527	-50	-62	-26
10	14.2	-777	42	132	30	908	-37	-79	-24
11	11.4	-1,971	58	98	35	2,373	-52	-63	-28
12	10.5	-1,544	71	94	39	1,918	-63	-61	-30
13	13.0	-1,364	59	53	25	1,529	-58	-41	-22
14	12.1	-1,330	51	65	27	1,476	-49	-46	-22
15	11.6	-1,790	60	149	36	2,193	-54	-88	-28
16	12.2	-1,387	62	143	32	1,641	-59	-87	-26
17	9.5	-2,069	74	116	41	2,611	-67	-73	-32
18	9.9	-1,831	68	96	39	2,277	-61	-63	-31
19	12.1	-1,863	46	119	31	2,184	-41	-74	-25
20	9.8	-3,202	102	84	40	4,030	-100	-57	-32
21	11.6	-1,307	55	102	35	1,586	-50	-64	-27
22	11.8	-346	37	802	22	483	-36	-348	-17
23	10.6	-726	57	99	34	881	-81	-81	-38
24	19.7	-729	21	253	15	779	-19	-160	-13
25	13.2	-836	45	128	31	984	-39	-81	-25
26	12.6	-323	48	121	33	387	-42	-77	-26
27	10.2	-370	47	120	31	455	-43	-75	-25
28	12.4	-429	51	106	33	515	-46	-70	-26
29	13.3	-390	43	103	29	460	-38	-65	-24
30	13.5	—	12	74	10	—	-10	-47	-8
31	17.0	—	28	88	18	—	-26	-58	-15
32	24.7	—	15	322	10	—	-14	-204	-9
33	20.3	—	20	221	12	—	-20	-93	-10
34	6.4	—	100	1,584	94	—	-61	-360	-52
35	8.2	-1,523	94	172	54	2,016	-90	-120	-80
36	7.7	-1,979	100	94	48	2,598	-95	-64	-38
37	11.5	-693	42	78	26	819	-39	-49	-21
38	13.2	-794	39	90	19	931	-47	-62	-17
39	8.2	—	60	20,704	58	—	-42	-3,606	-37
40	7.3	—	82	10,973	69	—	-61	-1,948	-44
41	7.4	—	83	3,250	70	—	-59	-645	-44
42	8.4	-153	84	21,380	65	221	-59	-3,762	-40
43	8.1	—	60	12,413	58	—	-43	-2,199	-38
44	7.2	-353	70	6,220	66	652	-50	-1,145	-42
45	6.9	-281	89	3,289	81	419	-58	-641	-47
46	11.9	—	27	13,349	21	—	-24	-7,140	-15
47	10.5	—	27	303	21	—	-23	-135	-16
48	12.5	-458	9	740,688	9	424	-8	-200,308	-8
49	12.4	-374	7	77,049	7	352	-6	-19,315	-6
50	15.8	—	22	262	18	—	-20	-138	-14
51	17.0	—	21	735,875	22	—	-18	-537,799	-18
52	10.6	-186	33	115	37	313	-32	-59	-28
53	13.0	-290	31	155	19	301	-28	-71	-16
54	10.4	—	43	121	33	—	-40	-57	-24
55	12.7	-348	—	11	11	319	—	-12	-12
56	18.8	—	16	17,302	15	—	-14	-9,023	-13
57	18.1	—	27	773	20	—	-24	-349	-17
58	11.9	—	35	428	25	—	-31	-200	-19
59	23.3	—	15	39,798	15	—	-13	-20,977	-12
60	19.1	-506	20	35,292	18	478	-17	-19,120	-15

Appendix Table A10. Continued.

Sample cell number[1]	Simple average IROR[2]	Upper IROR threshold[3]				Lower IROR threshold[4]			
		Subsequent treatment cost	Commercial thin yield	Final harvest yield	Stumpage price	Subsequent treatment cost	Commercial thin yield	Final harvest yield	Stumpage price
61	13.2	-337	—	46	13	289	—	-32	-12
62	22.7	-298	17	155,569	16	294	-14	-85,539	-14
63	7.2	-210	89	5,717	84	309	-55	-1,068	-47
64	6.3	—	160	1,733	93	—	-135	-386	-56
65	13.0	—	40	2,336,026	27	—	-37	*[5]	-19
66	10.1	-326	18	12,511	15	349	-15	-4,638	-11
67	19.2	—	41	*[5]	36	—	-44	*[5]	-43
68	17.0	—	18	1,449	19	—	-18	-915	-18
69	22.9	-764	15	30,292	11	632	-23	-27,743	-16
70	15.7	-348	24	225	15	261	-20	-99	-12
71	11.6	-210	102	1,988	57	344	-87	-407	-41
72	32.7	-181	2	*[5]	12	238	-45	*[5]	-41
73	12.2	-163	79	110	41	213	-67	-66	-30
74	21.5	—	17	71	11	—	-14	-46	-9
75	[6]4.4	—	—	—	—	—	—	—	—
76	5.3	—	61	79	63	—	-340	-84	-64
77	4.6	—	763	407	218	—	-336	-201	-83

Note: The sensitivity of the data changes were calculated independently for each data group. No joint data group changes were tested.

[1]*See table 2 for description of sample cell number.*

[2]*This is the simple average IROR of all non-zero cases in the cell.*

[3]*The upper IROR threshold is the average percentage data change required to increase the IROR level by one percentage point of interest above the original estimate.*

[4]*The lower IROR threshold is the average percentage data change required to lower the IROR level one percentage point of interest below the original estimate.*

[5]*The percent exceeds 9,999,999.99.*

[6]*Only one case had a non-zero IROR, therefore no sensitivity calculated for the cell.*

Appendix Table A11. Weighted average IROR under the direct cost option of the FIP treatment, by sampling cell

Species group and practice	State														Total
	Missouri	Alabama	Arkansas	Florida	Georgia	Louisiana	Mississippi	North Carolina	Oklahoma	South Carolina	Texas	Virginia	Other South	Eastern residual	
Southern pine, plant bare land	—	14.1	13.7	13.2	15.5	14.6	14.9	11.8	—	14.3	12.7	13.7	9.1	—	13.9
Southern pine, site preparation and planting	—	9.5	10.5	11.8	12.3	12.1	13.3	9.1	9.9	10.5	9.7	11.3	7.8	—	10.7
Southern pine and oak-pine, precommercial thin, and release	10.4	—	9.6	—	12.8	13.5	12.3	—	6.9	—	12.1	13.3	5.8	—	
Southern pine, and oak-pine, cull tree removal	1.0	—	10.0	—	7.9	22.6	—	—	—	—	—	—	8.7	—	9.2
Northern pine, site preparation and planting	—	—	—	—	—	—	—	6.4	—	—	—	—	—	—	—
Eastern residual	—	—	—	—	—	—	—	—	—	—	—	—	—	5.8/40.9	—
Total	5.6	10.4	10.7	12.6	12.3	14.1	10.4	9.1	8.3	7.5	11.5	11.8	—	—	—

Species group and practice	State										Total
	Michigan	Minnesota and Wisconsin	Vermont	Maine	New Hampshire	New York	Pennsylvania	Indiana	Missouri	Other North	
Northern pine, and spruce-fir, plant bare land	8.5	6.1	—	7.3	—	—	8.0	—	—	7.3	7.4
Northern pine, and spruce-fir, site preparation and planting	8.1	5.8	—	—	—	—	5.5	—	—	5.4	6.0
Northern pine, and spruce-fir, precommercial thin, and release	—	—	—	8.5	10.2	—	—	—	—	10.0	9.7
Northern pine, and spruce-fir, prune	14.8	11.7	—	—	—	—	—	—	—	7.4	10.3
Oak-hickory, precommercial thin, and release	—	—	—	—	—	—	8.4	10.3	4.5	12.1	8.0
Oak-hickory, cull tree removal	—	—	—	—	—	—	—	5.1	4.9	5.0	
Maple-beech-birch, precommercial thin, and release	12.4	—	9.5	18.9	8.6	22.5	17.1	—	—	17.5	15.3
Maple-beech-birch, cull tree removal	13.6	—	—	—	—	11.9	—	—	—	13.5	
Total	10.1	5.2/8.9	8.3	9.4	9.5	20.0	9.6	14.6	5.6	—	—

Species group and practice	Region		Total
	Pacific coast	Rocky mountains	
Douglas-fir and ponderosa pine, plant	5.7	—	5.7
Douglas-fir and ponderosa pine, precommercial thin and release	16.7	—	16.7
All types, plant	—	1.0	1.0
Douglas-fir and ponderosa pine, precommercial thin and release	—	3.3	3.3
Rocky mountains residual	—	3.0	3.0
Total	9.4	2.9	—

Appendix Table A12. Financial return and yield results by broad practice groups under the total cost option

Species group and practice	Average IROR	Total B/C ratio @ 6-3/8%	Total PNW @ 6-3/8%	Cases earning 6-3/8%	Average MAI increase	Total yield increase	
						Sawtimber	Pulpwood
	(percent)		*(mil. dollars)*	*(percent)*	*(cu ft/ ac/yr)*		*(mil. cu ft)*
Southern pine, plantings	10.7	3.2	28.04	89	108.1	320.1	229.8
Southern pine and oak-pine, timber stand improvement	8.5	2.8	4.02	72	45.4	45.2	33.4
Northern conifer, plantings	6.1	0.5	-0.18	29	122.5	298.1	27.9
Northern conifer, timber stand improvement	7.6	0.8	0.30	50	24.6	13.5	3.7
Hardwood, planting	9.4	15.3	6.02	57	44.0	6.1	2.0
Oak-hickory, timber stand improvement	4.3	0.8	0.45	37	9.5	25.6	2.4
Black walnut & cove hardwood, timber stand improvement	19.5	12.0	7.81	77	16.3	10.9	0.2
Northern hardwood, timber stand improvement	12.6	3.2	2.48	76	10.4	13.5	4.6
Western conifers, planting	4.8	3.2	0.95	47	67.1	2.3	2.4
Western conifers, timber stand improvement	6.7	1.6	0.53	30	15.6	2.6	0.5
Total, all species and practices	9.4	3.0	50.44	63	74.8	737.8	306.8

Appendix Table A13. Weighted average IROR under the direct cost option of the FIP treatment, by detailed species and practice groups

Species	Practice							
	Plant bare land	Site preparation and planting	Understory release	Precom-mercial thin	Intermediate	Prune and intermediate	Prune	Total
Slash pine	13.8	12.2	17.0	27.2	3.2	—	—	12.2
Longleaf pine	11.3	13.9	—	—	8.8	—	—	13.2
Loblolly pine	14.0	10.1	12.6	13.8	7.7	—	—	11.0
Shortleaf pine	3.9	5.9	6.8	—	8.6	—	—	7.5
Virginia pine	4.6	4.8	—	—	4.2	—	—	4.2
Oak-pine	—	—	—	—	4.8	—	—	4.8
Red pine	8.2	6.9	—	—	6.4	3.8	13.3	8.2
White pine	6.7	5.7	7.4	—	9.8	12.6	8.4	7.7
Jack pine	—	5.1	—	—	7.0	—	—	5.2
Spruce-fir	6.8	6.7	—	—	3.6	—	—	6.1
Hemlock	—	—	—	—	1.9	—	—	1.9
Larch	7.5	0.0	—	—	—	—	—	0.7
Oak-hickory	2.3	7.1	—	—	4.7	—	—	4.7
Cove hardwood	—	4.4	—	—	16.0	—	—	14.5
Black walnut	14.0	14.0	—	—	16.9	—	14.6	24.0
Northern hardwood	—	—	—	—	15.0	—	—	15.0
White birch	—	—	—	—	14.3	—	—	14.3
Douglas-fir	12.4	7.2	—	—	14.8	—	—	10.8
Ponderosa pine	—	2.0	—	—	3.7	—	—	3.2
Lodgepole pine	—	—	—	—	1.1	—	—	1.1
Total	11.6	10.1	11.4	20.9	8.6	24.0	11.9	10.2

Appendix Table A14. Percentage of cases that exceeded the silvicultural thresholds and the additional percentage that could not earn 6 3/8% by detailed species and practice groups

Species	Practice							
	Plant bare land	Site preparation and planting	Understory release	Precommercial thin	Intermediate	Prune and intermediate	Prune	Total
Slash pine	[1]24 / [2]0	6 / 1	0 / 0	0 / 0	82 / 0	—	—	11 / 1
Longleaf pine	29 / 0	0 / 0	—	—	44 / 0	—	—	11 / 0
Loblolly pine	9 / 0	7 / 0	3 / 0	0 / 0	20 / 10	—	—	7 / 0
Shortleaf pine	17 / 50	0 / 78	11 / 6	—	33 / 0	—	—	20 / 19
Virginia pine	0 / 100	0 / 100	—	—	78 / 0	—	—	41 / 47
Oak-pine	—	—	—	—	70 / 11	—	—	70 / 11
Red pine	11 / 11	3 / 16	—	—	0 / 33	64 / 0	3 / 3	10 / 11
White pine	23 / 18	19 / 45	0 / 0	—	9 / 7	16 / 0	0 / 22	17 / 22
Jack pine	—	0 / 100	—	—	0 / 0	—	—	0 / 87
Spruce-fir	24 / 17	8 / 11	—	—	35 / 30	—	—	23 / 18
Hemlock	—	—	—	—	18 / 82	—	—	18 / 82
Larch	0 / 0	100 / 0	—	—	—	—	—	58 / 0
Oak-hickory	50 / 0	0 / 33	—	—	56 / 1	100 / 0	—	54 / 2
Cove hardwood	—	33 / 0	—	—	28 / 0	0 / 0	—	29 / 0
Black walnut	40 / 0	10 / 0	—	—	9 / 20	0 / 0	5 / 0	11 / 5
Northern hardwood	—	—	—	—	19 / 1	—	—	19 / 1
White birch	—	—	—	—	28 / 0	—	—	28 / 0
Douglas-fir	0 / 0	27 / 0	—	—	26 / 26	—	—	23 / 11
Ponderosa pine	—	80 / 9	—	—	45 / 29	—	—	61 / 19
Lodgepole pine	—	—	—	—	33 / 67	—	—	33 / 67
Total	15 / 10	10 / 10	4 / 1	0 / 0	33 / 6	19 / 1	3 / 7	17 / 8

[1]*Percentage of cases that exceeded silvicultural thresholds.*
[2]*Additional percentage of cases that failed to earn 6-3/8%*

Appendix Table A15. Weighted average increase in MAI per acre by detailed species and practice groups

Species	Practice							
	Plant bare land	Site preparation and planting	Understory release	Precom-mercial thin	Intermediate	Prune and intermediate	Prune	Total
Slash pine	103.8	105.0	87.9	52.5	4.5	—	—	99.9
Longleaf pine	57.3	100.4	—	—	5.1	—	—	86.6
Loblolly pine	126.0	105.7	91.2	43.1	12.9	—	—	102.7
Shortleaf pine	49.1	64.1	38.4	—	5.6	—	—	25.4
Virginia pine	50.2	46.7	—	—	9.9	—	—	13.8
Oak-pine	—	—	—	—	3.2	—	—	3.2
Red pine	131.6	107.6	—	—	34.9	16.0	0.0	104.4
White pine	122.5	129.5	108.5	—	40.0	34.6	0.0	92.3
Jack pine	—	59.2	—	—	35.0	—	—	57.7
Spruce-fir	105.9	107.8	—	—	3.6	—	—	83.9
Hemlock	—	—	—	—	-3.0	—	—	-3.0
Larch	116.0	0.0	—	—	—	—	—	10.8
Oak-hickory	39.1	100.8	—	—	9.5	0.0	—	10.3
Cove hardwood	—	43.6	—	—	26.9	10.0	—	29.1
Black walnut	33.1	34.6	—	—	4.1	5.3	0.0	12.1
Northern hardwood	—	—	—	—	9.8	—	—	9.8
White birch	—	—	—	—	32.7	—	—	32.7
Douglas-fir	177.8	105.0	—	—	39.9	—	—	77.0
Ponderosa pine	—	12.4	—	—	1.6	—	—	5.0
Lodgepole pine	—	—	—	—	0.7	—	—	0.7
Total	121.5	104.1	78.6	48.1	11.8	18.1	0.0	73.8

Mills, Thomas J., and Daria Cain. 1978. Timber yield and financial return performance of the 1974 Forestry Incentives Program. USDA For. Serv. Res. Pap. RM-204, 56 p. Rocky Mt. For. and Range Exp. Stn., For. Serv., U.S. Dep. Agric., Fort Collins, Colo. 80526.

Analysis of the timber production performance of the 1974 Forestry Incentives Program (FIP) showed that the average "real" rate of return on timber-associated inputs and outputs of the 1974 investments was 10-1/4% on the direct treatment costs. Seventy-five percent of the cases earn a 6-3/8% return. The first rotation yield increase is estimated at 1.04 billion cubic feet, mostly softwoods, occurring within 50 years of the initial treatment. The program overall had high average returns, but some major segments had low returns. Five recommendations, aimed at eliminating low return segments by developing silvicultural guidelines for the screening of cases, development of maximum cost standards, and insuring the follow-up treatments are taken, are proposed.

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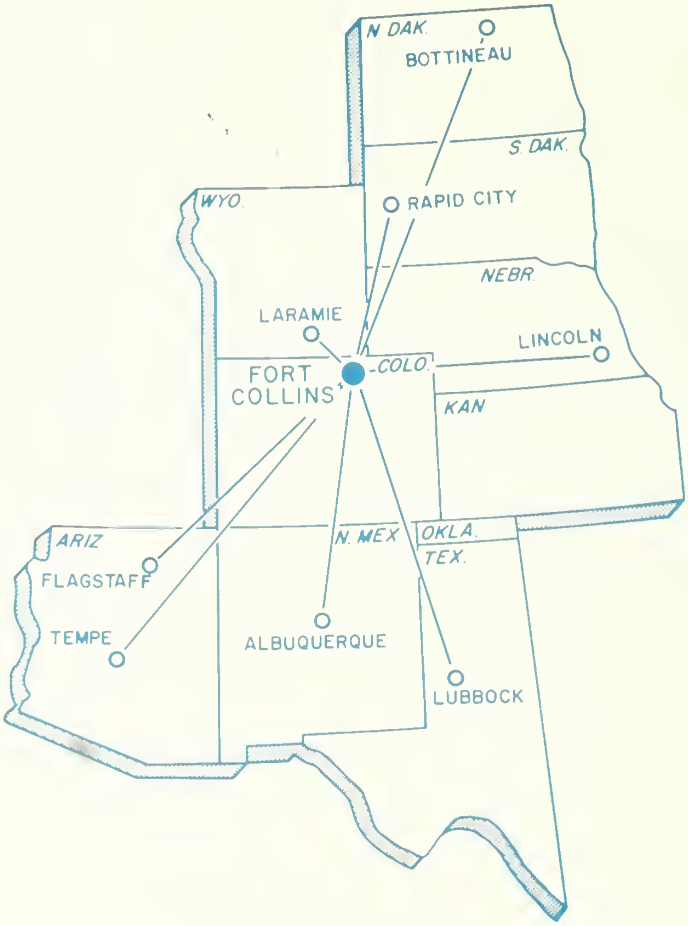
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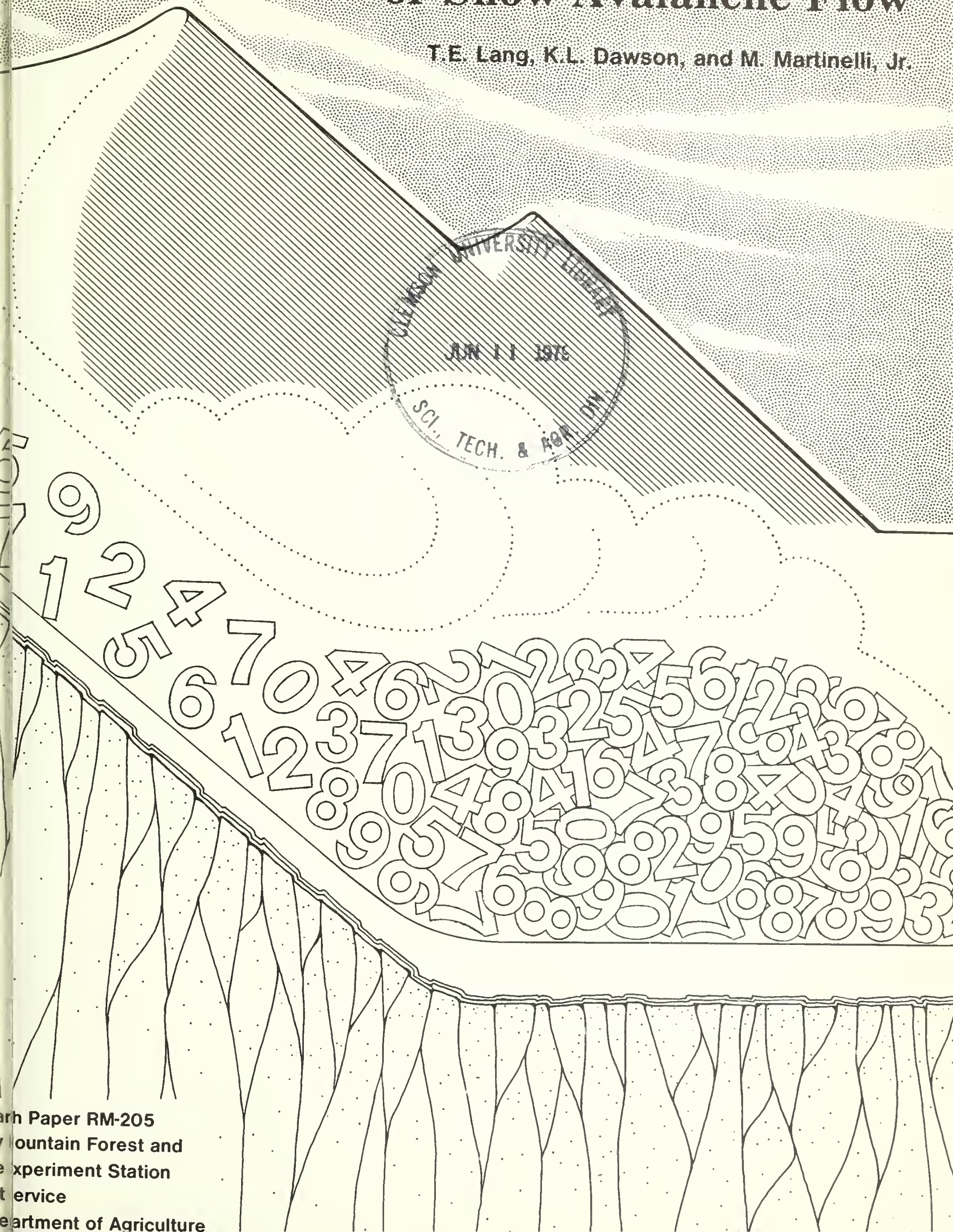
Numerical Simulation of Snow Avalanche Flow

T.E. Lang, K.L. Dawson, and M. Martinelli, Jr.



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Abstract

A numerical, finite difference computer program based on the Navier-Stokes equations is modified to give avalanche runout distance, velocity of the leading edge of the avalanche and depth of debris in the runout zone. The program requires a longitudinal profile of the avalanche path, thickness of the snow in the starting zone, and two friction coefficients. Kineomatic viscosity (or coefficient of internal friction) is expressed as an average for the entire avalanche path. Slope inclinations and coefficient of surface friction can be varied for every 10- to 20-m increment of the avalanche path. The program can be modified to allow for variable width of flow and for snow entrainment during flow. In test cases, the program predicted results consistent with observations for a number of avalanche events.

Research Paper RM-205 February 1979

Numerical Simulation of Snow Avalanche Flow [1]

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[1] *This paper reports findings of research done under Cooperative Agreement 16-627 CA between the USDA Forest Service and Montana State University.*

[2] *Dawson is now Research Engineer, Boeing Aircraft Company, Seattle, Wash.*

[3] *Central headquarters is maintained in Fort Collins, Colo. in cooperation with Colorado State University.*

Description of the Avalanche Computer Code

Basic Features of the SOLASURF Code

The governing equations of motion incorporated in the SOLASURF code in finite difference form are the Navier-Stokes equations:

$$\frac{Du}{Dt} = g_x - \frac{1}{\rho}\frac{\partial p}{\partial x} + \upsilon \nabla^2 u$$

$$\frac{Dv}{Dt} = g_y - \frac{1}{\rho}\frac{\partial p}{\partial y} + \upsilon \nabla^2 v . \quad [1]$$

In equation [1], u and v are velocity components; g_x and g_y are gravity components; ρ, is the density of the incompressible fluid and is combined with pressure, p, to become the actual term solved for in the code and referred to as "pressure;" υ is the kinematic viscosity (or internal friction). The two linear operators of equation [1] are

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y}$$

and [2]

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}.$$

Additionally, we impose the condition of conservation of mass for an incompressible fluid given by

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0. \quad [3]$$

Consistent with the usual finite difference approach, the fluid domain is divided into a uniform grid of rectangular cells, surrounded by a single-cell thickness of boundary cells. The notations associated with the grid layout are shown in figure 1.

In the code IBAR[4] and JBAR are the number of flow domain cells in the x and y directions, respectively, and IMAX and JMAX are the corresponding number of cells including the boundary cells. Five 2-dimensional arrays with the dimensions IMAX by JMAX, establish the major memory allocation. The arrays are the current velocity components u and v, the updated velocity components u_n and v_n, and the pressure, p, in each cell. Limiting the size of these arrays is the primary method of controlling running time on the computer.

[4]*Names in capital letters refer to parameters used in the SOLASURF code.*

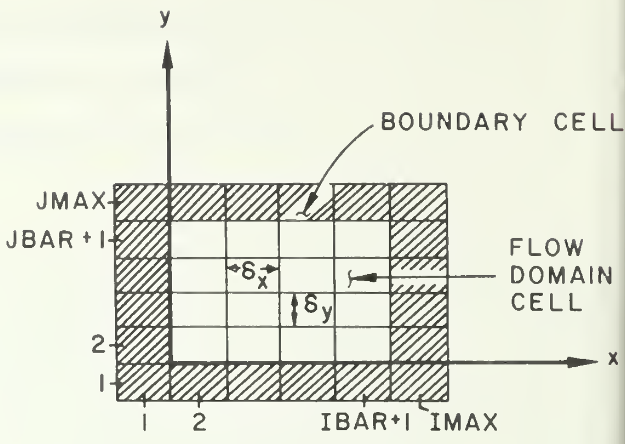

Figure 1.—Grid layout.

The algorithm starts with an initial distribution of fluid in the domain and computes a pressure and velocity distribution using a finite difference version of equation [1]. In general, the computed velocity components do not satisfy equation [3], so that small adjustments of cell pressure are required to achieve a zero-divergence condition to a prescribed level of accuracy controlled by parameters EPSI and DZRO (Hirt, Nichols and Romero 1975). The initial calculation of velocity and pressure using equation [1] is the start of a cycle (CYCLE) of calculations, and each small adjustment of parameters in one sweep of the cells is an iteration (ITER).

In the SOLASURF code, a choice between four types of boundary conditions is given for each boundary. In the modified version, a single type of boundary condition is imposed along each edge. The left wall, considered the crown face of the avalanche, is designated a rigid, slip-free boundary in the notation of Hirt, Nichols and Romero (1975). The right wall, which is placed beyond the runout terminus, is a continuative outflow boundary, as is the top boundary. The bottom boundary is modified from the rigid no-slip or free-slip options given in SOLASURF to model different friction conditions that might be encountered in an avalanche flow. Details of the various aspects of the modified program are given in the next section.

Output from SOLASURF includes two types of data, depending upon user preference. The more complete output at the end of an integral number of cycles, as controlled by the parameter CWPRT, is a listing of the velocity and pressure in each cell. At the end of cycles for which the complete printout is not requested, a single line is printed which includes the cycle number (CYCLE), number of iterations in that cycle (ITER), time increment (DELT), total time into

low (TIME), fluid volume (FVOL), maximum slope-
parallel velocity in the flow (UMAX), leading edge
lope-parallel velocity (UEDG), and cell number of
he leading edge of the avalanche (LDEG).

An additional input parameter is TWFIN, which is he time estimate for the avalanche flow. Normally, his is set at a large value to be sure the complete valanche flow is represented in a run. However, it nay also be used to terminate computations, in which ase an extended printout of the flow distribution is utput.

Remaining input parameters needed for program xecution are detailed in the next section, since they re associated directly with major modifications nade to the code. A complete description and an xample of the input data required are given in Appendix A.

The name adapted for the modified version of SOLASURF for the simulation of avalanche flow and unout distance is program AVALNCH, which will be ised in subsequent references to the code.

The program is set up to use a specific set of units. All linear dimensions are expressed in meters, and ime in seconds. Velocity has the units m/s; the pressure/density ratio has the units m^2/s^2; the kinematic viscosity has units m^2/s, and acceleration due o gravity is set at 9.80 m/s^2.

Modifications of the SOLASURF Code

There are several limitations to developing a iumerical model for avalanche runout prediction. First, material properties must be expressed in iominal values, since point values of the properties as a function of slope, position and time are unknown. Second, the calculations should be low-cost, because computer and manpower resources are often limited. Third, representation of the flow should be simple and not require complex interpretation of parameter ypes and ranges. These three constraints have been met in the AVALNCH code with the imposition of several major modifications that are described below.

If a grid array, based upon the original requirements of SOLASURF, is fit to an avalanche slope profile, it appears as shown in figure 2. This involves a sizable number of elements in the y direction, since at no location can the slope exceed the ratio δ_y/δ_x. With this restriction, δ_y is of the same order as δ_x (10 to 30 m) for slopes of from 30 to 50 degrees, so that an avalanche 2 m high occupies only a small fraction of one cell. An improvement on the grid of figure 2 is that shown in figure 3. The primary difficulty is the sensitivity of the governing equations in AVALNCH to height changes between successive cells along the path. This is not remedied by the grid of figure 3. The final grid layout, which appears most adaptable to the avalanche problem, is shown in figure 4, and is the one currently programmed. For each cell, the value of ΔH (fig. 3) is input, from which gravity components are calculated by the equations

$$g_x = g \sin\phi, \qquad \sin\phi = \frac{\Delta H}{DELX} \qquad [4]$$

$$g_y = g \cos\phi, \quad \cos\phi = \sqrt{1 - \sin^2\phi}.$$

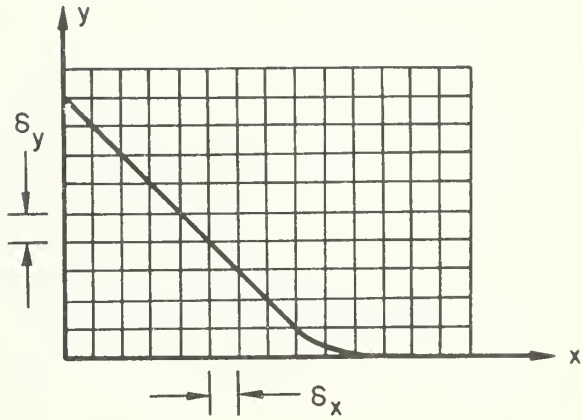

Figure 2.—Avalanche profile and grid.

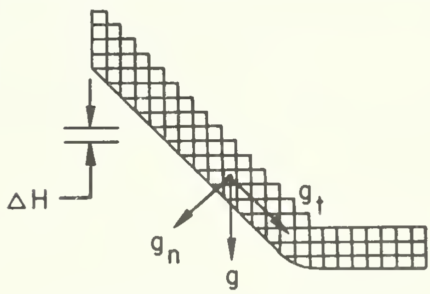

Figure 3.—Improved grid layout.

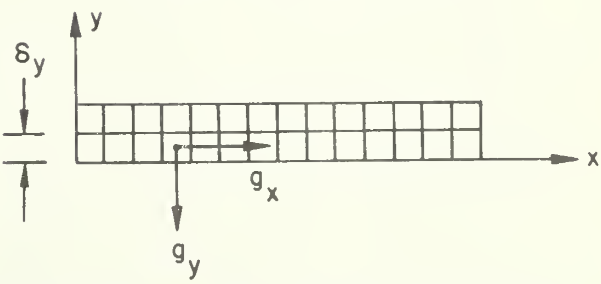

Figure 4.—Equivalent grid layout for avalanche flow.

Angle ϕ is the average angle of the slope at the cell being specified. With this arrangement, δy can be selected independent from δx, where δx, is the slope-parallel increment along the avalanche path. For local instrusions, such as a level road bed, we set $\Delta H=0$ for the cells in the road cut. In some cases a road cut may also cause an increase in the airborne component of a flowing avalanche by deflecting flow upward and entraining air. This can be represented in program AVALNCH by reducing the values of ν and f (the coefficient of friction at the lower boundary) on the basis of available physical data.

The complex flow associated with a vertical drop is not representable in the present formulation. The g_x and g_y values enter the governing equations in AVALNCH at the stage of preliminary calculation of the velocity and pressure distribution at the start of each cycle. The ratio δ_y/δ_x enters later when boundary conditions are imposed, and when the updated flow height is computed. By numerical experimentation, it is determined that, whereas the limit of $\delta_y/\delta_x < 1.0$ is a sensitive parameter to numerical stability, values of $g_y/g_x > 1.0$ are readily handled. The difference is that rapid variation in velocity between cells is permissible, but rapid variation in boundary height is not. The values of $\Delta H(HN(I))$ for each cell are input as a one-dimensional array following specification of the snow height, H(I), also a one-dimensional array.

Velocity at the lower boundary, u_s, is determined by linear interpolation between the corresponding velocities in the boundary cell, u_1, and the lowest flow-domain cell u_2, (fig. 5) in which velocity u_1 is expressed in terms of velocity u_2. We generalize this relationship from that of the SOLASURF code by specifying that

$$u_1 = u_2 (1 - 2f) \qquad [5]$$

which is equivalent to a surface velocity given by

$$u_s = u_2 (1 - f) \qquad [6]$$

For $f = 0$, $u_1 = u_2$, and the surface is slip-free, and for $f = 1$, $u_1 = -u_2$, so that $u_s = 0$ a no-slip condition. For intermediate values of f, the boundary is a partial slip wall. Since f reflects friction at the boundary, we refer to this as the "friction coefficient," which is one of two basic parameters that must be sized for the avalanche runout problem.

Two options for input of f are given in AVALNCH. If f is constant over the entire path, then this value is input by specifying parameter, FRK. If f is a variable over the path, then a one-dimensional array, FRC(I), is specified, and FRK = 0.0. If the friction is actually to equal zero, it must be input by the array. If, in a particular application, values of $f > 1.0$ are used, this can be interpreted as a penetration of the surface roughness into the flow. The surface roughness where $u_s = 0.0$ is defined by

$$r = \frac{f-1}{2f} \quad (f \geq 1) \qquad [7]$$

as denoted in figure 5. There is an artificial aspect to this interpretation in that the quantity of flowing fluid is not reduced correspondingly due to $r > 0$. Thus, the analogy that perhaps most closely represents the case $f > 1.0$ is sparsely spaced rock protrusions or tree trunks that slow the flow significantly, but do not trap large fractions of it. The variation in r for different values of f, as predicted by equation [7], is shown in figure 6.

The other parameter in AVALNCH requiring specification is the kinematic viscosity, ν (NU). It is input as a single constant over the entire flow path, since information on possible variation of this parameter is generally lacking. When we learn enough to be able to specify changes in this variable down the path, program AVALNCH, as written, can easily accommodate this.

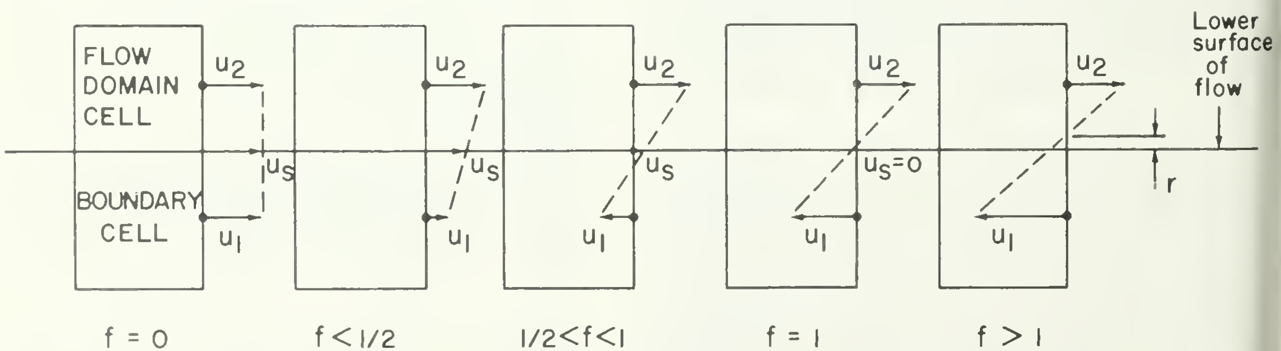

Figure 5.—Effect of friction on boundary flow.

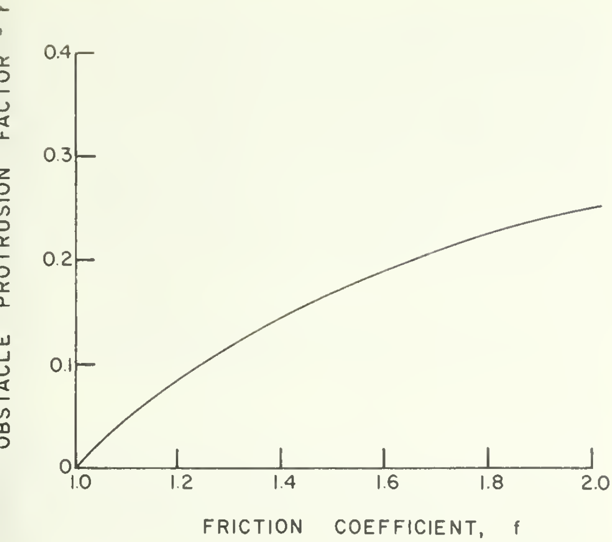

Figure 6.—Obstacle protrusion factor, r, versus friction coefficient f≥1.0.

From case studies it has been determined that the internal circulation in a flow is a function of the number of cells used in the y direction, for a fixed number of cells in the x direction. Since values for f and υ must be established from case studies rather than from controlled experiments, their absolute values are not important. Thus, to standardize the cell geometry for all avalanche runs, a single cell height of the same dimension as the maximum thickness[5] of the fracture face is used. Flow height[5] as given by program AVALNCH, is the height of the "core material" and not of the snowdust cloud that accompanies mixed flow and powder avalanches. Actual field observations of "core height" are very difficult because, in most cases, only the dust cloud can be seen or photographed. A second flow domain cell is assumed above the avalanche cell, so that JBAR = 2 for all cases. Based upon this selection of a flow domain geometry, f and υ are sized from a number of modeled avalanche runs.

Besides numerical stability problems associated with the variable boundary option in SOLASURF, another difficulty is flow of mass through the boundary. Initial avalanche runs showed gradual disappearance of mass until, at some point downstream, the avalanche left the flow domain completely. This problem is reduced by using the standardized grid of figure 4, and is eliminated by inserting a multiplicative factor equal to the ratio of original volume to current volume in the height update section (4000 section) of the code (Appendix B). This ratio is close to unity, so that the correction on each cycle is small, but sufficient to eliminate the monotonic divergence observed without the correction.

[5] *The term "thickness" is used to designate the dimension of a snow layer perpendicular to the sliding surface. When speaking of the flowing snow, however, the term "flow height" is used to describe the dimension perpendicular to the slope to avoid using the term "flow thickness," which could be misunderstood as relating to the viscosity of the flowing snow.*

One difficulty of the circulating flow condition is in obtaining an accurate value for the average advance or "group" velocity of the fluid. (A "group" velocity is needed rather than a particle velocity.) The particle velocity, which reflects circulation as well as translation, listed in the expanded output of the flow profile is the maximum value of particle velocity (UMAX) and is used to predict the next time increment (DELT) in AVALNCH. To obtain the "group" velocity in a mathematically rigorous manner requires a lengthy calculation. Instead, an approximate calculation utilizing the cell number of the leading (LDEG) and trailing (KTEG) edges of the avalanche is used. These cells are designated as the first occurring from opposite directions in which the flow height is 1% (or less) of the original avalanche height. Once the leading edge is located, the time change for advance of this edge to the next cell divided into the cell length is one estimate of the avalanche slope-parallel velocity (UEDG). Since fraction distance into the cells is not known, a nominal velocity estimate must be based upon averaging the values of UEDG over several (three to five) cells. Furthermore, UEDG can not be computed until the leading edge has left the cell, so that the listed values of UEDG must actually be associated with the cell previous to the current leading edge cell (LDEG).

A condition observed in early runs on avalanches was a tendency of the flow to reach a near steady-state shallow flow, not unlike equilibrium open channel flow, and to run out for considerable distances. Since this is not observed in most avalanches, a velocity dependent surface friction law is incorporated in the code (6000 section) in which the friction coefficient is increased exponentially with decrease in speed. The relationship established between f and u is:

$$f = f_o \left(1 + 20e^{-1.25u}\right) \qquad [8]$$

where f_o is the initial value selected for f. This surface friction-velocity relationship is written into the program to be operable anytime after the primary acceleration phase of the avalanche flow. A plot of equation [8] showing the variation in f/f_o versus u is given in figure 7. Although an actual quantitative physical basis for this phenomenon is not known, this

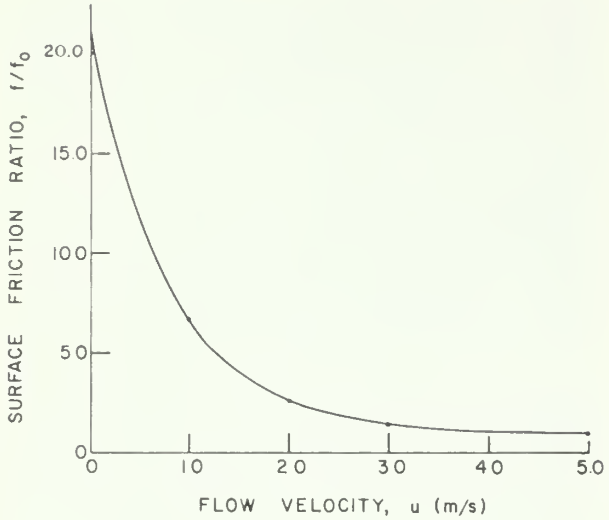

Figure 7.—Surface friction coefficient ratio as a function of flow velocity for "Fast-Stop" option in AVALNCH.

"fast-stop" option is a better representation for most avalanche flows than what is observed without it.

Apart from user program limits, there are five default conditions within AVALNCH which can terminate calculations. They are:

1. Number of iterations (ITER) within a cycle reaches 500.
2. Duration of avalanche flow exceeds time specified (TWFIN).
3. Leading edge flow velocity (UEDG) drops to less than 5% of maximum flow velocity achieved during the flow.
4. Leading edge of flow reaches lower limit of grid.
5. Leading edge of flow does not advance to a new cell in 50 cycles.

Parameter overflow occurs for condition 1. For conditions 2 through 5, the flow distribution is printed and an end statement is given prior to termination.

These are the major modifications incorporated in program AVALNCH. Other minor modifications have been made that can be identified by comparing the listing of AVALNCH (Appendix B) to that of SOLASURF (Hirt, Nichols and Romero 1975).

Characteristics of Fluid Modeling Equations

Having reviewed the various features that have been incorporated in program AVALNCH, we consider the physical conditions that are modeled in the computer formulation. The Navier-Stokes equations are equations of motion for laminar fluid flow. If internal viscosity is greater than zero, then, the flow is also considered to be rotational. In laminar, rotational flow fluid particles tend to follow curved paths along streamlines, and circulation patterns are evident. In contrast, particle motion in turbulent flow is completely random, and streamlines or flow path lines are not evident. From the study of numerous avalanche films, our conclusion is that for flowing and mixed motion avalanches the flow is often rotational and laminar. See Perla and Martinelli (1976) for description of avalanche motion.

At the extremes of avalanche motion are the cases of sliding rigid-blocks (sliding motion) for which internal viscosity is large, and turbulent flow (powder avalanches) for which viscosity is low. The low viscosity of turbulent flow is attributable to a large air-fraction in the flow and small snow particles, which produces the snow dust clouds surrounding the larger mixed motion avalanches. However, even in this case, there is a core of denser snow within the snow dust cloud that acts as a piston to drive or propel the airborne component. For this type of avalanche, program AVALNCH can be used, but it models only the flow of the core material, not the snow dust cloud. Once the snow is in motion, subsequent flow height predicted by the program is the height of the core material, not that of the snow dust cloud.

Most field observations of the flow height of this type of avalanche are to the top of the snow dust cloud, which gives no information on the type of flow that the core exhibits. However, based upon evidence from debris, the assumption of laminar rotational flow of the core material appears reasonable in many cases.

Program AVALNCH traces the snow flow starting from the initial, at-rest conditions of the release slab in the starting zone. Specification of the distribution of snow slab in the starting zone is, thus, a necessary part of the input. Any slab distibution may be input, the only restrictions are the following:

1. Only one height per slope-parallel cell may be specified; this height is assumed to be constant over the entire cell and is measured perpendicular to the slope.
2. Cell height is then set equal to the maximum slab thickness specified in the starting zone cells.

Snow entrainment as flow propagates down the slope is common in avalanche flow. To model this phenomenon. it is not accurate to specify snow thickness in downslope cells in the same way that starting zone material is specified. However, the modeling of snow entrainment is possible with program AVALNCH and is considered in detail in the section headed "Leading Edge Snow Entrainment Modeling."

Avalanche Models, and Evaluations Using Program AVALNCH

Intent of Case Studies

This part of the paper outlines a number of specific, recorded avalanche incidents to establish ranges for kinematic viscosity, υ, and surface friction, f. Ideally, these ranges would be established using detailed information from many avalanches based on the following factors: fracture thickness, slope-parallel cross section of the initially released slab, type of surface layer of snow on slope, velocity of flow, actual runout distance,[6] and distribution of terminal debris. Since such detailed data are seldom available, we used case studies to size f and υ to model overall runout response. Such a general approach is thought to have greater utility than one requiring highly accurate point variations in parameters because of the difficulty in obtaining such data for a wide range of snow and slope conditions.

Any, and ideally all of the above parameters, if measured, could be used to better quantify the values of υ and f. However, the tremendous variation in snow and slope conditions that occur throughout a winter season preclude the utility of a specific slope analysis taking into account point variations in parameters. In fact a program requiring this accuracy would not be of general applicability for runout prediction, since specification of parameters is seldom accurate except under very specialized conditions.

Ironton Park Avalanche Path

Location:	San Juan Mountains, Red Mountain Pass North; southeast slope of Hayden Mountain, Colorado.
Starting Zone:	Wide, uniform slope below Half Moon Basin, below timberline; elevation 3,230 to 3,450 m.
Track:	The entire slope; vertical drop 350 m; length 1,000 m.
Runout Zone:	Level bottom of Ironton Park and frozen lake.
Avalanches:	Large dry snow avalanche in 1958 crossed the road and left a debris pile approximately 1.5 m high on the road. No information is known on the starting zone fracture thickness or extent, nor on the type of snow constituting the flow.
Profile:	Ironton Quadrangle, Colorado (7.5').

Length (*m*)	Elevation (*m*)	
0	354	
70	293	
174	232	
265	171	
326	110	
418	49	
509	0	
814	0	Location of road (Cell 93)
997	0	Opposite side of flat
1,073	49	

The profile constructed from these data points is shown in figure 8. The data needed from this profile is obtained by first marking off the increment distance δ_x along the profile. This is selected to be 10 m slope distance in this case in order to describe the profile accurately and still keep the number of cells to less than the limit of 200 for AVALNCH. The change in elevation in each cell is taken directly from figure 8. For the present example only, the values of the elevation and change in elevation for each cell are listed in table 1. It should be noted that positive values of ΔH correspond to decreases in elevation across cells, and negative values of ΔH correspond to increases in elevation across cells (adverse slope). The values shown in table 1 for ΔH, carried out to tenths of a meter, were obtained by interpolation, and reflect an accuracy not necessary for meaningful avalanche prediction. In subsequent runs, whole number values for ΔH were used successfully, with much less time spent in data preparation. However, gross round-off of ΔH to the point of masking 5- to 20-m length

[6] *The term "runout distance" is used to indicate the horizontal distance from the start of the runout zone to the most distant end of the avalanche debris. In this paper, the term "travel distance" is used to mean the horizontal distance from the fracture face in the starting zone to the most distant end of the avalanche debris.*

perturbations in slope geometry is not recommended, as this order-of-magnitude perturbation can have a significant effect on the flow. Some of these conditions will be pointed out in the following avalanche cases.

In the case of the Ironton Park slope, little information is known about specific avalanches. Since the track is an open uniform slope, this example was used to examine the effect of varying the values of the kinematic viscosity, υ, and surface friction, f. A summary of the values of υ and f used for different travel distances is given in table 2. For most of the runs the initial slab thickness is set at 2 m for a downslope distance of 50 m, then a linear decrease in thickness out to 90 m, which is considered a large initial release. Other runs reported in table 2 for initial slab thickness other than the 2 m are vertically scaled modifications of the 2-m slab distribution.

The avalanche, which occurred in late December 1958 and deposited 1.5 m of snow on the road, is considered rare. Unfortunately, fracture line information is lacking. Occurrence of the avalanche in late December suggests moderate midwinter snow. On the basis of an initial slab thickness of 2 m, computer runs that characterize avalanche termination in the vicinity of the road are those for which values of υ and f sum to 1.0 to 1.1. For example, for $\upsilon = f = 0.5$, the avalanche leading edge is 60 m beyond the road, and the debris on the road is nominally 1.9 m deep (Appendix C). For $\upsilon = 0.4$, $f = 0.7$, the leading edge of the avalanche reaches the road, and for $\upsilon = 0.5$, $f = 0.6$, the leading edge is 20 m short of the road. It is apparent that by modifying υ and f by relatively small amounts a wide variety of snow conditions can be modeled. We further note from the results in table 2 the near correspondence of results when the values of υ and f are exchanged. That is, for $\upsilon = 0.4$ and $f = 0.7$, travel distance is approximately the same as for $\upsilon = 0.7$ and $f = 0.4$. Similar results are obtained for all other cases where υ is not equal to f reported in table 2. This indicates the nearly equal influence of these two parameters in determining travel distance when using the units of measure selected for these studies. Thus, in the present case, we consider $\upsilon = f = 0.5$ as representative of the flow, and adapt the practice of selecting $\upsilon = f$, except when physical conditions clearly indicate different values for υ and f are warranted.

The computer listing of the input and output data for the case $\upsilon = f = 0.5$ and a slab thickness of 2 m is shown in Appendix C. The listing includes the eight discrete input parameters, followed by the flow height, elevation change per cell, and the boundary friction coefficients, for the purpose of data verification. Finally, the gravity components, g_x and g_y, are printed for reference purposes. Any adverse grade in the slope profile shows up with negative values in the array for g_x. The values of g_y should always be negative. This completes printout of all input data needed for AVALNCH.

Outputs are the single line printouts of the avalanche flow status given after each cycle of calculation. By scanning the column of numbers labeled

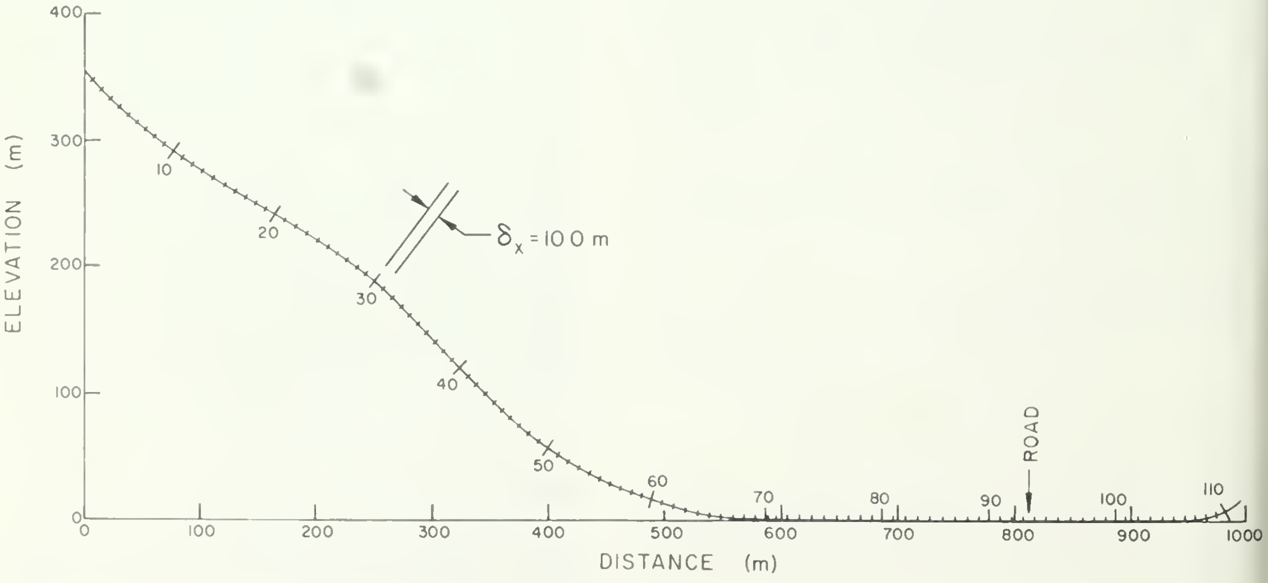

Figure 8.—Longitudinal profile of Ironton Park avalanche path.

Table 1. — Ironton Park profile elevation data

Station	Elevation (*m*)	ΔH (*m*)	Station	Elevation (*m*)	ΔH (*m*)	Station	Elevation (*m*)	ΔH (*m*)	Station	Elevation (*m*)	ΔH (*m*)	Station	Elevation (*m*)	ΔH (*m*)
0	357.0		23	226.2	4.6	46	81.4	6.0	69	2.0	0.9	92	0.0	0.0
1	350.5	6.5	24	221.4	4.8	47	75.4	6.0	70	1.3	0.7	93	0.0	0.0
2	344.3	6.2	25	216.4	5.0	48	69.8	5.6	71	0.8	0.5	94	0.0	0.0
3	338.1	6.2	26	211.2	5.2	49	64.6	5.2	72	0.4	0.4	95	0.0	0.0
4	331.9	6.2	27	205.8	5.4	50	59.4	5.2	73	0.1	0.3	96	0.0	0.0
5	325.4	6.5	28	200.2	5.6	51	54.4	5.0	74	0.0	0.1	97	0.0	0.0
6	319.2	6.2	29	194.4	5.8	52	49.8	4.6	75	0.0	0.0	98	0.0	0.0
7	313.0	6.2	30	188.2	6.2	53	45.6	4.2	76	0.0	0.0	99	0.0	0.0
8	306.8	6.2	31	182.0	6.2	54	41.4	4.2	77	0.0	0.0	100	0.0	0.0
9	300.3	6.5	32	175.8	6.2	55	37.4	4.0	78	0.0	0.0	101	0.0	0.0
10	293.8	6.5	33	169.6	6.2	56	33.4	4.0	79	0.0	0.0	102	0.0	0.0
11	287.6	6.2	34	163.1	6.5	57	29.8	3.6	80	0.0	0.0	103	0.0	0.0
12	281.8	5.8	35	156.3	6.8	58	26.2	3.6	81	0.0	0.0	104	0.0	0.0
13	275.8	6.0	36	148.9	7.4	59	22.8	3.4	82	0.0	0.0	105	0.0	0.0
14	270.0	5.8	37	141.7	7.2	60	19.4	3.4	83	0.0	0.0	106	0.0	0.0
15	264.4	5.6	38	134.5	7.2	61	16.4	3.0	84	0.0	0.0	107	1.0	−1.0
16	258.8	5.6	39	127.4	7.1	62	13.6	2.8	85	0.0	0.0	108	2.0	1.0
17	253.6	5.2	40	120.4	7.0	63	11.1	2.5	86	0.0	0.0	109	4.0	−2.0
18	249.0	4.6	41	113.4	7.0	64	8.9	2.2	87	0.0	0.0	110	7.0	−3.0
19	244.8	4.2	42	106.4	7.0	65	7.1	1.8	88	0.0	0.0			
20	240.6	4.2	43	99.8	6.6	66	5.5	1.6	89	0.0	0.0			
21	236.0	4.6	44	93.6	6.2	67	4.1	1.4	90	0.0	0.0			
22	230.8	5.2	45	87.4	6.2	68	2.9	1.2	91	0.0	0.0			

Table 2. — Ironton Park avalanche travel distance for different values of viscosity and surface friction coefficients

Run No.	Viscosity (m^2/s)	Friction coeff.	Initial slab thickness (*m*)	Travel Distance[1] (*m*)	U max (*m/s*) Cell No.	Comments
1	0.3	0.3	2.0	—	63/71	Avalanche flows out of grid at 25 m/s.
2	0.3	0.5	2.0	—	54/65	Avalanche flows out of grid at 16 m/s.
3	0.4	0.4	2.0	—	53/64	Avalanche flows out of grid at 15 m/s.
4	0.4	0.5	2.0	—	47/60	Avalanche flows out of grid at 8 m/s.
5	0.4	0.7	2.0	820	39/58	Avalanche stops on road. Max. debris depth: 2.4 m.
6	0.45	0.45	2.0	—	47/62	Avalanche flows out of grid at 8 m/s.
7	0.45	0.5	2.0	—	44/59	Avalanche flows out of grid at 2.5 m/s.
8	0.5	0.5	2.0	880	42/58	Avalanche stops 60 m beyond road. Max. debris depth 2.2 m.
9	0.5	0.6	2.0	790		Avalanche stops 20 m in front of road.
10	0.5	0.7	2.0	740	33/55	Avalanche stops 70 m in front of road. Max. debris depth 2.1 m.
11	0.6	0.5	2.0	790	37/56	Avalanche stops 20 m in front of road. Max. debris depth 2.2 m.
12	0.6	0.6	2.0	730	33/55	Avalanche stops 80 m in front of road. Max. debris depth 2.2 m.
13	0.6	0.7	2.0	700	33/55	Avalanche stops 110 m in front of road. Max. debris depth 2.0 m.
14	0.7	0.4	2.0	820	39/63	Avalanche stops on road. Max. debris depth 2.0 m.
15	0.7	0.5	2.0	740	39/55	Avalanche stops 70 m in front of road. Max. debris depth 2.7 m.
16	0.7	0.6	2.0	710	29/54	Avalanche stops 100 m in front of road. Max. debris depth 2.0 m.
17	0.4	0.4	1.5	820	39/63	Avalanche stops on road. Max. debris depth 1.5 m.
18	0.45	0.45	0.5	720	33/56	Avalanche stops 90 m in front of road. Max. debris depth 2.4 m.
19	0.5	0.5	1.5	690	20/51	Avalanche stops 120 m in front of road.
20	0.5	0.5	1.0	640	14/50	Avalanche stops 50 m onto flat. Max. debris depth 1.4 m.
21	0.5	0.5	0.75	160		After initial transient, avalanche decelerates continuously and stops on a bench of the slope.

[1] Travel distance is the horizontal distance from the crown of the avalanche to the leading edge of the terminal debris

UEDG and averaging over several cells, we see that the maximum velocity achieved by the avalanche is about 42 m/s in the vicinity of cell 64. This corresponds to a distance approximately 530 m (fig. 8), which is the start of the runout zone. The avalanche stops in cell 99, one cell short of the grid limit. The final listing of data is the extended output. By scanning the column labeled H (Appendix C), we find the final position of debris to extend from cell 91 (about 20 m in front of road), where the depth of debris is 0.8 m, to cell 99 where the debris depth is 0.02 m (Appendix C). Although velocity components persist in columns for u and v, these must be considered components of the circulation and are assumed to be negligible. Values for velocities and pressure outside the range of the flow domain can be ignored.

Holding ν and f constant at 0.5, the thickness of the initial slab is varied from 0.5 to 2.0 m, and travel distance is noted as shown in figure 9. These results show a nonlinear dependence of runout distance with slab height with the "fast-stop" option having a significant effect on flow of the shallower avalanches.

An avalanche with a 2-m average slab thickness is considered unusual. What is perhaps more realistic is a thickness of 1.5 m, for which $\nu = f = 0.4$ in order that the debris reach the road (table 2, run 17). Thus, we conclude that sensitive parameters that influence avalanche travel distance are the viscosity and friction coefficients and initial slab thickness. Correlation between these parameters is expected as additional avalanche occurrences are evaluated.

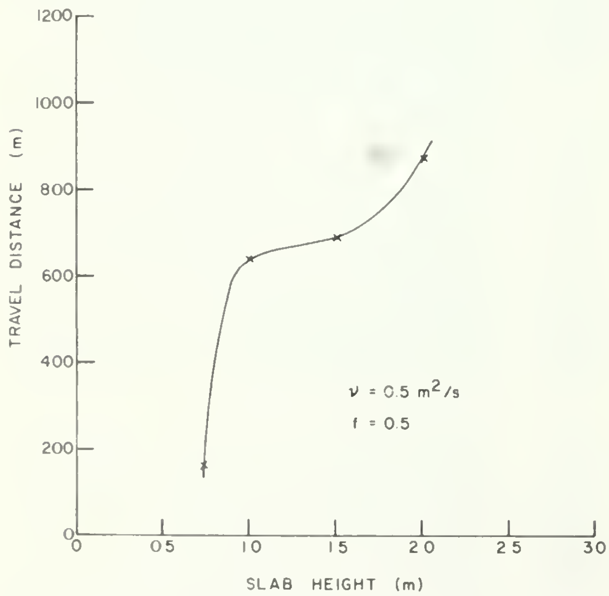

Figure 9.—Avalanche travel distances versus initial slab height for the Ironton Park path, holding viscosity and friction coefficients constant.

The principal conclusions we obtain from this study of the Ironton Park profile are:

1. Values of ν and f in the range 0.4 to 0.5 represent nominal values for early winter, dry hardpack snow in thick-slab avalanches.

2. Cell lengths of the order of tens-of-meters in the slope-parallel direction, coupled with cell heights of 1 to 2 m in the slope-normal direction, can be selected to reasonably model the avalanche flow.

3. Parameters that are identified to strongly influence avalanche travel distance are the kinematic viscosity, friction coefficient, and initial slab thickness. Ranges of values for these parameters should be established as additional case studies of specific avalanche paths are modeled.

Pallavicini Avalanche Path

Location:	Front range of Colorado Rockies; north slope of summit point 3,700 m southwest of Arapaho Basin ski area.
Starting Zone:	Bowl-shaped depression in the north facing slope; above and below timberline; elevation 3,415 to 3,660 m.
Track:	Wide opening in the heavily timbered slope; vertical drop 390 m; length 823 m.
Runout Zone:	Flat bottom of the Snake River Valley; under severe conditions the avalanche may run across the 152-m-wide valley and reach the highway on the opposite slope.
Avalanches:	The starting zone is controlled intensively by explosives and protective skiing, so that large avalanches are unlikely unless deposition occurs from a prolonged storm.
Profile:	By a process described in detail for the Ironton Park avalanche path, the profile for the Pallavicini path is computed as shown in figure 10. Of particular note is the steep 80 m starting zone, in which the avalanch-

ing slab initially spans the upper 50 m. A second noteworthy characteristic of the profile is the adverse slope beyond the creek (cell 96) of 20% average grade.

The primary consideration in evaluating the Pallavicini path is to obtain qualitative information on the effect of the adverse grade in slowing and stopping avalanches. Good field data show that, in this path, only deep dry-snow slab avalanches with a significant airborne fraction ever reach the road. Most small midwinter avalanches stop between the grade change at about 400 m (cell 48) and the creek (cell 96), (fig. 10). The path is divided into 10-m increments or cells, and the avalanche starting zone is assumed to be 50 m long. Table 3 summarizes the computer runs made using the Pallavicini profile.

An avalanche of 0.75 m thickness stops quickly when vicosity and friction are set equal to 0.55. What might be considered nominal flow for an avalanche 0.75 m in thickness occurs when viscosity and friction are reduced to 0.5. In this case, the debris stops in cell 53, which is a bench in the lower part of the track (fig. 10). Flow of a 2-m avalanche with v and f at 0.5 (table 3, Run 8) ends 40 m beyond the creek, but does not reach the road. It is necessary to drop v and f to 0.4 for a 2-m avalanche to reach the road (Run 10). This indicates that a deep, dry avalanche with an airborne phase is modeled for v and f in the range of 0.4. Since many avalanches with an average fracture face height of 2 m on the Pallavicini Path are known to stop in the vicinity of the creek, a value of 0.6 seems reasonable for v and f.

The 20% adverse slope beyond the creek in the Pallavicini Path is an effective mechanism for stopping avalanches that flow into this region, and mounding of the debris is noted in the AVALNCH prediction (table 3). Reynolds number, Re, which accounts for both inertial and viscous effects, is computed at the point of first occurrence of zero slope in the avalanche path, and is plotted in figure 11 versus runout distance for two of the paths analyzed. For Ironton Park, runout is across a frozen lake of zero slope. The 20% adverse slope of the Pallavicini path results in a 3.5 reduction of runout distance for Re = 240, and up to a 5.7 reduction at Re = 560. These results are based upon a nominal flow depth of H = 2 m. Reynolds number, Re, defined as

$$Re = \frac{UH^*}{v}$$

was computed using U = the velocity of the avalanche leading edge at the instant it enters the runout zone, $H^* = 4H$ and v is the kinematic viscosity which is usually near 0.5.

So far we have concentrated on the large avalanche that flows onto the adverse grade. For the smaller avalanche that stops in the track, flow height is a sensitive parameter that controls the distance of flow. Comparing Runs 1 and 2 in table 3, the

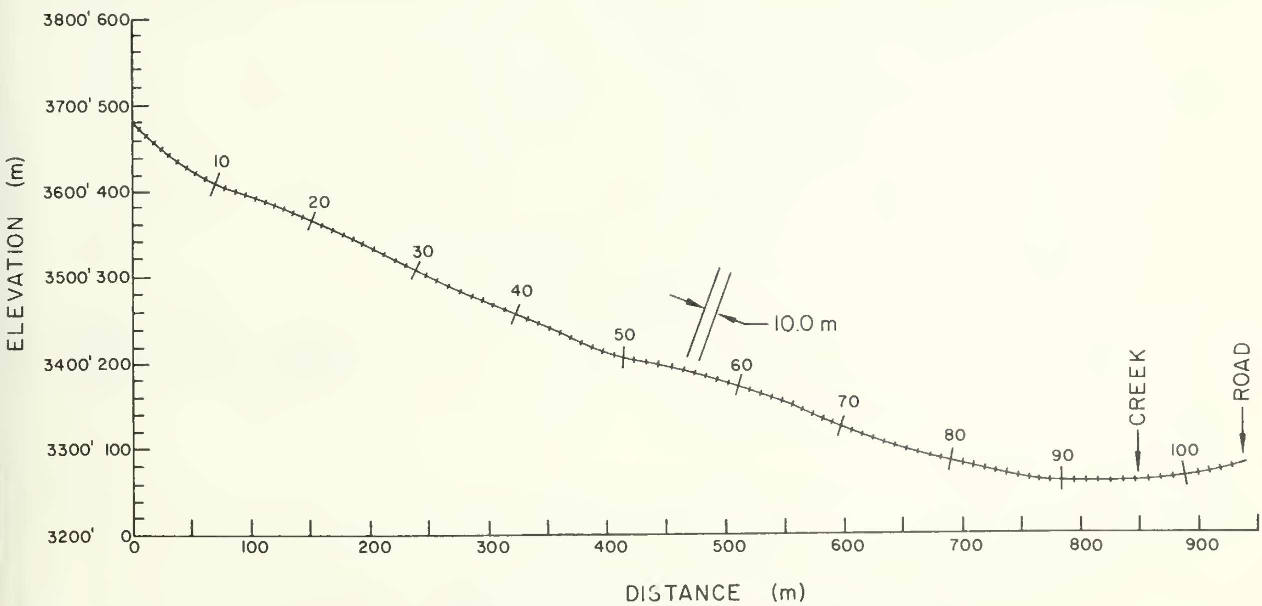

Figure 10.—Longitudinal profile of Pallavicini avalanche path.

Table 3. — Travel distance for the Pallavicini Avalanche for specified flow conditions

Run No.	Viscosity (m^2/s)	Friction Coeff.	Initial Thickness of slab (m)	Travel Distance (m)	Comments
1	0.55	0.55	0.75	130	Avalanche stops in cell 17. Maximum debris depth is 0.7 m and covers 80 m of slope.
2	0.50	0.50	0.75	440	Avalanche stops in cell 53. Maximum debris depth is 0.6 m and covers 130 m of slope.
3	0.5	0.5	1.00	780	Avalanche stops at cell 90. Maximum depth, 1.0 m; extent 100 m. Initial slab 40 m extent.
4	0.6	0.6	1.00	710	Avalanche stops in cell 82. Maximum debris depth is 0.8 m and covers 170 m of slope.
5	0.5	0.5	1.50	860	Avalanche stops at cell 97, 10 m beyond creek maximum depth 3.0 m, extent 40 m.
6	0.6	0.6	1.50	850	Avalanche stops at creek (cell 96). Maximum debris depth is 1.5 m and covers 60 m of slope.
7	0.6	0.6	2.00	870	Avalanche stops at cell 98 just beyond creek. Maximum debris depth 7.4 m. Avalanche covers 40 m of slope.
8	0.5	0.5	2.00	890	Avalanche stops at cell 100. Maximum depth 3.6 m, extent 40 m. Adverse slope is effective.
9	0.45	0.45	2.00	910	Avalanche stops at cell 102. Maximum depth 9.0 m; extent 40 m.
10	0.4	0.4	2.00	—	Avalanche leaves grid at cell 105 with velocity of 5.0 m/s.

sensitivity of travel distance to the values of υ and f is pronounced. This indicates that the mechanisms to stop the small avalanche on a positive slope are the surface friction and kinematic viscosity coupled with local variation in slope profile. Since friction and viscosity are not well defined for different snow conditions, it is unlikely that programming for the small avalanche will be systematically correct for all avalanche incidents.

The major conclusions we draw from this analysis of the Pallavicini avalanche path are:

1. For the deep-slab, high air content avalanche flow, values of υ and f of the order 0.4 yield results consistent with observed avalanche behavior on this slope.

2. The dominant characteristic of adverse slope in halting avalanches is noted, which substantiates long standing physical evidence. The effectiveness of adverse slopes of different angles and heights to stop avalanches is considered in greater detail in the section headed "Sensitivity of Runout Distance to Various Parameters."

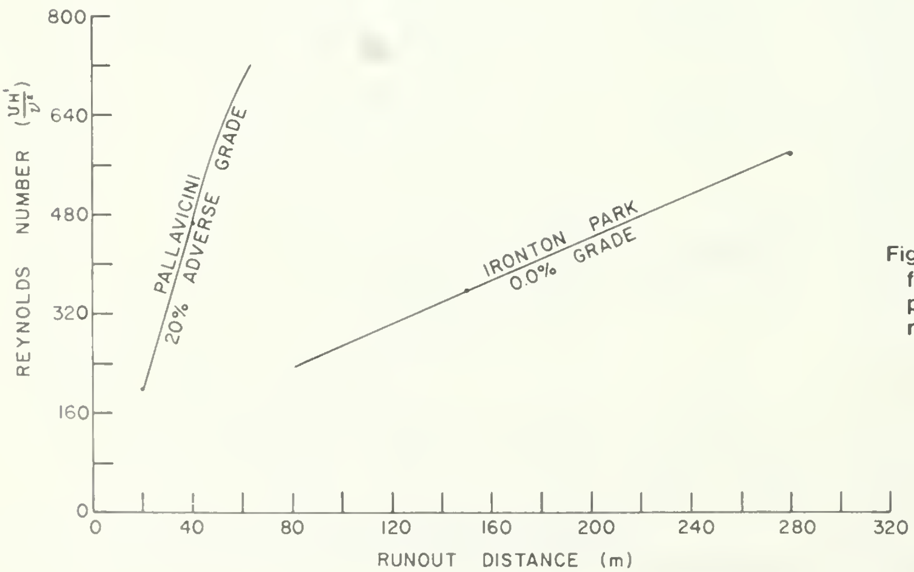

Figure 11.—Reynolds number as a function of runout distance for paths with different grade in the runout zone.

Hematite Gulch Avalanche Path

Location: Highway 110 north of Howardsville, Colo.

Starting Zone: South facing bowl-shaped basin.

Track: Vertical drop approximately 915 m; length, approximately 670 m. In upper reach, flow is open sheet flow, which changes to gully flow over 55% of total path.

Runout Zone: Broad valley of bare ground and rocks cut by the Animas River.

Avalanche: A wet slab avalanche occurred on May 7, 1975. Fracture thickness was between 1 and 1.5 m and tapered off at the flanks to about 0.5 m. Approximately one-fourth of the snow in the starting zone was released. The flow emerged from the gully and flowed into the Animas River.

Profile: Howardsville Quadrangle, Colorado (7.5'). A centerline profile of the path is shown in figure 12. Three bends of 45, 30, and 35 degrees, starting with the uppermost, are indicated on the profile. Extent of the gully is indicated also.

The slope-parallel cell dimension is taken as 20 m in this case, resulting in a total of 112 cells to represent the entire path. An embankment occurs upslope from both the road and the river which can not be duplicated accurately in AVALNCH, since actual modeling would require depositing snow in the depressions formed by the banks.[7] Instead the road is shown one cell wider than actual, with these cells level ($g_x = 0$), and the friction set at f = 0.9, a large value. The wet snow of this avalanche is assumed to have high viscosity (υ = 0.55). Friction is also assumed large, at f = 0.55, over the entire path, with local increases at the bends (f = 0.65), and in the runout zone where the flow crosses bare, rocky ground (f = 0.9). Initial slab thickness is 1.5 m over a downslope span of 40 m (two cells).

The leading edge of the avalanche stopped in the Animas River (cell 110), the debris extended 80 m upslope from the river, with a maximum height of 0.8 m. Maximum velocity of the flow after leaving the steep starting-zone was 26 m/s in cell 15. The flow encountered bare ground at cell 89, just below the lowest bend of the path. The velocity of the leading edge at this point was 10 m/s.

[7] *Recent research with the computer code SMAC, a more elaborate version of SOLASURF, indicates that it will handle this condition.*

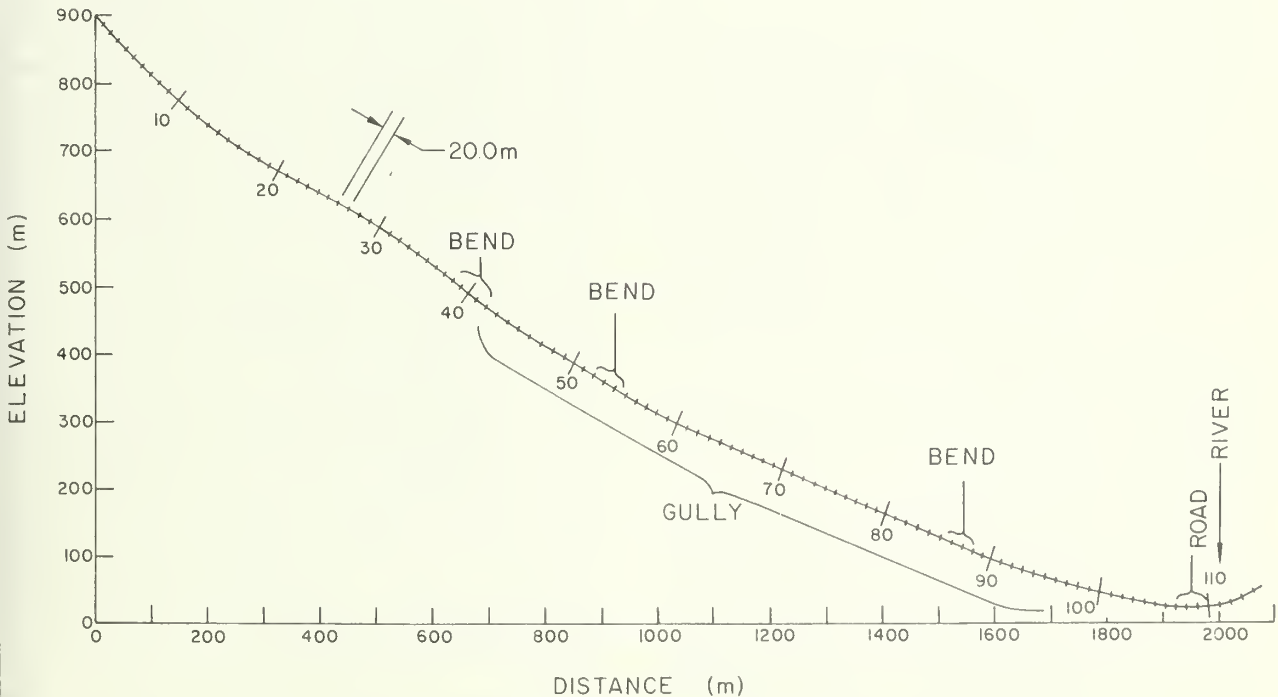

Figure 12.—Longitudinal profile of Hematite Gulch avalanche path.

At Hematite Gulch avalanches are known to cross the road and river and flow across the valley. Increasing initial slab thickness to 2 m and dropping υ and f values of 0.5 and 0.4 approximately models the worst case avalanche condition. However, specific data on the worst case event is lacking for this path, so no attempt is made at computer simulation.

Conclusions drawn from this analysis are:

1. Viscosity and friction coefficient values on the order of 0.55 appear to model wet spring snow of the high viscosity type.
2. Friction set at 0.9 for bare ground with rocks appears to be consistent with the nominal value of 0.55 for the remainder of the profile in stopping the avalanche as was observed.
3. For the volume of snow set in motion, the river and road represent an imposing barrier for stopping the flow.
4. Some mechanism should be incorporated in AVALNCH to account for contracting and spreading of the flow when local geometry dictates three-dimensional flow conditions.

Stanley Avalanche Path

Location:	Front range Colorado; south of Berthoud Pass; southeast slope of the east shoulder of Stanley Mountain.
Starting Zone:	No. 1. A bowl-shaped depression on the slope above timberline; elevation 3,540 to 3,780 m. No. 2. Wind blown snow slab along a treeline extending upward from 3,470 m elevation.
Track:	Vertical drop 730 m; length 1,700 m. U.S. Highway 40 crosses at two elevations. One crossing is at about 1,300 m, the second at about 1,700 m, in the valley bottom.
Runout Zone:	Lower section of the track with a gentle slope and the valley of Clear Creek.
Avalanches:	Stanley frequently blocks the upper highway. Most avalanches do not reach the valley bottom; however, a few of the larger avalanches have been known to overrun the lower highway and come to rest at the foot of the opposite slope. Most avalanches releasing at starting zone No. 2 stop at or above the upper highway. Most large avalanches released in starting zone No. 1 stop between the two highways.
Profile:	Berthoud Pass Quadrangle, Colorado (7.5'). A centerline profile of the eastern most of the three tracks of Stanley is shown in figure 13. The slope above the upper road is uniform except for a small rise at the starting zone.

Major consideration is modeling the upper road to represent the different types of flow adequately. The upper road is three lanes wide with a turnout, which is equivalent to one cell of 20 m. Two additional cells are placed at zero grade to represent the uphill highway cut and the snowplow embankment of the downhill side, so that three zero grade cells ($g_x = 0$) constitute the road intrusion. These three cells, plus one additional on each side of the road, are specified with large friction (f = 0.9) to simulate the irregular snow profile in the vicinity of the road. For the remainder of the path, typical midwinter hard pack snow coefficient values are assumed with $\upsilon = f =$ 0.55, which are also assumed across the lower road since it offers little resistance to flowing snow.

Results of several "typical" avalanche runs are listed in table 4. We see that 1-m deep avalanches starting in release zone No. 2 are trapped at the road consistent with a number of sightings. A 1.5-m deep avalanche starting in release zone No. 1 barely passes the road, then regains speed and finally stops between the roads. Increasing the avalanche thickness to 2 m and starting in release zone No. 1, the avalanche crosses the lower road. Tapered avalanche slabs 2.5 and 3 m thick at the crown, and 1 m thick at the toe 100 m downslope, behave similarly to the 2-m avalanche. The 3-m avalanche flows out of the grid but is slowing rapidly on the adverse grade past the creek. Comparing runs Nos. 1 and 3, and Nos. 5 and 6, we conclude that length of the starting slab does not change flow limits significantly. Flow length could be important when the leading part of the flow fills a recess (road cut, creek recess, etc.) and the flow is long enough so that the trailing part flows over the snow-filled recess. This phenomenon cannot be modeled exactly by AVALNCH except to fill the recess by changing the profile of the path prior to making the computer run.

A field observation on March 4, 1977, showed that an avalanche released by explosives in starting zone

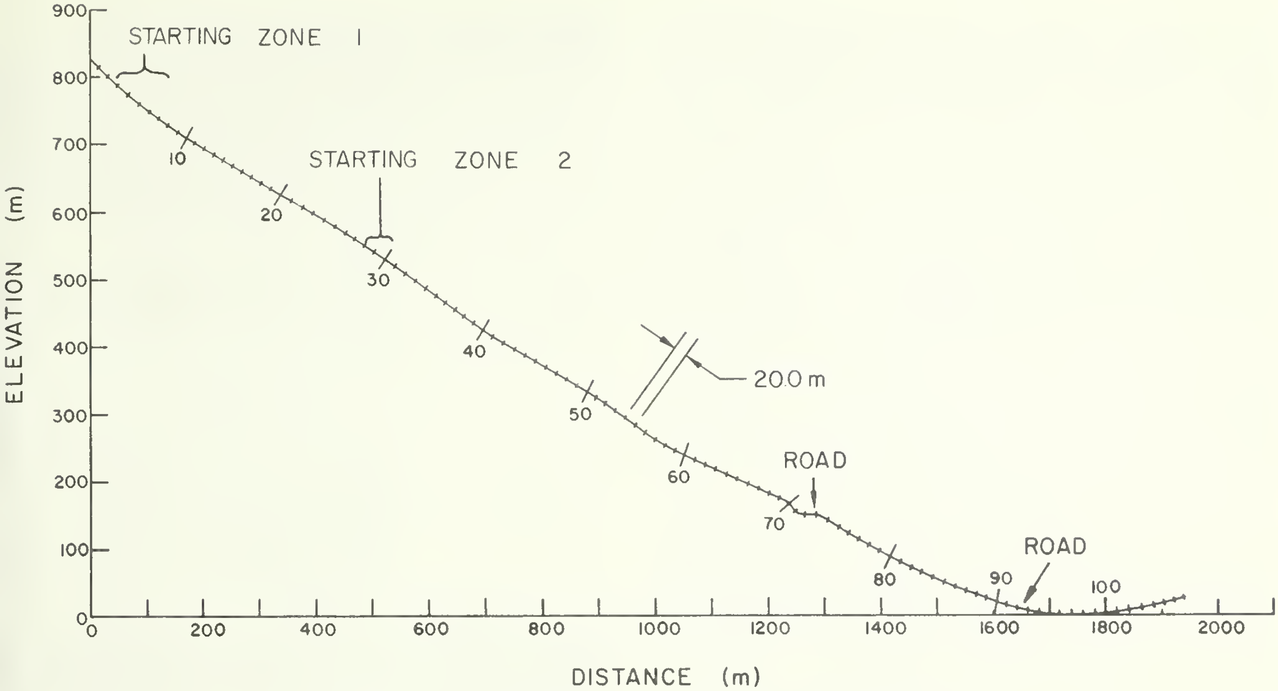

Figure 13.—Longitudinal profile of Stanley avalanche path.

Table 4.—Travel distance and maximum velocity for the Stanley Avalanche for specified flow conditions

Run No.	Starting Zone No.	Viscosity (m^2/s)	Friction Coeff.	Initial Thickness of slab (m)	Maximum Velocity m/s	Cell No.	Travel Distance (m)	Cell No.	Comments
1	1	0.55	0.55	1.0	9	35	1,300	74	Initial 40-m slab stops in upper road; 1.3 m max. depth; extent 100 m; upper road f = 0.55.
2	2	0.60	0.60	1.0	8	34	770	73	Initial 40-m slab stops in upper road; 1.1 m max. depth; extent 160 m; upper road f = 0.6.
3	2	0.55	0.55	1.0	10	34	800	74	Initial 100-m slab stops in upper road; 1.8 max. depth; extent 280 m; upper road f = 0.55.
4	1	0.55	0.55	1.5	22	10	1,600	90	Initial 60-m slab stops between roads; 0.5 m max. depth; extent 320 m; upper road f = 0.9 velocity across road V = 5 m/s, then to V = 13 m/s.
5	1	0.55	0.55	2.0	28	10	1,780	99	Initial 60-m slab stops past second road; 7.3 m max. depth; extent 20 m; upper road f = 0.9; velocity across road V = 23 m/s.
6	1	0.55	0.55	2.0 tapered to 1.0	28	74	1,780	99	Initial 100-m slab stops past second road; 8.6 m max. depth; extent 20 m; upper road f = 0.55; velocity across road V = 23 m/s.
7	1	0.55	0.55	2.0	28	74	1,780	99	Initial 60-m slab stops past second road; 8.6 m max. depth; extent 20 m; upper road f = 0.55; velocity across road V = 26 m/s.
8	1	0.55	0.55	2.5 tapered to 1.0	45	75	1,820	101	Initial 100-m slab stops past second road; 9.0 m max depth; extent 20 m; upper road f = 0.55, velocity across road V = 45 m/s.
9	1	0.55	0.55	3.0	60	78	Flows out of grid		Initial 100-m slab flows out of grid at V = 37 m/s, upper road f = 0.55; velocity across road V = 59 m/s.

No. 1 reached a speed of 33 m/s above the upper road. Most debris stopped in the upper road (cell 70-73) with a small amount extending to cell No. 85. Average fracture face thickness was 1.51 m, and average slab thickness in the starting zone was 1.19 m. The case that best matches this occurrence is Run 4 in table 4. The greatest discrepancy is in the two velocity values, which is probably due to the difference between the slab thickness used in the calculations and the flow height actually attained in the field.

The upper road intrusion modeled for Stanley is apparently sufficient to stop the smaller avalanches, and yet, permit the larger ones to flow beyond. User judgment is warranted in setting up these intrusion models for each case that is encountered.

Finally, it is noted that on the near uniform slope in release zones Nos. 1 and 2, avalanche velocity for the 1- and 1.5-m avalanches approximates the quoted condition that flow velocity reaches 80% of maximum speed after the avalanche has covered a distance equal to 25 times the initial slab thickness (Voellmy 1964). An alternate statement that is less precise is that the avalanche accelerates rapidly at the start, then flows on at a near equilibrium flow rate if the slope is constant. This physical condition is generally observed in the AVALNCH results.

General conclusions derived from the Stanley avalanche study include:

1. Heavy midwinter dry snowpack of 1- to 2-m thick slabs may be modeled with $v = f = 0.55$.
2. Slab length has secondary effect on avalanche flow, under restrictions of modeling by AVALNCH.
3. Individual road cut modeling must be subject to user judgment. The specific modeling of the upper road on Stanley as outlined herein has yielded physically reasonable results.

Number 3 East Avalanche off Max's Mountain, Alyeska Ski Area, Girdwood, Alaska

Location: Northwest slope of Baumann Bump (Max's Mountain); 5 km east of Girdwood, Alaska, or 64 km southeast of Anchorage, Alaska, on the north side of Turnagain Arm.

Starting Zone: One of a series of narrow rocky slots at an elevation of about 760 m.

Track: Open slope with two benches: one at about 400 m, the other at about 230 m.

Runout Zone: Deeply incised stream valley.

Avalanche: Avalanches often start in cold, dry snow at the top of the mountain and encounter damp or wet snow on the lower slopes. Debris stops in the stream channel with only airborne particles crossing the canyon.

Profile: Seward (D-6) Quadrangle, Alaska (15' x 22.5'). A centerline profile of the No. 3 East, Max's Mountain path is shown in figure 14. The several rapid changes in elevation on the profile were not modified in order to see if AVALNCH could handle them, even though such rapid changes are physically unlikely because of snow cover smoothing.

The avalanche path is modeled by 129 slope parallel cells, each 10 m long. A frequent condition on this path is dry snow down to an elevation of approximately 400 m and wet, viscous snow below this elevation. All avalanches observed in the past several years have stopped on the slope or in the gully at cell 116 with no flow onto the bench of the gun tower.

Three runs were made to model different conditions known to occur on this slope. In two runs the initial slab was taken as 1.5 m thick and 40 m in extent. In the third run slab thickness was reduced to 1 m.

Run No. 1: High viscosity ($v = 0.7$) is assigned the slab to simulate wet snow in the starting zone. Friction is set at f=0.7 to cell 80 and f=0.9 to cell 129, to model moderate friction on the upper path and large friction on the lower path.

Results show maximum velocity attained is 20 m/s at cell 12, and the avalanche enters cell 115 at a speed of 10 m/s and stops in cell 116. The debris is scattered over 120 m to a depth of 0.94 m in cell 116.

Run No. 2: Midwinter deep snowpack viscosity is assumed with $v = 0.55$ m^2/s. Friction is set at f=0.5 to cell 72, f=0.7 from cell 73 through 80, and f=0.9 for the remainder of the path. This is intended to simulate dry snow running on a dry upper path and onto wet snow on the lower path. The avalanche attains a maximum speed of 27 m/s at cell 33, enters cell 115 at 10 m/s, and stops at cell 116. Debris covers 90 m, to a maximum depth of 1.4 m in cell 116.

Run No. 3: The same viscosity and friction conditions as in Run No. 2 are assumed. The only difference is that the thickness of the initially released slab is set at 1 m. Under these conditions, the flow does not reach the creek, but stops at cell 100. As noted from figure 14, cell 100 is in the middle of a flatter part of the slope that starts at cell 92.

This reduction in slope coupled with the assigned viscosity and friction for this region are apparently sufficient to halt the avalanche.

Conclusions drawn from this example are:

1. Friction values in the range of 0.7 to 0.9 are large, and seldom should values larger than this be used for clear slopes.
2. Program AVALNCH remains stable for rapid variations in g_x when the slope changes significantly between the adjacent cells. Sign changes for g_x in the case of adverse slopes are readily handled by AVALNCH.
3. No. 3 East Max's Mountain path is a good example that there is a physical basis for treating friction as a variable quantity over the path.

Imogene Avalanche Path

Location: Second unnamed drainage north of middle fork of Mineral Creek; top elevation 3,780 m; east facing slope.

Starting Zone: Broad basin with large rock outcrops; lower portion has small rock outcrops and grass.

Track: Narrowing V-shaped depression, grass, and willows.

Runout Zone: Broad fan, grass and willows.

Avalanches: Runout is into the Mineral Creek valley. An avalanche has crossed the highway twice since 1951. Both runs were full-track. Total vertical drop is 670 m; length of path is 1,730 m.

Profile: Silverton Quadrangle, Colorado (7.5'). This path is characterized by a constricted region from 520 to 880 m distance along the path as

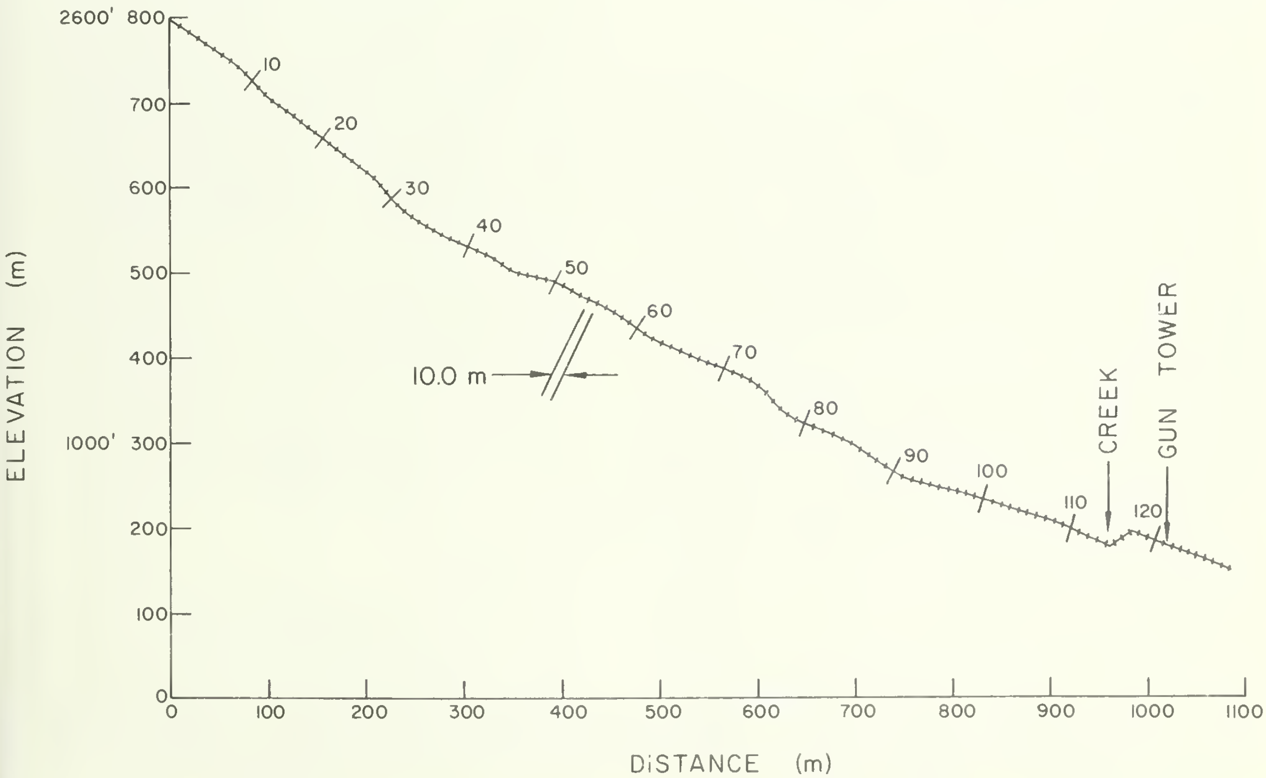

Figure 14.—Longitudinal profile of Number 3 East avalanche path (Max's Mountain).

noted in figure 15. After flow crosses the creek and road, the avalanche encounters adverse grade.

The path is modeled by 91 cells each 20 m long. Initial flow height is set at 1.5 m, and the extent of the starting slab along the fall line is 100 m. Viscosity is set at a nominal midwinter value of 0.5. The friction coefficient is varied in three ways in the constricted region of the flow, for the three computer runs carried out.

Run No. 1: Friction coefficient at 0.5 over the entire path. Flow velocity is maximum at 26 m/s (cell 16) and decreases until flow stops at cell 85 midway between the creek and the road. Debris height reaches a maximum of 5.5 m for a distance of 140 m. The leading edge velocity at exit from the constricted region is 20 m/s.

Run No. 2: The friction coefficient is increased to 0.6 for cells in the constricted region. Flow stops, as in run No. 1, at cell 85. Debris depth is 5.5 m maximum over 160-m extent. Although stopping distance is equal for the two cases, the velocity of the leading edge emerging from the constricted region in this case is 17 m/s, a decrease of 15% from run No. 1.

Run No. 3: The friction coefficient is decreased to 0.4 for cells in the constricted region. Flow again stops in cell 85 with maximum debris depth of 5.6 m, extending for 140 m. Flow velocity coming out of the constricted region is about 24 m/s, an increase of 20% over that of run No. 1.

Conclusions drawn from the study of this avalanche path are:

1. Varying the friction coefficient in the constricted zone of the avalanche track had no effect on total runout distance. This implies that travel distance on the Imogene path is dominantly controlled by the geometry of the runout zone itself. Generally, the dynamics of constrictions suggests that the surface friction decreases in importance because flow depth increases, and viscosity increases in importance because circulation increases. However, little information exists on flow of snow, so that we have no basis

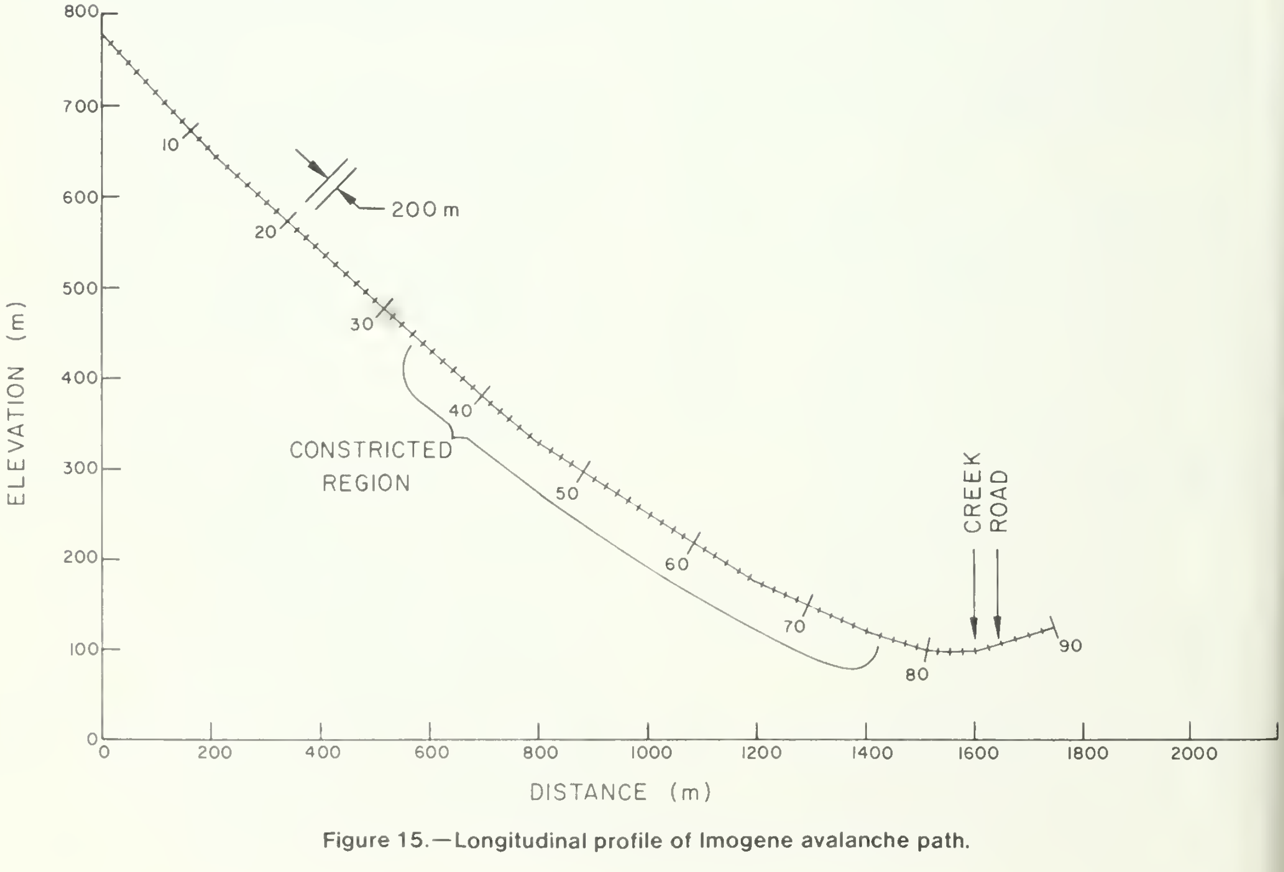

Figure 15.—Longitudinal profile of Imogene avalanche path.

for selecting any one criterion over another. Our previous conclusions that υ and f have approximately equal influence suggests that, in the case of a constriction, no adjustment should be made.

2. Little information is known on flow properties of snow, and further research is warranted in this area.

Numerical Studies with Program AVALNCH

Equilibrium Flow Calculation

To establish upper limits on the flow velocity that can be attained as a function of slope steepness, equilibrium flow calculations were carried out for 30-, 40-, and 50-degree slopes. Surface friction and viscosity coefficients were assigned values from 0.4 to 0.6, which is representative of the range of these parameters in avalanche cases considered previously. To obtain steady-state flow, continuity in-flow and out-flow boundary conditions were imposed at the upper and lower boundaries, respectively. A single cell depth of flow over the entire domain was then specified and iteration to steady flow was carried out. Results of these calculations are shown in figure 16, in which equilibrium velocity is plotted versus flow height of the core material with slope angle, friction, and viscosity as parameters. In actual avalanche runout cases, the flow is rotational because continuous geometry changes cause local circulation. For a flow to achieve the velocities shown in figure 16, it is necessary for the geometry to be constant and continuous, a condition that is unlikely in actual cases. Thus, the velocities shown in figure 16 can be considered upper limits, which are reported only for reference when interpreting actual flow results.

It is noted that in AVALNCH when computing equilibrium flow, the use of noninteger heights (e.g. 1.5 m) results in an unstable condition that is attributable to numerical round-off in certain instructions in the code. By recoding, the problem can be averted; however, since only transient conditions will be seen in all avalanche evaluations, this recoding is not attempted in the unmodified version of AVALNCH.

Variable Width Option for Program AVALNCH

The width of many avalanche paths vary. The version of AVALNCH used previously in this report does not account for variable width. The interpretation given previously in the results section should be per-unit-width, down the centerline of the flow as represented by the longitudinal profile with no provisions made for spreading or narrowing of the flow (two-dimensional version of code). For avalanche paths with only small variations in the flow width, the two-dimensional formulation is adequate. However, in this section we report the findings of a pseudo simulation of three-dimensional flow in which the two-dimensional flow height of each cell is adjusted each CYCLE of iteration to account for local changes in flow width. This approximation is not a complete three-dimensional formulation, for which height variation along a contour would be admitted. However, it will account for large variations in width consistent with the accuracy to be expected based upon the nominal slope and material properties we are able to establish for flowing snow.

The version of AVALNCH including the variable width option is listed in Appendix D. Arrows are used to identify changes and additions from the nonvariable width version listed in Appendix B. The specific type of change or addition can be determined by

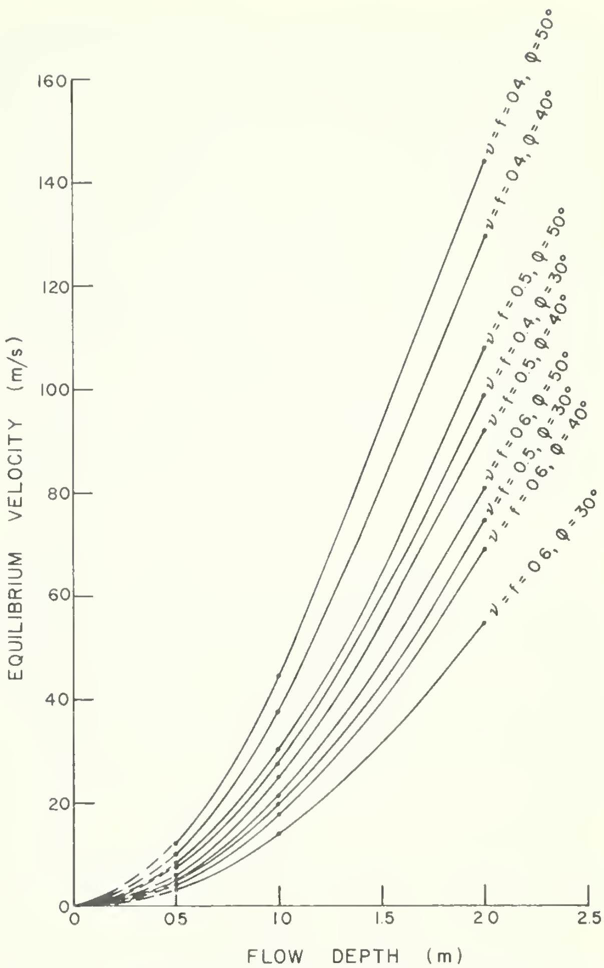

Figure 16.—Equilibrium velocity as a function of flow depth for different values of surface friction, f, viscosity, υ, and slope angle, φ.

comparing the two listings. For the variable width program, additional input includes a width factor, W(I), for each cell that can be read directly from a topographic map. The width factors are an array of numbers that follow card 4 in Appendix A, and have the same format as card 4. One approach to setting values for W(I) is to select a value of 1 for cells in the starting zone of the avalanche and adjusting this value for downslope cells as the width changes. In representing width change, even abrupt changes, the factors should vary gradually, since snow entrapment will smooth any irregular boundary.

For AVALNCH to accomodate increases in height of the flow due to a constriction, it is necessary to include more than one row of cells above the row in which the avalanche initially flows.

Appendix D provides a grid five cells high for a flow that was initially only one cell high. This requires a total of seven cells high (five active and two boundary), in place of four cells of the non-variable height code. This change increases the storage allocation of the code, and computer running time. For the Imogene path, described below, computer time is more than doubled to account for variable width.

The Imogene avalanche path is used as an example of a path with variable width. The outline of this path is depicted by the solid lines in figures 17 and 18. The

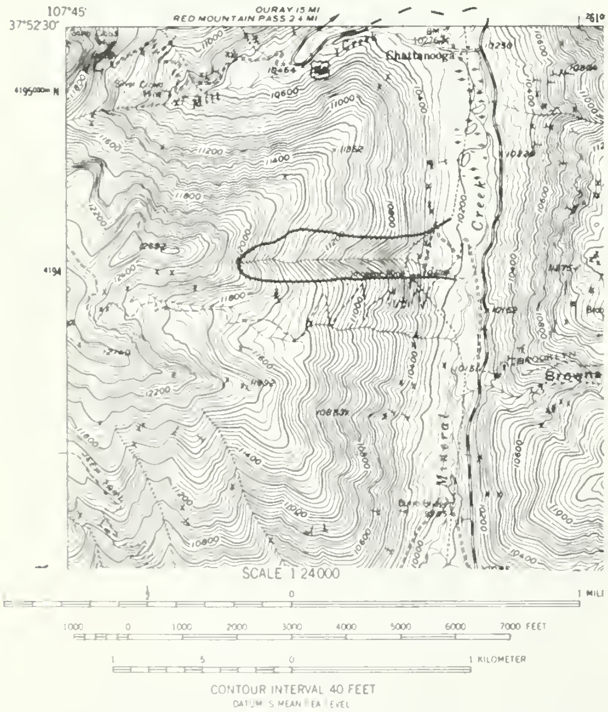

Figure 17.—Topography map of Imogene avalanche path, from which geometric path data was taken.

Figure 18.—Photograph of Imogene and adjacent avalanche paths (Miller, Armstrong and Armstrong 1976).

shaded region in figure 17 is the assumed extent of the starting zone. The dashed lines are the assumed boundaries of the flow after release. Under these assumptions, the width factor read directly from figure 17 is plotted in figure 19, from which individual cell values are interpolated.

Results of the variable flow calculations show that the flowing snow emerges from the constricted region of the path at a speed of approximately 23 m/s and comes to rest in cell 85. Thus, Run No. 3 of the Imogene path is roughly duplicated, indicating that by decreasing the friction coefficient in the constricted area, the overall effect of flow constriction is modeled. We note that the variable width flow stops in cell 85, the same as reported in the section on the Imogene path for constant width flows. Cell 85 is the first cell of adverse grade (20%) after the flow crosses the creek bed. This amount of adverse grade is significant in stopping snow flow over a broad range of entering velocities. Thus, a meaningful number for comparison of the different runs is the velocity of the leading edge of the flow entering cell 85. The leading edge velocity and the final maximum debris height are listed in table 5 for the variable width runs of this section and the three constant-width runs of the Imogene path section. The reported velocity is the average of the velocities computed for cells 80 through 84, which, by averaging, reduces total computational variations.

We conclude from these results that the various assumptions made in modeling the constricted zone, bring about an overall effect on terminal flow that is small compared to the influence of terminal zone geometry. Significant variation in snow debris height is noted from table 5. For the constant flow-width cases, two active cells are used to represent vertical motion. By comparing the two-cell-high runs with the variable-width runs having three, four and five cells vertically, we note apparent numerical instability in height prediction when flow enters the upper boundary cell layer. The same effect occurs also in the variable-width runs in the constricted zone where flow height increases by a factor of 2.5. With this increase in height, flow is in the cell next to the upper boundary cell for the three-cell-height case, and still one cell or more below the boundary cell in the four and five cell cases. The subsequent differences arising from interpolating with a boundary cell in one case, and with an active cell in the other, is the source for the differences in terminal speeds between the three- and four-cell cases. For consistent results one cell height should be maintained between the cell of maximum flow height and the upper boundary cell, at all points along the path. It appears that if accurate prediction of debris height is not required, all models predict terminal velocities within the limits of accuracy encountered on selecting values for υ and f (to represent material and surface conditions).

Based upon these results, we conclude that we have a choice of ways to account for moderate constriction (or expansion) of factors up to 2 or 3. One approach is to use the variable-width code at a cost more than double that for the constant-width code. Alternatively, we can use the constant-width code and reduce friction in the constricted region.

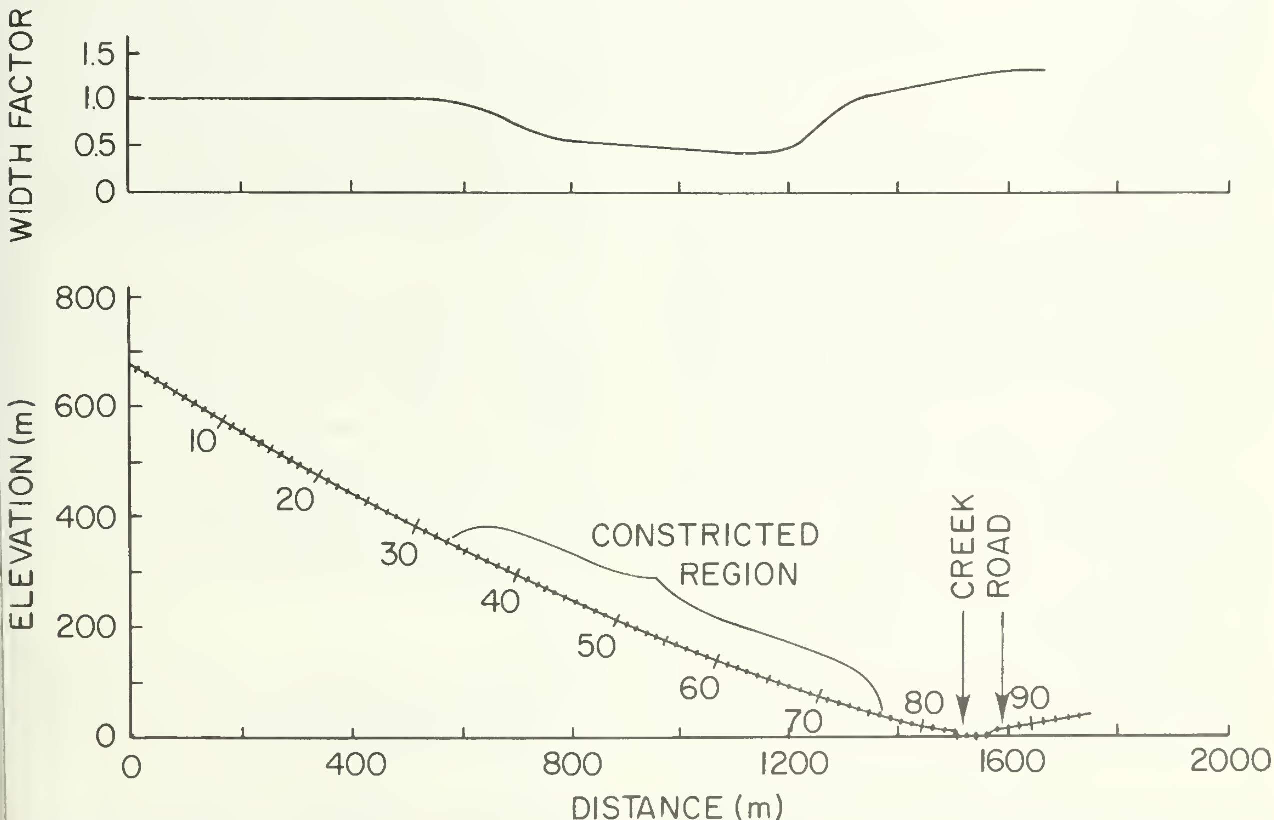

Figure 19.—Longitudinal profile of Imogene avalanche path and width fraction.

Table 5.—Summary of leading edge terminal velocity and maximum debris height for the Imogene Avalanche path.

Run No.	Description of numerical simulation in computer run	Average flow velocity into cell 85 (m/s)	Maximum height of snow debris (m)
1	Constant width flow. Friction f = 0.5 over path, and f = 0.4 in constriction region. Two-cell-height model of flow regime.	10.98	5.6
2	Constant width flow. Friction F = 0.5 over entire path. Two-cell-height model of flow regime.	10.74	5.5
3	Constant width flow. Friction f = 0.5 over path, and f = 0.6 in constriction region. Two-cell-height model of flow regime.	10.68	5.5
4	Variable width flow. Friction f = 0.5 over entire path. Three-cell-height model of flow regime.	11.9	2.9
5	Variable width flow. Friction f = 0.5 over entire path. Four-cell-height model of flow regime.	12.9	3.1
6	Variable width flow. Friction f = 0.5 over entire path. Five-cell-height model of flow regime.	12.9	3.2

This is physically incorrect because it does not account for proper mass distribution but it gives acceptable results. If prediction of the distribution of terminal debris in cases of pile-up on adverse grade is required, then cost differences between the two methods is removed. This occurs because a height of more than two active cells is then needed in the constant-width code also, which is the factor that increases cost.

A possible application of the variable-width code is in modeling avalanche flow in which flow from a tributary comes into that of the main stream. In this case, the tributary inflow is estimated in terms of the fractional increase it introduces over mainstream flow height. Denoting this factor by η_j and main stream flow width fraction by w_j for cell j on the path, then the adjustment of flow height, accounting for both width variation and tributary inflow, is

$$h_{j_{new}} = \eta_j \frac{w_{j-1}}{w_j} h_j .$$

In actual application of this equation, account must also be taken of the time sequencing between main and tributary flows. This feature has not been programmed into the variable-width code, but it warrants consideration in order to evaluate the worst-case occurrence for some types of avalanche paths.

Sensitivity of Runout Distance to Various Parameters

Results are reported from numerical experimentation carried out with the Ironton Park avalanche path. Runout of this path is onto a flat frozen lake surface. Because of the simple geometry of this path, alteration of the path was introduced into the computer model to assess the sensitivity of the flow to different parameters. Among parameters considered were average thickness of the initially released slab, friction and viscosity of the flow, adverse grade in the runout zone, and spreading angle of the flow in the runout zone. The thickness, friction, and viscosity parameters have already been evaluated and are reported in table 2. The adverse grade and terminal flow speading angle parameters remain to be assessed. These were introduced separately into the Ironton Park runout by artificially representing their effect. For example, although an actual avalanche would not spread appreciably on the flat surface, numerical spreading was introduced in the computer model. Thus, the effect of spreading on runout distance was appraised without introducing the attendant slope rolloff, which must actually produce the phenomenon. The effect of adverse grade was likewise modeled by simple specification of gravity components in place of those corresponding to the lake surface.

In the modeling of flow spreading, angle ϕ was introduced starting at cell 73 (fig. 8), which is the first cell on the surface of the lake. Angle $\phi/2$ is then the angle between the centerline of the flow and one of the flow boundaries. Results are presented in figure 20 of spreading angle, ϕ, versus runout distance for $\upsilon = f = 0.5$ and an initial release slab thickness of 2 m. Spreading begins at 615 m distance (cell 73). An angle change from 0 to 45 degrees, holding all other parameters constant, decreased travel distance by 21%.

Results of various adverse slopes in the runout zone of the Ironton Park path are shown in figure 21. As expected, travel distance continues to shorten as the adverse grade steepens, finally becoming asymptotic at 615 m for an infinitely steep slope.

Using the data in figures 20 and 21 and table 2, a measure of the sensitivity of runout distance to the various parameters can be formulated for the Ironton Park avalanche path. For example, by selecting a nominal set of values for the different parameters, we can then vary a specific parameter by a given amount and note the change in runout distance. Spreading angle was nominally set at $\phi = 10$ degrees, and 20% and 40% increases in angle were introduced to evaluate change in runout distance. Adverse slope was nominally set at 10 degrees, and 20% and 40% increases were evaluated. The same procedure was followed using nominal values of viscosity and friction at 0.5, and slab thickness at 2 m. Results of these computations are shown in figure 22. It should be noted that most of the variations of parameters with runout distance are nonlinear (figs. 9, 20, and 21), and the selection of a nominal value was arbitrary. An attempt was made to select values that did not lie in either a flat or a steep portion of any curve.

The intent, then, was to establish order-of-magnitude estimates of the relative importance of the parameters for a simple avalanche path. The extent to which this goal was achieved is indicated in figure 22. Runout distance is most sensitive to the thickness of slab with a mean effect that a 30% variation in slab thickness results in a 70% change in runout distance.

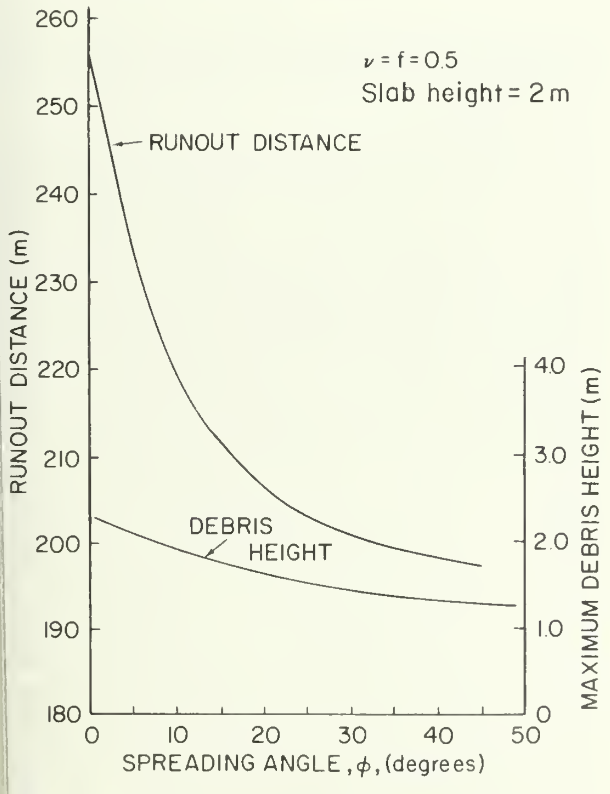

Figure 20.—Avalanche runout distance and maximum terminal debris height as a function of flow spreading angle for the Ironton Park avalanche path.

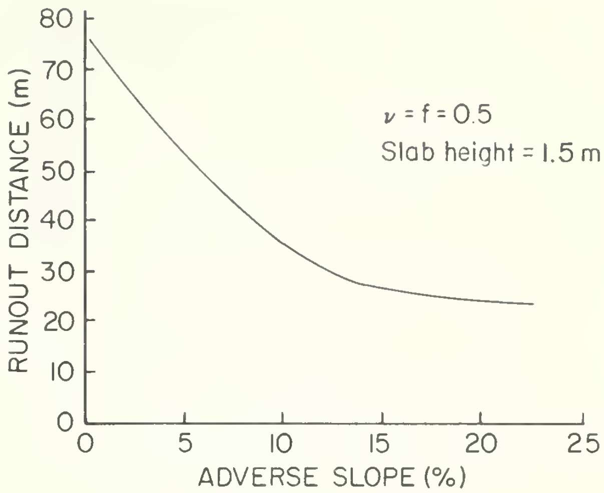

Figure 21.—Avalanche runout distance as a function of adverse slope angle for the Ironton Park avalanche path.

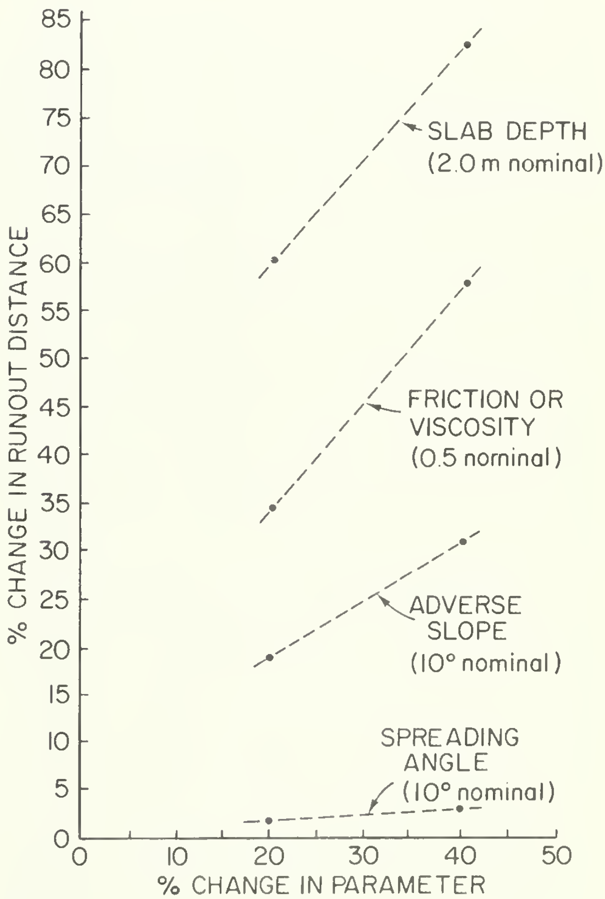

Figure 22.—Change in avalanche runout distance as a function of change in various flow parameters for the Ironton Park avalanche path.

This is followed by viscosity or friction in which a 30% change in parameter results in a 45% change in runout distance. Adverse slope change of 30% corresponds to 25% change in runout distance, and 30% change in spreading angle amounts to only about a 2% change in runout distance. One parameter not reported in figure 22 is the slope-parallel length of snow slab released, but it is determined to have negligible effect on runout distance (see the section on Stanley path.)

The primary conclusion we draw from these results is that the parameters of adverse grade and spreading angle, which can most readily be evaluated from topography maps, have the least effect on runout distance. The parameters of slab thickness and friction and viscosity of the flow, have the greatest effect on runout distance. These are much more difficult to evaluate, and certainly deserve special attention in future avalanche research.

Leading Edge Snow Entrainment Modeling

Many avalanches entrain additional snow as they move down the slope. Generally, the entrained snow is loose and lightweight—the result of recent snowfall. Thus, we envision two possible influences on flow. First, the volume of the moving mass increases; since more mass is being accelerated, flow velocity at any point on the path should be lower than what it would be in the absence of entrainment. Second, the loose snow at the leading edge may reduce friction by air entrainment at the flow boundary interface. This would speed up the flow. To model the case of reduced friction in AVALNCH, we simply decrease the value of the friction coefficient, f. We noted previously that reducing friction to f = 0.4 on the Pallavicini path results in snow runout that duplicated avalanches with a significant airborne component.

To model the effect of an increase in mass due to entrainment requires modifications to AVALNCH. As currently written, program AVALNCH converts elevation change of each finite difference cell along the path to components of gravity, g_x and g_y. Hence, gravity components along the entire path are specified initially. Thus, if we attempt to simply represent the snow mass at the leading edge by specifying a non-zero height of snow in all cells, then all snow on the sloping path will accelerate since g_x and g_y are specified. This is not the desired result. We want the avalanche to encounter stationary snow, which is then brought up to the speed of the advancing volume. To model this, consistent with the finite difference representation used, we simply introduce one cell of stationary snow at the leading edge of the avalanche each time the flow enters a new cell. The momentum balancing the ITER phase of the numerical methodology in AVALNCH accelerates this new snow and assimilates it into the mass of flowing snow, with a corresponding increase in volume.

The following changes are necessary to introduce constant-depth leading-edge snow entrainment over the entire length of an avalanche path:

1. Specify thickness of entrained snow by parameter HNT, and insert instruction of the form HNT = 0.05 (units of meters) following instruction 55 in Appendix B.
2. Insert the following statements after instruction 264 in Appendix B:

```
HIT          = H(LDEG)
H(LDEG)      = HIT + HNT
U(LDEG, 2)   = HIT * U(LDEG, 2)/H(LDEG)
U(LDEG, 1)   = U(LDEG, 2) * (1.0—2.0 *
                 FRC(LDEG))
V(LDEG, 2)   = HIT * V(LDEG, 2)/H(LDEG)
FVφL         = FVφL + HNT * DELX
FVφL1        = FVφL1 + HNT * DELX
```

If a variable entrainment thickness is to be modeled, then a one-dimensional array must be specified and the thickness values read into AVALNCH as part of the input data.

As a simple example, the Ironton Park avalanche path described previously is used to evaluate the effect of mass entrainment. Additional mass, expressed as a fraction of the maximum avalanche slab thickness of 2 m, is assumed over the entire path (fig. 8). Based upon snow entrainment thickness of 0.02 m (1% of slab thickness), 0.05 and 0.1 m, the nominal leading edge velocity versus cell number along the path, is shown in figure 23 for each case. It is seen that slowdown occurs as entrainment thickness is increased. However, as the flow comes off the sloping part of the path, the total momentum of the moving mass must increase with an increase in entrainment thickness, because more snow is accelerated by gravity than when entrainment is absent. Thus, if entrainment were eliminated in the runout zone, the enlarged avalanche mass (due to entrainment on the slope) entering the runout zone should flow farther than in the case of no entrainment. The imposed continued entrainment in the runout zone acts to resist the continued motion of the mass. For Ironton Park the two effects apparently cancel, and runout distances of the different cases do not vary signifi-

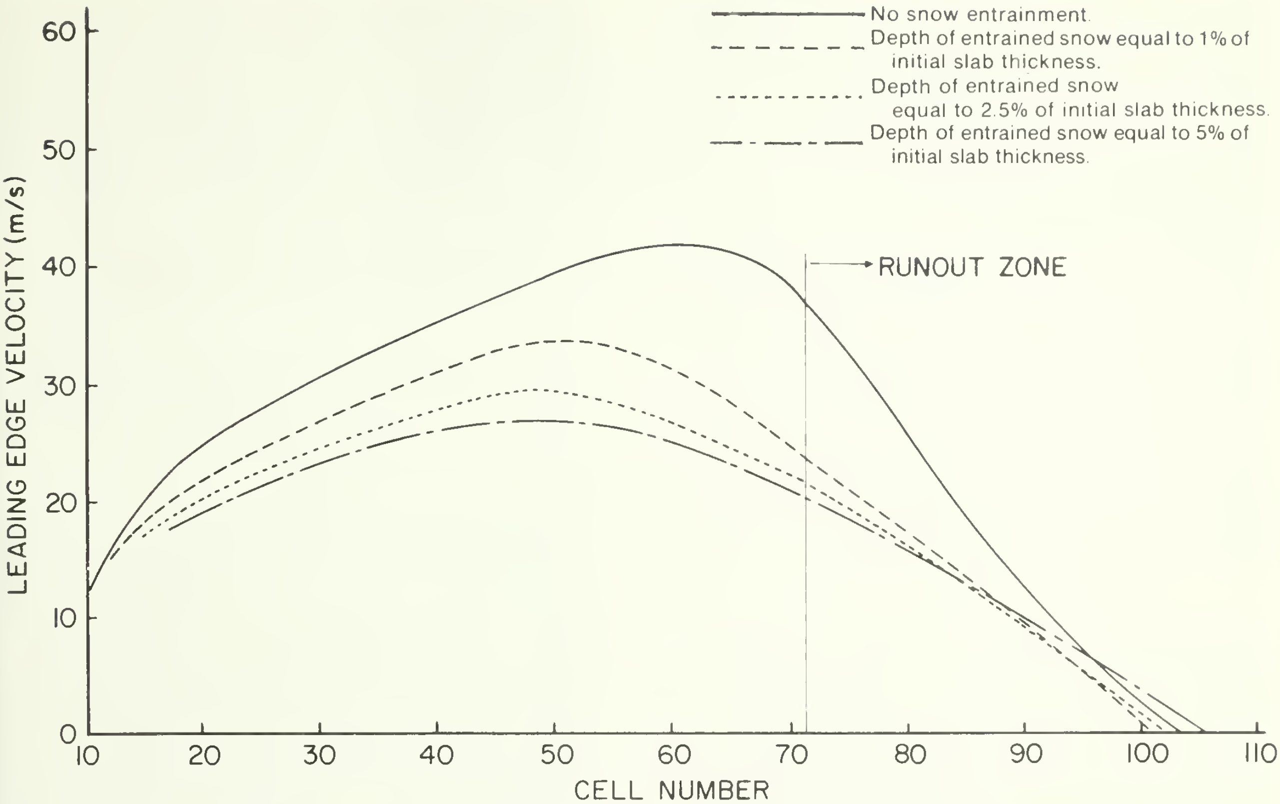

Figure 23.—Leading edge velocity variation with cell number along the Ironton Park avalanche path for different leading edge mass entrainment heights.

cantly. It is expected, however, that for paths with short runout zones, such as the Pallavacini, avalanches with entrained snow would run further than those without.

The results of figure 23 are based upon a two-cell vertical grid, for which flow heights of the snow entrainment cases exceeded values that correspond to accurate prediction of snow distribution. Thus, it is not possible from the data obtained to compute momentum values for the different cases. However, based upon the findings in the section headed "Variable Width Option for Program AVALNCH," we can expect the predicted velocities and travel distances to be realistic and slow down in the runout zone to be more uniform and gradual than for the zero entrainment case. A more accurate five-cell vertical model was run for the 5% entrainment case and showed that momentum of the entrainment case does not exceed that of the zero entrainment case. It also showed runout to be one or two cells farther than is reported for the two-cell vertical case. All of the entrainment cases could be rerun using a more refined vertical scale (with increase in computer expense); however, the results presented demonstrate that there is no fundamental difficulty in representing the entrainment problem. More rational evaluation can be carried out when more actual avalanche events are available for reference.

Discussion and Summary

A computer code applicable for predicting snow avalanche runout distance has been developed based upon two-dimensional, viscous fluid dynamic equations. Basic parameters of surface friction, fluid viscosity, and local terrain variations are accounted for separately by empirical evaluations based on known avalanche occurrences. The primary objective in developing the code was to model gross avalanche response and limiting-case events. Only gross response was modeled because of lack of knowledge about the properties of flowing snow. In particular, specification of internal viscosity and surface friction as functions of distance along the avalanche path are related in some, as yet unknown, manner to particle size in the flow, surface conditions, air entrainment, density distribution, and other factors that make each avalanche distinct.

In modeling gross response, local variations or gradual changes in parameter values with travel along the path are assumed to be averaged out, provided the dominant characteristics of the flow are represented. Empirical evaluations are based on specific avalanche events in order to successively develop technology in modeling. A simple avalanche slope (see section on Ironton Park Avalanche Path) was used to establish nominal, total-path values for the coefficients of surface friction and internal viscosity based upon known early winter avalanches. It was established that, with the units of measure used, friction and viscosity coefficients of approximately equal value and of the order $f = \nu = 0.5$ model the flow. In addition, some technique is needed to duplicate the slowdown dynamics of avalanches. An exponential dependence of surface friction on avalanche velocity at the time of terminal flow was selected based on numerous observations, although rare exceptions are noted where avalanches have flowed inordinate distance for reasons unknown.

The second avalanche path studied is the Pallavicini, where a terminal adverse grade is effective in stopping the larger avalanches. On this path, it is known that only avalanches having a significant airborne fraction reach the road (fig. 10). To match this occurrence, friction and viscosity were reduced to $\nu = f = 0.4$. It should be emphasized that only the more consolidated central core of the avalanche, not the turbulent airborne dust cloud, is modeled. Data are scarce concerning airborne avalanches or the airborne component of mixed motion avalanches. There is even a lack of information on the distribution of terminal debris from such avalanches which would help define the amount and distribution of snow in the snow dust cloud.

The third and fourth examples reported are the Hematite Gulch and Stanley avalanche paths, which are considered because of their local terrain anomalies. Hematite Gulch has three bends in the path, and the avalanche modeled ran out onto rocky, bare ground (fig. 12). Gross modeling of this spring, wet snow avalanche was achieved by letting $f = \nu = 0.55$, for most of the path, with values of $f = \nu = 0.65$ at the bends. For runout onto the rocky ground, friction was set at $f = 0.9$ and viscosity left at $\nu = 0.55$. For these values the model showed the avalanche flowing to the recorded terminal debris zone. Lacking sufficient field data, further evaluation of local terrain effects, as depicted by the Hematite Gulch path, is not warranted. Flow velocities along the path as the avalanche advances are additional basic data needed to see how well the model duplicates the actual event. This type of data would result in more accurate specifications of f and ν.

The Stanley path (fig. 13) is a rather uniform slope interrupted by two highway cuts. Small to moderate size avalanches are known to be trapped by the upper road cut, and large avalanches to flow to the lower road cut. Predicted response was obtained using midwinter snowpack conditions $\nu = f = 0.55$ over the entire path. At the road cuts, friction was increased to $f = 0.9$ to represent, in some sense, the resistance of the road bed and snow embankments to flow.

The fifth avalanche path analyzed is at Alyeska, Alaska, very close to the ocean (see section on Number 3 East Avalanche). The typical effect of the maritime climate is a wet, viscous snowpack on the lower part of the slope and drier snow farther up the mountain. Thus, the initially released slab is often relatively dry ($\nu = 0.55$) and flows over a similar snowpack ($f = 0.5$). Farther along the path, friction is increased to $f = 0.7$ to 0.9 to account for the viscous effects of the wet snow in the lower part of the path. Based upon this modeling, a slab 1 m deep and 40 m long in the slope-parallel direction stopped short of the gully at the foot of the slope (fig. 14), whereas a similar slab 1.5 m deep flowed into the gully. Data from the area are rather general, however, and about all we can say is that ν and f values are consistent with those found satisfactory for other evaluations.

The final example reported is the Imogene path which depicts the classic "dog bone" or contraction-expansion flow common to many paths. The first attempt to model this variable width characteristic involved adjustment of the friction coefficient, f. However, evidence is lacking as to whether f should be increased or decreased particularly for a viscous material like snow. Later a pseudo-variable-width option added to program AVALNCH verified that f should be increased. This result, the outcome of a numerical analysis, warrants further verification from field measurements.

Having established a basis for selection of values for ν and f to model "typical" cases of avalanche flow, we next studied particular aspects of avalanche flow to which our numerical model is applicable. This is not to suggest that specification of ν and f is automatic for different avalanche cases. Each avalanche evaluation must be considered seperately, but as experience is gained in specifying ν and f and assessing the results of analysis, credibility of the methodology should improve. One factor that aids in establishing credibility is the small range of ν and f needed to model a wide variety of avalanches from the large airborne avalanche to the wet, viscous, spring avalanche. This advantage over other previously developed analysis schemes is the direct result of separating flow properties from local geometry effects. An additional feature of program AVALNCH is that the basic numerical approach of subdividing the flow domain into an array of cells permits the user to incorporate additional information later.

Since open channel equilibrium flow has been used in most dynamic evaluations of avalanches, one numerical study using program AVALNCH was to establish equilibrium flow velocity as functions of ν, f, flow height, and slope angle. It is not anticipated that this data will be extremely useful in the future; however, it is included for completeness.

As mentioned above, a variable width option of program AVALNCH is reported that permits evaluation of snow flow as the width of the flow changes. This phenomenon occurs when snow flows into a constricting region such as a gully, or into an expanding region such as an alluvial fan. The three-dimensional effect is represented by maintaining continuity of flow, not by a more accurate accounting which would require the introduction of a three-dimensional grid. This is another example where a numerical capability was developed, but cannot be verified until better field data, including flow velocities, are available. The variable width runs on the Imogene path establish the friction, f, should be increased in constricting flow when the constant width version of the code is used.

Perhaps the most significant numerical study reported is the sensitivity or error analysis of the basic pararmeters in avalanche flow. These parameters are the friction and kinematic viscosity, slab thickness, adverse grade, and flow spreading angle. By establishing nominal values for these parameters, then allowing one parameter to vary, the change in avalanche runout distance can be computed. For nominal 30% changes in each of these parameters, imposed separately, runout distance is found to change by 70% for slab thickness, 45% for friction or viscosity, 25% for adverse grade, and 2% for spreading angle. Thus, a scale of the relative importance of different types of field measurements and observations needed for a better definition of snow avalanche dynamics is set.

The final study involves evaluation of the effect on avalanche dynamics when loose snow is entrained into the flow at the leading edge of the avalanche. Leading edge entrainment can result in change of the surface friction, as well as gradual increase of the volume of snow in motion. In the study reported, only the effect of volume increase is considered for a particular path. For the Ironton Park path, snow entrainment did not result in appreciable change in runout distance. The additional momentum due to increased mass moving down the slope was apparently cancelled by the resistance of the snow that was entrained during flow over the level runout zone. The primary benefit of this study was to set up a mechanism in AVALNCH for treating snow entrainment.

There are several notes of caution that should be mentioned concerning the use of program AVALNCH

1. The program predicts only the flow characteristics of the core material—not the snow dust cloud. In cases where avalanches run beneath structures such as bridges, the failure to account for the snow dust cloud could lead to underdesign of the structure.

2. Limited field observations indicate that long runout distances are not necessarily associated with extra thick slabs as indicated by the program. In Colorado, thick slabs are usually in wind deposition areas and are usually hard slabs. Such snow is strongly bonded and resists disintegration as it moves downslope. As a result, flow height is roughly equal to initial slab thickness, runout distance is not great, and the debris tends to mound up in the runout zone. Fresh soft slab, on the other hand, is weakly bonded and quickly fluidized after fracture. This leads to greater flow heights, longer runout distances, greater speeds, and a uniform, shallow layer of debris in the runout zone. Hence, more field data are needed to establish better estimates of kinematic viscosity and surface friction for various types of snow. The current program can handle this situation if given proper input.

In summary, a computer code has been developed based upon transient fluid dynamic equations to model snow avalanche flow. In test cases the program has predicted results consistent with known field observations for a number of avalanche events. Capability to modify the program to treat special conditions such as variable width flow, variable friction, snow entrainment, and other features has been demonstrated. Further refinement and application of the program to more complex flow conditions are basically limited by a lack of field data on avalanche flow which can be used for verification.

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Appendix A
Input Data Format

The following input data is needed for program AVALNCH:

Card 1: FORMAT (20A4)

Columns 1 through 80: title and identification information.

Card 2: FORMAT (8F 10.0)

Columns 1 through 10: IBAR* — number of cells in x direction.
Columns 11 through 20: JBAR* — number of cells in y direction.
Columns 21 through 30: DELX — cell dimension in meters, x direction.
Columns 31 through 40: DELY — cell dimension in meters, y direction.
Columns 41 through 50: NU — kinematic viscosity (m^2/s).
Columns 51 through 60: FRK** — surface friction coefficient.
Columns 61 through 70: TWFIN — avalanche flow time in seconds.
Columns 71 through 80: CWPRT — cycles between extended printouts.

*Using version of AVALNCH listed in Appendix B, IBAR ≤ 200, and JBAR = 2. These limits can be changed by changing the dimension statement in the code.

**FRK = 0.0 if different values are to be used for different cells of the path.

**FRK ≠ 0.0 if a constant value is to be used over the entire path (in this case list value to be used).

Card 3: FORMAT (8F 10.0)

Columns 1 through 10: thickness of avalanche slab in cell 1 in meters.
Columns 11 through 20: thickness of avalanche slab in cell 2 in meters.
Columns 21 through 30: thickness of avalanche slab in cell 3 in meters.
Columns 31 through 40: thickness of avalanche slab in cell 4 in meters.
Columns 41 through 50: thickness of avalanche slab in cell 5 in meters.
Columns 51 through 60: thickness of avalanche slab in cell 6 in meters.
Columns 61 through 70: thickness of avalanche slab in cell 7 in meters.
Columns 71 through 80: thickness of avalanche slab in cell 8 in meters.
(Continue on succeeding cards for IBAR entrees, including zero-thickness cells.)

Card 4: FORMAT (8F 10.0)

(Take these data from longitudinal profile of slope)

Columns 1 through 10: change of height from cell 1 to cell 2 in meters.
Columns 11 through 20: change of height from cell 2 to cell 3 in meters.
Columns 21 through 30: change of height from cell 3 to cell 4 in meters.
Columns 31 through 40: change of height from cell 4 to cell 5 in meters.
Columns 41 through 50: change of height from cell 5 to cell 6 in meters.
Columns 51 through 60: change of height from cell 6 to cell 7 in meters.
Columns 61 through 70: change of height from cell 7 to cell 8 in meters.
Columns 71 through 80: change of height from cell 8 to cell 9 in meters.
(continue on succeeding cards for IBAR entrees)

Card 5: FORMAT (8F 10.0)

(This set of data required if FRK = 0.0 on card 4)

Columns 1 through 10: friction coefficient in cell 1.
Columns 11 through 20: friction coefficient in cell 2.
Columns 21 through 30: friction coefficient in cell 3.
Columns 31 through 40: friction coefficient in cell 4.
Columns 41 through 50: friction coefficient in cell 5.
Columns 51 through 60: friction coefficient in cell 6.
Columns 61 through 70: friction coefficient in cell 7.
Columns 71 through 80: friction coefficient in cell 8.
(continue on succeeding cards for IBAR entrees)

Two example data decks are shown following the first for friction specified in an array, and the second for friction constant over the flow domain.

EXAMPLE NO. 1: INPUT OF INDIVIDUAL CELL FRICTION VALUES

TITLE	IRØNTØN PARK AVALANCHE: CØLØRADØ						
PARAMETERS	13	2	10	1.5	0.4	0.0	500	1000
SNOW	1.5	1.5	0.0	0.0	0.0	0.0	0.0	0.0
THICKNESS	0.0	0.0	0.0	0.0	0.0			
HEIGHT CHANGE	6	5	7	7.2	6	6	5	5
PER CELL	4	2	1	0	-1.2*			
CELL	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7
FRICTION	0.7	0.7	0.7	0.7	0.7			

*Negative sign denotes adverse grade.

EXAMPLE No. 2: INPUT OF CONSTANT FRICTION OVER PATH

TITLE	NØ. 3 EAST MAX'S MØUNTAIN: ALYESKA ALASKA.							
PARAMETERS	25	2	10	2	0.4	0.4	500	1000
	2.0	2.0	2.0	0.0	0.0	0.0	0.0	0.0
SNOW	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
THICKNESS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.0							
	7	7	7	6	6	6	7	6
HEIGHT CHANGE	6	5	5	5	5	4	4	3
PER CELL	3	2	1	0	0	0	0	0
	0							

Appendix B
Fortran Listing of AVALNCH—Unit Width Version

```
C    PROGRAM AVALNCH.
*
C   EQUIVALENT HORIZONTAL GRID OPTION
*
C      THIS PROGRAM HAS BEEN DEVELOPED TO NUMERICALLY SOLVE (USING
C      FINITE DIFFERENCE TECHNIQUES) THE NAVIER - STOKES EQUATIONS
C      FOR TRANSIENT FLUID FLOW PROBLEMS.  IT WILL BE USED TO SIMULATE
C      THE PROBLEM OF SNOW AND ICE AVALANCHES ON SLOPES OF VARYING SLOPE.
       DIMENSION U(202,4),V(202,4),UN(202,4),VN(202,4),P(202,4),FR(202),
      1XPUT( 8),H(202),HN(202),JT(202),NAME(20),GX(202),GY(202),FRC(202)
       REAL NU
       INTEGER CYCLE
       READ (105,45) NAME
       WRITE (108,35)
       WRITE (108,45) NAME
*
C * * READ AND PRINT INITIAL INPUT DATA
*
       READ(105,25) (XPUT(I),I=1,8)
       IBAR=XPUT(1) ; JBAR=XPUT(2) ; DELX=XPUT(3) ; DELY=XPUT(4)
       NU=XPUT(5)  ;  FRK=XPUT(6)  ;  TWFIN=XPUT(7)  ;  CWPRT=XPUT(8)
       WRITE (108,50) (XPUT(I),I=1,8)
    25 FORMAT(8F10.0)
    35 FORMAT(1H1)
    45 FORMAT(20A4)
    47 FORMAT(6X'I'7X'J'8X'U'13X'V'13X'P'13X'H'9X,'SUR CELL')
    48 FORMAT(4X,I3,5X,I3,4(4X,1PE10.3),6X,I2)
    49 FORMAT(2X'CYCLE='I3,2X'ITER='I3,2X'DELT='1PE9.2,2X'TIME='E9.2,2X,
     1'FVOL='E9.2,2X'UMAX='E9.2,2X'UEDG='E9.2,2X'LDEG='I3)
    50 FORMAT(1H ,1X'IBAR='F4.0,2X'JBAR='F3.0,2X'DELX='F6.2,2X'DELY='F5.2
     1,2X'NU='F4.2,2X'FRK='F4.2,2X'TWFIN='F5.0,2X'CWPRT='F5.0)
    60 FORMAT(8F10.0)
    61 FORMAT(8F10.3)
    70 FORMAT(1H0,35X,'FLOW HEIGHT')
    71 FORMAT(1H0,25X'ELEVATION CHANGE FOR EACH CELL')
    72 FORMAT(1H0,25X,'BOUNDARY FRICTION COEFFICIENTS')
    73 FORMAT(1H0,25X,'SLOPE-PARALLEL GRAVITY COMPONENT')
    74 FORMAT(1H0,25X,'SLOPE-NORMAL GRAVITY COMPONENT')
    75 FORMAT(1H0,30X,'END OF INPUT DATA'//)
    82 FORMAT(5X,'PROBLEM RUNNING TIME EXCEEDED-CALCULATIONS TERMINATED')
    83 FORMAT(5X,'AVALANCHE AT END OF GRID-CALCULATIONS TERMINATED')
    84 FORMAT(5X,'FLOW VELOCITY NEGLIGIBLE-CALCULATIONS TERMINATED')
*
C * * COMPUTE CONSTANT TERMS AND INITIALIZE NECESSARY VARIABLES
*
        IMAX=IBAR+2 ; JMAX=JBAR+2
        IM1=IMAX-1  ; JM1=JMAX-1
        RDX=1.0/DELX
        RDY=1.0/DELY
        DELM=DELY/100.
        DELT=1.0
        IM2=IMAX-2
        JM2=JMAX-2
        T=FLG=UEDG1=0.0
        CYCLE=ITER=IND=LDEG=0
        G=9.8 ; OMG=1.7 ; EPSI=.001 ; ALPHA=0.1 ; GAMMA=0.1 ; DZRO=1.0
        G=9.8 ; OMG=1.7 ; EPSI=.05  ; ALPHA=0.1 ; GAMMA=0.1 ; DZRO=1.0
        BETA= OMG/(2.*DELT*(RDX**2+RDY**2))
        ICPRT=INT(CWPRT)
        IF(ICPRT.EQ.1) ICPRT=2
        DO 100 I=1,IMAX
```

```
      H(I)=HN(I)=JT(I)=GX(I)=GY(I)=FRC(I)=0.0
      DO 100 J=1,JMAX
  100 U(I,J)=V(I,J)=UN(I,J)=VN(I,J)=P(I,J)=0.0
*
C * * SPECIAL INPUT DATA
*
      READ(105,60)(H(I),I=2,IM1)
      READ(105,60)(HN(I),I=2,IM1)
      IF(FRK.GT.0.0) GO TO 120
      READ(105,60) (FRC(I),I=2,IM1)
      GO TO 130
  120 DO 125 I=2,IM1
  125 FRC(I)=FRK
  130 CONTINUE
      DO 150 I=2,IM1
      FR(I)=FRC(I)
      SP=HN(I)/DELX
      CP=SQRT(1.0-SP*SP)
      GX(I)=G*SP
  150 GY(I)=-G*CP
      WRITE(108,70)
      WRITE(108,61)(H(I),I=2,IM1)
      WRITE(108,71)
      WRITE(108,61)(HN(I),I=2,IM1)
      WRITE(108,72)
      WRITE(108,61) (FRC(I),I=2,IM1)
      WRITE(108,73)
      WRITE(108,61)(GX(I),I=2,IM1)
      WRITE(108,74)
      WRITE(108,61)(GY(I),I=2,IM1)
      WRITE(108,75)
      DO 240 I=2,IM1
      JT(I)=INT(H(I)*RDY+1.E-6)+2
      IF(JT(I).GT.JM1) JT(I)=JM1
  240 HN(I)=0.0
      H(1)= H(2)
      H(IMAX)= H(IM1)
      JT(1)= JT(2)
      JT(IMAX)= JT(IM1)
*
C * * CALCULATE HYDROSTATIC PRESSURE
*
      DO 280 I=2,IM1
      JT1=JT(I)
      DO 280 J=2,JT1
  280 P(I,J)=-GY(I)*(H(I)-(FLOAT(J)-1.5)*DELY)
      ASSIGN 4280 TO KRET
      GO TO 2000
*
C * * START CYCLE
*
 1000 CONTINUE
      ITER=0
      FLG=1.
      ASSIGN 3000 TO KRET
*
C * * COMPUTE TEMPORARY U AND V
*
      DO 1100 I=2,IM1
      JT1=JT(I)
      DO 1100 J=2,JT1
      FUX=((UN(I,J)+UN(I+1,J))*(UN(I,J)+UN(I+1,J))+ALPHA*ABS(UN(I,J)+UN(
     1I+1,J))*(UN(I,J)-UN(I+1,J))-(UN(I-1,J)+UN(I,J))*(UN(I-1,J)+UN(I,J)
     2)-ALPHA*ABS(UN(I-1,J)+UN(I,J))*(UN(I-1,J)-UN(I,J)))/(4.*DELX)
      FUY=((VN(I,J)+VN(I+1,J))*(UN(I,J)+UN(I,J+1))
```

```
      1+ALPHA*ABS(VN(I,J)+VN(I+1,J))*(UN(I,J)-UN(I,J+1))
      2-(VN(I,J-1)+VN(I+1,J-1))*(UN(I,J-1)+UN(I,J))
      3-ALPHA*ABS(VN(I,J-1)+VN(I+1,J-1))*(UN(I,J-1)-UN(I,J)))/(4.*DELY)
       FVX=((UN(I,J)+UN(I,J+1))*(VN(I,J)+VN(I+1,J))+ALPHA*ABS(UN(I,J)+UN(
      1I,J+1))*(VN(I,J)-VN(I+1,J))-(UN(I-1,J)+UN(I-1,J+1))*(VN(I-1,J)+VN(
      2I,J))-ALPHA*ABS(UN(I-1,J)+UN(I-1,J+1))*(VN(I-1,J)-VN(I,J)))/(4.*DE
      3LX)
       FVY=((VN(I,J)+VN(I,J+1))*(VN(I,J)+VN(I,J+1))+ALPHA*ABS(VN(I,J)+VN
      1(I,J+1))*(VN(I,J)-VN(I,J+1))-(VN(I,J-1)+VN(I,J))*(VN(I,J-1)+VN(I,J
      2))-ALPHA*ABS(VN(I,J-1)+VN(I,J))*(VN(I,J-1)-VN(I,J)))/(4.*DELY)
       VISX= NU*((UN(I+1,J)-2.*UN(I,J)+UN(I-1,J))/DELX**2+
      1          (UN(I,J+1)-2.*UN(I,J)+UN(I,J-1))/DELY**2)
       VISY= NU*((VN(I+1,J)-2.*VN(I,J)+VN(I-1,J))/DELX**2+
      1          (VN(I,J+1)-2.*VN(I,J)+VN(I,J-1))/DELY**2)
       U(I,J)= UN(I,J)+DELT*((P(I,J)-P(I+1,J))*RDX + GX(I)-FUX-FUY+VISX)
 1100 V(I,J)= VN(I,J)+DELT*((P(I,J)-P(I,J+1))*RDY + GY(I)-FVX-FVY+VISY)
*
C * * SET BOUNDARY CONDITIONS
*
 2000 CONTINUE
      HN(1)= HN(2)
      HN(IMAX)=HN(IM1)
      JT(1)=JT(2)
      JT(IMAX)=JT(IM1)
C   LEFT WALL RIGID AND SLIP FREE.
C   RIGHT WALL CONTINUOUS OUTFLOW.
      DO 2200 J=1,JMAX
      U(1,J)=0.0
      V(1,J)=V(2,J)
      IF(ITER.GT.0) GO TO 2200
      U(IM1,J)=U(IM2,J)
      V(IMAX,J)=V(IM1,J)
 2200 CONTINUE
C   TOP WALL CONTINUOUS OUTFLOW.
C   BOTTOM WALL RIGID - WITH FRICTION
      DO 2500 I=1,IMAX
      IF(ITER.GT.0) GO TO 2400
      V(I,JM1)=V(I,JM2)
      U(I,JMAX)=U(I,JM1)
 2400 V(I,1)=0.0
 2500 U(I,1)=U(I,2)*(1.0-2.0*FRC(I))
*
C * * FREE SURFACE BOUNDARY CONDITIONS
*
      DO 2650 I=2,IM1
      JT1=JT(I)
      IF(JT(I+1).LT.JT(I)) U(I,JT1)=U(I,JT1-1)
      V(I,JT1)= V(I,JT1-1)-DELY*RDX*(U(I,JT1)-U(I-1,JT1))
 2650 U(I,JT1+1)= U(I,JT1)
      GO TO KRET,(3000,4280)
 3000 CONTINUE
*
C * * HAS CONVERGENCE BEEN REACHED
*
      IF(FLG.EQ.0.) GO TO 4000
      ITER=ITER+1
      IF(ITER.LT.500) GO TO 3050
      IF(CYCLE.LT.10) GO TO 4000
      T=1.E+10
      GO TO 4000
 3050 FLG=0.0
*
C * * COMPUTE UPDATED CELL PRESSURE AND VELOCITIES
*
      JB1=2
```

```
      DO 3500 I=2,IM1
      JT1=JT(I)
      DO 3500 J=2,JT1
      IF(JT1.EQ.JB1) GO TO 3060
      IF(J.NE.JB1 .AND. J.NE.JT1) GO TO 3200
      IF(J.EQ.JT1) GO TO 3100
      GO TO 3200
 3060 CONTINUE
      F=V(I,J)+DELY*RDX*(U(I,J)-U(I-1,J))
      DFDP=DELT*RDY*(1.0+2.0*DELY**2*RDX**2)
      DELP1=-F/DFDP
 3100 ETA=DELY/(HN(I)-(FLOAT(JT1)-2.5)*DELY)
      DELP=(1.0-ETA)*P(I,JT1-1)-P(I,JT1)
      IF(JB1.EQ.JT1) DELP=0.5*(DELP+DELP1)
      GO TO 3300
 3200 D=RDX*(U(I,J)-U(I-1,J))+RDY*(V(I,J)-V(I,J-1))
      IF(ABS(D/DZRO).GE.EPSI) FLG=1.0
      DELP= -BETA*D
 3300 P(I,J)=P(I,J)+DELP
      U(I,J)=U(I,J)+DELT*RDX*DELP
      U(I-1,J)=U(I-1,J)-DELT*RDX*DELP
      V(I,J)=V(I,J)+DELT*RDY*DELP
 3500 V(I,J-1)=V(I,J-1)-DELT*RDY*DELP
      GO TO 2000
 4000 CONTINUE
*
C * * COMPUTE NEW POSITION FOR TOP SURFACE
*
      DO 4100 I=2,IM1
      JT1=JT(I)
      HV= RDY*(HN(I)-FLOAT(JT1-2)*DELY)
      UAV= 0.5*(U(I-1,JT1) + U(I,JT1))
      H(I)=HN(I)*FVOL1/FVOL+DELT*(HV*V(I,JT1)+(1.0-HV)*V(I,JT1
     1-1)-0.5*RDX*(UAV*HN(I+1)+GAMMA*ABS(UAV)*(HN(I)-HN(I+1))
     2   -UAV*HN(I-1)-GAMMA*ABS(UAV)*(HN(I-1)-HN(I))))
 4100 CONTINUE
*
C * * CALCULATE CELL IN WHICH SURFACE IS LOCATED AND UPDATE ARRAY
*
      DO 4250 I=2,IM1
      IF(H(I).LT.DELM) H(I)=0.0
      JT(I)=INT(H(I)*RDY+1.0E-6)+2
      IF(JT(I).GT.JM1) JT(I)=JM1
 4250 CONTINUE
      ASSIGN 4280 TO KRET
      GO TO 2000
 4280 CONTINUE
*
C * * CALCULATE TOTAL FLUID VOLUME
*
      FVOL=0.0
      DO 4300 I=2,IM1
 4300 FVOL=FVOL+H(I)*DELX
      IF(CYCLE.EQ.0) FVOL1=FVOL
*
C * * FIND LEADING AND TRAILING EDGES OF AVALANCHE AND LD. EDGE VELOCITY
*
      LDEG1=LDEG
      I=IM2
 4400 IF(H(I).GT.DELM) GO TO 4500
      I=I-1
      GO TO 4400
 4500 LDEG=I
      I=2
 4600 IF(H(I).GT.DELM) GO TO 4700
```

```
      I=I+1
      GO TO 4600
 4700 KTEG=I
      IF(LDEG.EQ.LDEG1) GO TO 4800
      IF(CYCLE.GT.0) UEOG=OELX/TC
      IF(CYCLE.EQ.0) UEOG=5.0
      TC=OELT
      INFLO=1
      IF(UEOG.GT.UEOG1) UEOG1=UEOG
      GO TO 4910
 4800 TC=TC+OELT
      INFLO=INFLO+1
*
C * * AOVANCE U,V,H ARRAYS.
*
 4910 UMAX=VMAX=0.0
      OO 4900 I=1,IMAX
      OO 4900 J=1,JMAX
      IF(ABS(U(I,J)).GT.1.0E+04) U(I,J)=0.0
      UN(I,J)=U(I,J)
      IF(ABS(V(I,J)).GT.1.0E+04) V(I,J)=0.0
      VN(I,J)=V(I,J)
      IF(ABS(P(I,J)).LT.1.0E-16) P(I,J)=0.0
 4900 HN(I)=H(I)
      OO 4950 I=KTEG,LDEG
      DO 4950 J=2,JM1
      UT=ABS(UN(I,J))
      VT=ABS(VN(I,J))
      IF(UT.GT.UMAX) UMAX=UT
 4950 IF(VT.GT.VMAX) VMAX=VT
*
C * * LIST VELOCITY, PRESSURE, AND SURFACE POSITION
*
 5000 WRITE(108,49) CYCLE,ITER,DELT,T,FVOL,UMAX,UEOG,LOEG
      IF(CYCLE.EQ.ICPRT) GO TO 5030
      IF(CYCLE.NE.ICPRT) GO TO 6000
 5030 ICPRT= ICPRT + INT(CWPRT)
 5060 CONTINUE
      WRITE(108,47)
      OO 5250 I=1,IMAX
      JT1= JT(I)
      JT2=JT1+1
      DO 5250 J=1,JT2
      WRITE(108,48) I,J,U(I,J),V(I,J),P(I,J),H(I),JT1
 5250 CONTINUE
      IF(INO.EQ.2) GO TO 6520
      IF(INO.EQ.3) GO TO 6530
      IF(IND.EQ.4) GO TO 6540
*
C * * RECOMPUTE CONTROL PARAMETERS.
*
 6000 IF(CYCLE.EQ.0) GO TO 6300
      OTX=OELX/UMAX
      OTY=OELY/VMAX
      DELT=AMIN1(DTX,OTY)/3.0
      IF(ITER.LT.10) DELT=1.5*OELT
      IF(NU-1.E-6.LT.0.0) GO TO 6300
      OET=(OELX*OELY)**2/(2.*NU*(OELX**2+OELY**2))
      IF(DELT.LT.OET) GO TO 6300
      OELT=0.9*DET
 6300 T=T+DELT
      IF(CYCLE.EQ.0) GO TO 6400
      DAX=UMAX*DELT/DELX
      DAY=VMAX*DELT/DELY
      ALPHA=1.35*AMAX1(DAX,DAY)
```

```
      IF(ALPHA.GT.1.0) ALPHA=0.95
      GAMMA=ALPHA
      BETA=OMG/(2.*DELT*(RDX**2+RDY**2))
*
C * * TEST FOR PROGRAM TERMINATION.
*
 6400 IF(T.GT.TWFIN) IND=2
      IF(H(IM2).GT.DELM) IND=3
      IF(UEDG.LT.0.05*UEDG1) IND=4
      IF(INFLO.EQ.50) IND=4
      IF(IND.GT.1) GO TO 6500
      IF(CYCLE.LT.3) GO TO 6440
      AA=1.0+20.0*EXP(-1.25*UEDG)
      DO 6430 I=2,IM1
 6430 FRC(I)=AA*FR(I)
 6440 CYCLE=CYCLE+1
      GO TO 1000
 6500 T=T-DELT
      GO TO 5060
 6520 WRITE(108,82)
      GO TO 6600
 6530 WRITE(108,83)
      GO TO 6600
 6540 WRITE(108,84)
 6600 STOP
      END
```

Appendix C
Listing of Output Data from AVALNCH for Ironton Park Avalanche

IRONTON PARK AVALANCHE PATH - HORIZONTAL GRID OPTION.

IBAR=100. JBAR= 2. DELX= 10.00 DELY= 2.00 NU= .50 FRK= .50 TWFIN= 750. CWPRT=1000.

FLOW HEIGHT

2.000	2.000	2.000	2.000	2.000	1.500	1.000	.500
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000				

ELEVATION CHANGE FOR EACH CELL

6.500	6.200	6.200	6.200	6.500	6.200	6.200	6.200
6.500	6.500	6.200	5.800	6.000	5.800	5.600	5.600
5.200	4.600	4.200	4.200	4.600	5.200	4.600	4.800
5.000	5.200	5.400	5.600	5.800	6.200	6.200	6.200
6.200	6.500	6.800	7.400	7.200	7.200	7.100	7.000
7.000	7.000	6.600	6.200	6.200	6.000	6.000	5.600
5.200	5.200	5.000	4.600	4.200	4.200	4.000	4.000
3.600	3.600	3.400	3.400	3.000	2.800	2.500	2.200
1.800	1.600	1.400	1.200	.900	.700	.500	.400
.300	.100	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000				

BOUNDARY FRICTION COEFFICIENTS

.500	.500	.500	.500	.500	.500	.500	.500
.500	.500	.500	.500	.500	.500	.500	.500
.500	.500	.500	.500	.500	.500	.500	.500
.500	.500	.500	.500	.500	.500	.500	.500
.500	.500	.500	.500	.500	.500	.500	.500
.500	.500	.500	.500	.500	.500	.500	.500
.500	.500	.500	.500	.500	.500	.500	.500
.500	.500	.500	.500	.500	.500	.500	.500
.500	.500	.500	.500	.500	.500	.500	.500
.500	.500	.500	.500	.500	.500	.500	.500
.500	.500	.500	.500	.500	.500	.500	.500
.500	.500	.500	.500	.500	.500	.500	.500
.500	.500	.500	.500				

SLOPE-PARALLEL GRAVITY COMPONENT

6.370	6.076	6.076	6.076	6.370	6.076	6.076	6.076
6.370	6.370	6.076	5.684	5.880	5.684	5.488	5.488
5.096	4.508	4.116	4.116	4.508	5.096	4.508	4.704
4.900	5.096	5.292	5.488	5.684	6.076	6.076	6.076
6.076	6.370	6.664	7.252	7.056	7.056	6.958	6.860
6.860	6.860	6.468	6.076	6.076	5.880	5.880	5.488
5.096	5.096	4.900	4.508	4.116	4.116	3.920	3.920
3.528	3.528	3.332	3.332	2.940	2.744	2.450	2.156
1.764	1.568	1.372	1.176	.882	.686	.490	.392
.294	.098	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000	.000	.000	.000	.000
.000	.000	.000	.000				

SLOPE-NORMAL GRAVITY COMPONENT

-7.447	-7.689	-7.689	-7.689	-7.447	-7.689	-7.689	-7.689
-7.447	-7.447	-7.689	-7.983	-7.840	-7.983	-8.119	-8.119
-8.371	-8.702	-8.894	-8.894	-8.702	-8.371	-8.702	-8.597
-8.487	-8.371	-8.248	-8.119	-7.983	-7.689	-7.689	-7.689
-7.689	-7.447	-7.185	-6.592	-6.801	-6.801	-6.901	-6.999
-6.999	-6.999	-7.362	-7.689	-7.689	-7.840	-7.840	-8.119
-8.371	-8.371	-8.487	-8.702	-8.894	-8.894	-8.982	-8.982
-9.143	-9.143	-9.216	-9.216	-9.349	-9.408	-9.489	-9.560
-9.640	-9.674	-9.703	-9.729	-9.760	-9.776	-9.788	-9.792
-9.796	-9.800	-9.800	-9.800	-9.800	-9.800	-9.800	-9.800
-9.800	-9.800	-9.800	-9.800	-9.800	-9.800	-9.800	-9.800
-9.800	-9.800	-9.800	-9.800	-9.800	-9.800	-9.800	-9.800
-9.800	-9.800	-9.800	-9.800				

END OF INPUT DATA

CYCLE= 0	ITER= 3	DELT= 1.00E 00	TIME= .00E 00	FVOL= 1.30E 02	UMAX= .00E 00	UEDG= 5.00E 00	LDEG= 9
CYCLE= 1	ITER= 3	DELT= 1.00E 00	TIME= 1.00E 00	FVOL= 1.31E 02	UMAX= 7.09E 00	UEDG= 1.00E 01	LDEG= 10
CYCLE= 2	ITER= 1	DELT= 8.95E-02	TIME= 1.09E 00	FVOL= 1.30E 02	UMAX= 7.58E 00	UEDG= 1.00E 01	LDEG= 10
CYCLE= 3	ITER= 1	DELT= 3.12E-01	TIME= 1.40E 00	FVOL= 1.30E 02	UMAX= 9.19E 00	UEDG= 9.18E 00	LDEG= 11
CYCLE= 4	ITER= 3	DELT= 3.14E-01	TIME= 1.72E 00	FVOL= 1.30E 02	UMAX= 1.04E 01	UEDG= 9.18E 00	LDEG= 11
CYCLE= 5	ITER= 6	DELT= 3.13E-01	TIME= 2.03E 00	FVOL= 1.30E 02	UMAX= 1.22E 01	UEDG= 1.60E 01	LDEG= 12
CYCLE= 6	ITER= 1	DELT= 3.01E-01	TIME= 2.33E 00	FVOL= 1.30E 02	UMAX= 1.36E 01	UEDG= 1.60E 01	LDEG= 12
CYCLE= 7	ITER= 1	DELT= 2.73E-01	TIME= 2.60E 00	FVOL= 1.30E 02	UMAX= 1.46E 01	UEDG= 1.63E 01	LDEG= 13
CYCLE= 8	ITER= 1	DELT= 2.68E-01	TIME= 2.87E 00	FVOL= 1.30E 02	UMAX= 1.57E 01	UEDG= 1.63E 01	LDEG= 13
CYCLE= 9	ITER= 1	DELT= 2.66E-01	TIME= 3.14E 00	FVOL= 1.30E 02	UMAX= 1.68E 01	UEDG= 1.85E 01	LDEG= 14
CYCLE= 10	ITER= 1	DELT= 2.65E-01	TIME= 3.40E 00	FVOL= 1.30E 02	UMAX= 1.78E 01	UEDG= 1.85E 01	LDEG= 14
CYCLE= 11	ITER= 1	DELT= 2.64E-01	TIME= 3.67E 00	FVOL= 1.30E 02	UMAX= 1.88E 01	UEDG= 1.88E 01	LDEG= 15
CYCLE= 12	ITER= 1	DELT= 2.64E-01	TIME= 3.93E 00	FVOL= 1.29E 02	UMAX= 1.99E 01	UEDG= 1.88E 01	LDEG= 15
CYCLE= 13	ITER= 1	DELT= 2.52E-01	TIME= 4.18E 00	FVOL= 1.30E 02	UMAX= 2.08E 01	UEDG= 1.89E 01	LDEG= 16
CYCLE= 14	ITER= 1	DELT= 2.40E-01	TIME= 4.42E 00	FVOL= 1.30E 02	UMAX= 2.17E 01	UEDG= 3.97E 01	LDEG= 17
CYCLE= 15	ITER= 1	DELT= 2.30E-01	TIME= 4.65E 00	FVOL= 1.30E 02	UMAX= 2.25E 01	UEDG= 3.97E 01	LDEG= 17
CYCLE= 16	ITER= 1	DELT= 2.22E-01	TIME= 4.87E 00	FVOL= 1.30E 02	UMAX= 2.32E 01	UEDG= 2.13E 01	LDEG= 18
CYCLE= 17	ITER= 1	DELT= 2.15E-01	TIME= 5.09E 00	FVOL= 1.30E 02	UMAX= 2.39E 01	UEDG= 2.13E 01	LDEG= 18
CYCLE= 18	ITER= 1	DELT= 2.09E-01	TIME= 5.30E 00	FVOL= 1.30E 02	UMAX= 2.46E 01	UEDG= 2.29E 01	LDEG= 19
CYCLE= 19	ITER= 1	DELT= 2.04E-01	TIME= 5.50E 00	FVOL= 1.30E 02	UMAX= 2.51E 01	UEDG= 2.29E 01	LDEG= 19
CYCLE= 20	ITER= 1	DELT= 1.99E-01	TIME= 5.70E 00	FVOL= 1.30E 02	UMAX= 2.56E 01	UEDG= 2.42E 01	LDEG= 20
CYCLE= 21	ITER= 1	DELT= 1.95E-01	TIME= 5.90E 00	FVOL= 1.30E 02	UMAX= 2.61E 01	UEDG= 2.42E 01	LDEG= 20
CYCLE= 22	ITER= 1	DELT= 1.92E-01	TIME= 6.09E 00	FVOL= 1.30E 02	UMAX= 2.66E 01	UEDG= 2.54E 01	LDEG= 21
CYCLE= 23	ITER= 1	DELT= 1.88E-01	TIME= 6.28E 00	FVOL= 1.30E 02	UMAX= 2.71E 01	UEDG= 2.54E 01	LDEG= 21
CYCLE= 24	ITER= 1	DELT= 1.85E-01	TIME= 6.46E 00	FVOL= 1.30E 02	UMAX= 2.75E 01	UEDG= 2.63E 01	LDEG= 22
CYCLE= 25	ITER= 1	DELT= 1.82E-01	TIME= 6.64E 00	FVOL= 1.30E 02	UMAX= 2.79E 01	UEDG= 2.63E 01	LDEG= 22
CYCLE= 26	ITER= 1	DELT= 1.79E-01	TIME= 6.82E 00	FVOL= 1.30E 02	UMAX= 2.83E 01	UEDG= 2.73E 01	LDEG= 23
CYCLE= 27	ITER= 1	DELT= 1.77E-01	TIME= 7.00E 00	FVOL= 1.30E 02	UMAX= 2.86E 01	UEDG= 2.73E 01	LDEG= 23
CYCLE= 28	ITER= 1	DELT= 1.75E-01	TIME= 7.17E 00	FVOL= 1.30E 02	UMAX= 2.90E 01	UEDG= 2.81E 01	LDEG= 24
CYCLE= 29	ITER= 1	DELT= 1.73E-01	TIME= 7.35E 00	FVOL= 1.30E 02	UMAX= 2.93E 01	UEDG= 2.81E 01	LDEG= 24
CYCLE= 30	ITER= 1	DELT= 1.71E-01	TIME= 7.52E 00	FVOL= 1.30E 02	UMAX= 2.96E 01	UEDG= 2.88E 01	LDEG= 25
CYCLE= 31	ITER= 1	DELT= 1.69E-01	TIME= 7.69E 00	FVOL= 1.30E 02	UMAX= 2.99E 01	UEDG= 2.88E 01	LDEG= 25
CYCLE= 32	ITER= 1	DELT= 1.67E-01	TIME= 7.85E 00	FVOL= 1.30E 02	UMAX= 3.02E 01	UEDG= 2.94E 01	LDEG= 26
CYCLE= 33	ITER= 1	DELT= 1.66E-01	TIME= 8.02E 00	FVOL= 1.30E 02	UMAX= 3.04E 01	UEDG= 2.94E 01	LDEG= 26
CYCLE= 34	ITER= 1	DELT= 1.65E-01	TIME= 8.18E 00	FVOL= 1.30E 02	UMAX= 3.06E 01	UEDG= 3.00E 01	LDEG= 27
CYCLE= 35	ITER= 1	DELT= 1.63E-01	TIME= 8.35E 00	FVOL= 1.30E 02	UMAX= 3.08E 01	UEDG= 3.00E 01	LDEG= 27
CYCLE= 36	ITER= 1	DELT= 1.62E-01	TIME= 8.51E 00	FVOL= 1.30E 02	UMAX= 3.10E 01	UEDG= 3.05E 01	LDEG= 28
CYCLE= 37	ITER= 1	DELT= 1.61E-01	TIME= 8.67E 00	FVOL= 1.30E 02	UMAX= 3.12E 01	UEDG= 3.05E 01	LDEG= 28
CYCLE= 38	ITER= 1	DELT= 1.60E-01	TIME= 8.83E 00	FVOL= 1.30E 02	UMAX= 3.13E 01	UEDG= 3.09E 01	LDEG= 29
CYCLE= 39	ITER= 1	DELT= 1.60E-01	TIME= 8.99E 00	FVOL= 1.30E 02	UMAX= 3.14E 01	UEDG= 3.09E 01	LDEG= 29
CYCLE= 40	ITER= 1	DELT= 1.59E-01	TIME= 9.15E 00	FVOL= 1.30E 02	UMAX= 3.15E 01	UEDG= 3.12E 01	LDEG= 30
CYCLE= 41	ITER= 1	DELT= 1.59E-01	TIME= 9.31E 00	FVOL= 1.30E 02	UMAX= 3.16E 01	UEDG= 3.12E 01	LDEG= 30
CYCLE= 42	ITER= 1	DELT= 1.58E-01	TIME= 9.47E 00	FVOL= 1.30E 02	UMAX= 3.17E 01	UEDG= 3.14E 01	LDEG= 31
CYCLE= 43	ITER= 1	DELT= 1.58E-01	TIME= 9.62E 00	FVOL= 1.30E 02	UMAX= 3.17E 01	UEDG= 3.14E 01	LDEG= 31
CYCLE= 44	ITER= 1	DELT= 1.58E-01	TIME= 9.78E 00	FVOL= 1.30E 02	UMAX= 3.18E 01	UEDG= 3.16E 01	LDEG= 32
CYCLE= 45	ITER= 1	DELT= 1.57E-01	TIME= 9.94E 00	FVOL= 1.30E 02	UMAX= 3.18E 01	UEDG= 3.16E 01	LDEG= 32
CYCLE= 46	ITER= 1	DELT= 1.57E-01	TIME= 1.01E 01	FVOL= 1.30E 02	UMAX= 3.19E 01	UEDG= 3.18E 01	LDEG= 33
CYCLE= 47	ITER= 1	DELT= 1.57E-01	TIME= 1.03E 01	FVOL= 1.30E 02	UMAX= 3.20E 01	UEDG= 3.18E 01	LDEG= 33
CYCLE= 48	ITER= 1	DELT= 1.56E-01	TIME= 1.04E 01	FVOL= 1.30E 02	UMAX= 3.21E 01	UEDG= 3.18E 01	LDEG= 34
CYCLE= 49	ITER= 1	DELT= 1.56E-01	TIME= 1.06E 01	FVOL= 1.30E 02	UMAX= 3.22E 01	UEDG= 3.18E 01	LDEG= 34
CYCLE= 50	ITER= 1	DELT= 1.55E-01	TIME= 1.07E 01	FVOL= 1.30E 02	UMAX= 3.22E 01	UEDG= 3.20E 01	LDEG= 35
CYCLE= 51	ITER= 1	DELT= 1.55E-01	TIME= 1.09E 01	FVOL= 1.30E 02	UMAX= 3.23E 01	UEDG= 3.20E 01	LDEG= 35
CYCLE= 52	ITER= 1	DELT= 1.55E-01	TIME= 1.10E 01	FVOL= 1.30E 02	UMAX= 3.25E 01	UEDG= 3.22E 01	LDEG= 36
CYCLE= 53	ITER= 1	DELT= 1.54E-01	TIME= 1.12E 01	FVOL= 1.30E 02	UMAX= 3.28E 01	UEDG= 3.22E 01	LDEG= 36
CYCLE= 54	ITER= 1	DELT= 1.52E-01	TIME= 1.13E 01	FVOL= 1.30E 02	UMAX= 3.34E 01	UEDG= 3.24E 01	LDEG= 37
CYCLE= 55	ITER= 1	DELT= 1.50E-01	TIME= 1.15E 01	FVOL= 1.30E 02	UMAX= 3.37E 01	UEDG= 3.24E 01	LDEG= 37
CYCLE= 56	ITER= 1	DELT= 1.48E-01	TIME= 1.16E 01	FVOL= 1.30E 02	UMAX= 3.42E 01	UEDG= 3.31E 01	LDEG= 38
CYCLE= 57	ITER= 1	DELT= 1.46E-01	TIME= 1.18E 01	FVOL= 1.30E 02	UMAX= 3.45E 01	UEDG= 3.31E 01	LDEG= 38
CYCLE= 58	ITER= 1	DELT= 1.45E-01	TIME= 1.19E 01	FVOL= 1.30E 02	UMAX= 3.51E 01	UEDG= 3.40E 01	LDEG= 39
CYCLE= 59	ITER= 1	DELT= 1.43E-01	TIME= 1.21E 01	FVOL= 1.30E 02	UMAX= 3.53E 01	UEDG= 3.40E 01	LDEG= 39
CYCLE= 60	ITER= 1	DELT= 1.42E-01	TIME= 1.22E 01	FVOL= 1.30E 02	UMAX= 3.58E 01	UEDG= 3.48E 01	LDEG= 40
CYCLE= 61	ITER= 1	DELT= 1.40E-01	TIME= 1.23E 01	FVOL= 1.30E 02	UMAX= 3.62E 01	UEDG= 7.06E 01	LDEG= 41
CYCLE= 62	ITER= 1	DELT= 1.38E-01	TIME= 1.25E 01	FVOL= 1.30E 02	UMAX= 3.64E 01	UEDG= 7.06E 01	LDEG= 41
CYCLE= 63	ITER= 1	DELT= 1.37E-01	TIME= 1.26E 01	FVOL= 1.30E 02	UMAX= 3.68E 01	UEDG= 3.60E 01	LDEG= 42
CYCLE= 64	ITER= 1	DELT= 1.36E-01	TIME= 1.28E 01	FVOL= 1.30E 02	UMAX= 3.71E 01	UEDG= 3.60E 01	LDEG= 42
CYCLE= 65	ITER= 1	DELT= 1.35E-01	TIME= 1.29E 01	FVOL= 1.30E 02	UMAX= 3.75E 01	UEDG= 3.66E 01	LDEG= 43
CYCLE= 66	ITER= 1	DELT= 1.33E-01	TIME= 1.30E 01	FVOL= 1.30E 02	UMAX= 3.77E 01	UEDG= 3.66E 01	LDEG= 43
CYCLE= 67	ITER= 1	DELT= 1.33E-01	TIME= 1.32E 01	FVOL= 1.30E 02	UMAX= 3.80E 01	UEDG= 3.73E 01	LDEG= 44
CYCLE= 68	ITER= 1	DELT= 1.32E-01	TIME= 1.33E 01	FVOL= 1.30E 02	UMAX= 3.81E 01	UEDG= 3.73E 01	LDEG= 44
CYCLE= 69	ITER= 1	DELT= 1.31E-01	TIME= 1.34E 01	FVOL= 1.30E 02	UMAX= 3.83E 01	UEDG= 3.78E 01	LDEG= 45
CYCLE= 70	ITER= 1	DELT= 1.30E-01	TIME= 1.36E 01	FVOL= 1.30E 02	UMAX= 3.85E 01	UEDG= 3.78E 01	LDEG= 45
CYCLE= 71	ITER= 1	DELT= 1.30E-01	TIME= 1.37E 01	FVOL= 1.30E 02	UMAX= 3.87E 01	UEDG= 3.82E 01	LDEG= 46
CYCLE= 72	ITER= 1	DELT= 1.29E-01	TIME= 1.38E 01	FVOL= 1.30E 02	UMAX= 3.89E 01	UEDG= 3.82E 01	LDEG= 46
CYCLE= 73	ITER= 1	DELT= 1.28E-01	TIME= 1.39E 01	FVOL= 1.30E 02	UMAX= 3.91E 01	UEDG= 3.86E 01	LDEG= 47
CYCLE= 74	ITER= 1	DELT= 1.28E-01	TIME= 1.41E 01	FVOL= 1.30E 02	UMAX= 3.93E 01	UEDG= 3.86E 01	LDEG= 47
CYCLE= 75	ITER= 1	DELT= 1.27E-01	TIME= 1.42E 01	FVOL= 1.30E 02	UMAX= 3.95E 01	UEDG= 3.90E 01	LDEG= 48
CYCLE= 76	ITER= 1	DELT= 1.27E-01	TIME= 1.43E 01	FVOL= 1.30E 02	UMAX= 3.97E 01	UEDG= 3.90E 01	LDEG= 48
CYCLE= 77	ITER= 1	DELT= 1.26E-01	TIME= 1.44E 01	FVOL= 1.30E 02	UMAX= 3.98E 01	UEDG= 3.94E 01	LDEG= 49
CYCLE= 78	ITER= 1	DELT= 1.26E-01	TIME= 1.46E 01	FVOL= 1.30E 02	UMAX= 4.00E 01	UEDG= 3.94E 01	LDEG= 49
CYCLE= 79	ITER= 1	DELT= 1.25E-01	TIME= 1.47E 01	FVOL= 1.30E 02	UMAX= 4.01E 01	UEDG= 3.98E 01	LDEG= 50
CYCLE= 80	ITER= 1	DELT= 1.25E-01	TIME= 1.48E 01	FVOL= 1.30E 02	UMAX= 4.03E 01	UEDG= 3.98E 01	LDEG= 50
CYCLE= 81	ITER= 1	DELT= 1.24E-01	TIME= 1.49E 01	FVOL= 1.30E 02	UMAX= 4.04E 01	UEDG= 4.01E 01	LDEG= 51
CYCLE= 82	ITER= 1	DELT= 1.24E-01	TIME= 1.51E 01	FVOL= 1.30E 02	UMAX= 4.05E 01	UEDG= 4.01E 01	LDEG= 51
CYCLE= 83	ITER= 1	DELT= 1.23E-01	TIME= 1.52E 01	FVOL= 1.30E 02	UMAX= 4.06E 01	UEDG= 4.03E 01	LDEG= 52
CYCLE= 84	ITER= 1	DELT= 1.23E-01	TIME= 1.53E 01	FVOL= 1.30E 02	UMAX= 4.08E 01	UEDG= 4.03E 01	LDEG= 52
CYCLE= 85	ITER= 1	DELT= 1.23E-01	TIME= 1.54E 01	FVOL= 1.30E 02	UMAX= 4.09E 01	UEDG= 4.06E 01	LDEG= 53
CYCLE= 86	ITER= 1	DELT= 1.22E-01	TIME= 1.56E 01	FVOL= 1.30E 02	UMAX= 4.10E 01	UEDG= 4.06E 01	LDEG= 53
CYCLE= 87	ITER= 1	DELT= 1.22E-01	TIME= 1.57E 01	FVOL= 1.30E 02	UMAX= 4.11E 01	UEDG= 4.08E 01	LDEG= 54

CYCLE= 88	ITER= 1	DELT= 1.22E-01	TIME= 1.58E 01	FVOL= 1.30E 02	UMAX= 4.12E 01	UEDG= 4.08E 01	LDEG= 54
CYCLE= 89	ITER= 1	DELT= 1.21E-01	TIME= 1.59E 01	FVOL= 1.30E 02	UMAX= 4.13E 01	UEDG= 4.10E 01	LDEG= 55
CYCLE= 90	ITER= 1	DELT= 1.21E-01	TIME= 1.61E 01	FVOL= 1.30E 02	UMAX= 4.14E 01	UEDG= 4.10E 01	LDEG= 55
CYCLE= 91	ITER= 1	DELT= 1.21E-01	TIME= 1.62E 01	FVOL= 1.30E 02	UMAX= 4.14E 01	UEDG= 4.12E 01	LDEG= 56
CYCLE= 92	ITER= 1	DELT= 1.21E-01	TIME= 1.63E 01	FVOL= 1.30E 02	UMAX= 4.15E 01	UEDG= 4.12E 01	LDEG= 56
CYCLE= 93	ITER= 1	DELT= 1.20E-01	TIME= 1.64E 01	FVOL= 1.30E 02	UMAX= 4.16E 01	UEDG= 4.14E 01	LDEG= 57
CYCLE= 94	ITER= 1	DELT= 1.20E-01	TIME= 1.65E 01	FVOL= 1.30E 02	UMAX= 4.16E 01	UEDG= 4.14E 01	LDEG= 57
CYCLE= 95	ITER= 1	DELT= 1.20E-01	TIME= 1.67E 01	FVOL= 1.30E 02	UMAX= 4.17E 01	UEDG= 4.15E 01	LDEG= 58
CYCLE= 96	ITER= 1	DELT= 1.20E-01	TIME= 1.68E 01	FVOL= 1.30E 02	UMAX= 4.17E 01	UEDG= 4.15E 01	LDEG= 58
CYCLE= 97	ITER= 1	DELT= 1.20E-01	TIME= 1.69E 01	FVOL= 1.30E 02	UMAX= 4.18E 01	UEDG= 4.17E 01	LDEG= 59
CYCLE= 98	ITER= 1	DELT= 1.20E-01	TIME= 1.70E 01	FVOL= 1.30E 02	UMAX= 4.18E 01	UEDG= 4.17E 01	LDEG= 59
CYCLE= 99	ITER= 1	DELT= 1.20E-01	TIME= 1.71E 01	FVOL= 1.30E 02	UMAX= 4.19E 01	UEDG= 4.18E 01	LDEG= 60
CYCLE=100	ITER= 1	DELT= 1.19E-01	TIME= 1.73E 01	FVOL= 1.30E 02	UMAX= 4.19E 01	UEDG= 4.18E 01	LDEG= 60
CYCLE=101	ITER= 1	DELT= 1.19E-01	TIME= 1.74E 01	FVOL= 1.30E 02	UMAX= 4.19E 01	UEDG= 4.18E 01	LDEG= 61
CYCLE=102	ITER= 1	DELT= 1.19E-01	TIME= 1.75E 01	FVOL= 1.30E 02	UMAX= 4.20E 01	UEDG= 4.18E 01	LDEG= 61
CYCLE=103	ITER= 1	DELT= 1.19E-01	TIME= 1.76E 01	FVOL= 1.30E 02	UMAX= 4.20E 01	UEDG= 4.19E 01	LDEG= 62
CYCLE=104	ITER= 1	DELT= 1.19E-01	TIME= 1.77E 01	FVOL= 1.30E 02	UMAX= 4.20E 01	UEDG= 4.19E 01	LDEG= 62
CYCLE=105	ITER= 1	DELT= 1.19E-01	TIME= 1.78E 01	FVOL= 1.30E 02	UMAX= 4.20E 01	UEDG= 4.20E 01	LDEG= 63
CYCLE=106	ITER= 1	DELT= 1.19E-01	TIME= 1.80E 01	FVOL= 1.30E 02	UMAX= 4.20E 01	UEDG= 4.20E 01	LDEG= 63
CYCLE=107	ITER= 1	DELT= 1.19E-01	TIME= 1.81E 01	FVOL= 1.30E 02	UMAX= 4.20E 01	UEDG= 4.20E 01	LDEG= 64
CYCLE=108	ITER= 1	DELT= 1.19E-01	TIME= 1.82E 01	FVOL= 1.30E 02	UMAX= 4.20E 01	UEDG= 4.20E 01	LDEG= 64
CYCLE=109	ITER= 1	DELT= 1.19E-01	TIME= 1.83E 01	FVOL= 1.30E 02	UMAX= 4.20E 01	UEDG= 4.20E 01	LDEG= 65
CYCLE=110	ITER= 1	DELT= 1.19E-01	TIME= 1.84E 01	FVOL= 1.30E 02	UMAX= 4.21E 01	UEDG= 4.20E 01	LDEG= 65
CYCLE=111	ITER= 1	DELT= 1.19E-01	TIME= 1.86E 01	FVOL= 1.30E 02	UMAX= 4.21E 01	UEDG= 4.20E 01	LDEG= 65
CYCLE=112	ITER= 1	DELT= 1.19E-01	TIME= 1.87E 01	FVOL= 1.30E 02	UMAX= 4.20E 01	UEDG= 2.80E 01	LDEG= 66
CYCLE=113	ITER= 1	DELT= 1.19E-01	TIME= 1.88E 01	FVOL= 1.30E 02	UMAX= 4.20E 01	UEDG= 2.80E 01	LDEG= 66
CYCLE=114	ITER= 1	DELT= 1.19E-01	TIME= 1.89E 01	FVOL= 1.30E 02	UMAX= 4.20E 01	UEDG= 4.20E 01	LDEG= 67
CYCLE=115	ITER= 1	DELT= 1.19E-01	TIME= 1.90E 01	FVOL= 1.30E 02	UMAX= 4.20E 01	UEDG= 4.20E 01	LDEG= 67
CYCLE=116	ITER= 1	DELT= 1.19E-01	TIME= 1.92E 01	FVOL= 1.30E 02	UMAX= 4.19E 01	UEDG= 4.20E 01	LDEG= 68
CYCLE=117	ITER= 1	DELT= 1.19E-01	TIME= 1.93E 01	FVOL= 1.30E 02	UMAX= 4.19E 01	UEDG= 4.20E 01	LDEG= 68
CYCLE=118	ITER= 1	DELT= 1.19E-01	TIME= 1.94E 01	FVOL= 1.30E 02	UMAX= 4.18E 01	UEDG= 4.20E 01	LDEG= 69
CYCLE=119	ITER= 1	DELT= 1.20E-01	TIME= 1.95E 01	FVOL= 1.30E 02	UMAX= 4.18E 01	UEDG= 4.20E 01	LDEG= 69
CYCLE=120	ITER= 1	DELT= 1.20E-01	TIME= 1.96E 01	FVOL= 1.30E 02	UMAX= 4.15E 01	UEDG= 4.20E 01	LDEG= 69
CYCLE=121	ITER= 1	DELT= 1.20E-01	TIME= 1.98E 01	FVOL= 1.30E 02	UMAX= 4.15E 01	UEDG= 2.79E 01	LDEG= 70
CYCLE=122	ITER= 1	DELT= 1.20E-01	TIME= 1.99E 01	FVOL= 1.30E 02	UMAX= 4.13E 01	UEDG= 2.79E 01	LDEG= 70
CYCLE=123	ITER= 1	DELT= 1.21E-01	TIME= 2.00E 01	FVOL= 1.30E 02	UMAX= 4.13E 01	UEDG= 4.15E 01	LDEG= 71
CYCLE=124	ITER= 1	DELT= 1.21E-01	TIME= 2.01E 01	FVOL= 1.30E 02	UMAX= 4.10E 01	UEDG= 4.15E 01	LDEG= 71
CYCLE=125	ITER= 1	DELT= 1.22E-01	TIME= 2.02E 01	FVOL= 1.30E 02	UMAX= 4.10E 01	UEDG= 4.15E 01	LDEG= 71
CYCLE=126	ITER= 1	DELT= 1.22E-01	TIME= 2.04E 01	FVOL= 1.30E 02	UMAX= 4.07E 01	UEDG= 2.74E 01	LDEG= 72
CYCLE=127	ITER= 1	DELT= 1.23E-01	TIME= 2.05E 01	FVOL= 1.30E 02	UMAX= 4.07E 01	UEDG= 2.74E 01	LDEG= 72
CYCLE=128	ITER= 1	DELT= 1.23E-01	TIME= 2.06E 01	FVOL= 1.30E 02	UMAX= 4.03E 01	UEDG= 4.08E 01	LDEG= 73
CYCLE=129	ITER= 1	DELT= 1.24E-01	TIME= 2.07E 01	FVOL= 1.30E 02	UMAX= 4.03E 01	UEDG= 4.08E 01	LDEG= 73
CYCLE=130	ITER= 1	DELT= 1.24E-01	TIME= 2.09E 01	FVOL= 1.30E 02	UMAX= 4.00E 01	UEDG= 4.08E 01	LDEG= 73
CYCLE=131	ITER= 1	DELT= 1.25E-01	TIME= 2.10E 01	FVOL= 1.30E 02	UMAX= 4.00E 01	UEDG= 2.70E 01	LDEG= 74
CYCLE=132	ITER= 1	DELT= 1.25E-01	TIME= 2.11E 01	FVOL= 1.30E 02	UMAX= 3.95E 01	UEDG= 2.70E 01	LDEG= 74
CYCLE=133	ITER= 1	DELT= 1.26E-01	TIME= 2.12E 01	FVOL= 1.30E 02	UMAX= 3.96E 01	UEDG= 4.00E 01	LDEG= 75
CYCLE=134	ITER= 1	DELT= 1.26E-01	TIME= 2.14E 01	FVOL= 1.30E 02	UMAX= 3.96E 01	UEDG= 4.00E 01	LDEG= 75
CYCLE=135	ITER= 1	DELT= 1.26E-01	TIME= 2.15E 01	FVOL= 1.30E 02	UMAX= 3.92E 01	UEDG= 4.00E 01	LDEG= 75
CYCLE=136	ITER= 1	DELT= 1.28E-01	TIME= 2.16E 01	FVOL= 1.30E 02	UMAX= 3.92E 01	UEDG= 2.64E 01	LDEG= 76
CYCLE=137	ITER= 1	DELT= 1.28E-01	TIME= 2.17E 01	FVOL= 1.30E 02	UMAX= 3.87E 01	UEDG= 2.64E 01	LDEG= 76
CYCLE=138	ITER= 1	DELT= 1.29E-01	TIME= 2.19E 01	FVOL= 1.30E 02	UMAX= 3.87E 01	UEDG= 2.64E 01	LDEG= 76
CYCLE=139	ITER= 1	DELT= 1.29E-01	TIME= 2.20E 01	FVOL= 1.30E 02	UMAX= 3.82E 01	UEDG= 2.60E 01	LDEG= 77
CYCLE=140	ITER= 1	DELT= 1.31E-01	TIME= 2.21E 01	FVOL= 1.30E 02	UMAX= 3.82E 01	UEDG= 2.60E 01	LDEG= 77
CYCLE=141	ITER= 1	DELT= 1.31E-01	TIME= 2.23E 01	FVOL= 1.30E 02	UMAX= 3.76E 01	UEDG= 2.60E 01	LDEG= 77
CYCLE=142	ITER= 1	DELT= 1.33E-01	TIME= 2.24E 01	FVOL= 1.30E 02	UMAX= 3.76E 01	UEDG= 2.56E 01	LDEG= 78
CYCLE=143	ITER= 1	DELT= 1.33E-01	TIME= 2.25E 01	FVOL= 1.30E 02	UMAX= 3.69E 01	UEDG= 2.56E 01	LDEG= 78
CYCLE=144	ITER= 1	DELT= 1.35E-01	TIME= 2.27E 01	FVOL= 1.30E 02	UMAX= 3.69E 01	UEDG= 2.56E 01	LDEG= 78
CYCLE=145	ITER= 1	DELT= 1.35E-01	TIME= 2.28E 01	FVOL= 1.30E 02	UMAX= 3.62E 01	UEDG= 2.49E 01	LDEG= 79
CYCLE=146	ITER= 1	DELT= 1.38E-01	TIME= 2.29E 01	FVOL= 1.30E 02	UMAX= 3.62E 01	UEDG= 2.49E 01	LDEG= 79
CYCLE=147	ITER= 1	DELT= 1.38E-01	TIME= 2.31E 01	FVOL= 1.30E 02	UMAX= 3.54E 01	UEDG= 2.49E 01	LDEG= 79
CYCLE=148	ITER= 1	DELT= 1.41E-01	TIME= 2.32E 01	FVOL= 1.30E 02	UMAX= 3.54E 01	UEDG= 2.43E 01	LDEG= 80
CYCLE=149	ITER= 1	DELT= 1.41E-01	TIME= 2.34E 01	FVOL= 1.30E 02	UMAX= 3.46E 01	UEDG= 2.43E 01	LDEG= 80
CYCLE=150	ITER= 1	DELT= 1.45E-01	TIME= 2.35E 01	FVOL= 1.30E 02	UMAX= 3.46E 01	UEDG= 2.43E 01	LDEG= 80
CYCLE=151	ITER= 9	DELT= 1.45E-01	TIME= 2.36E 01	FVOL= 1.30E 02	UMAX= 3.37E 01	UEDG= 2.34E 01	LDEG= 81
CYCLE=152	ITER= 1	DELT= 1.48E-01	TIME= 2.38E 01	FVOL= 1.30E 02	UMAX= 3.37E 01	UEDG= 2.34E 01	LDEG= 81
CYCLE=153	ITER= 7	DELT= 1.48E-01	TIME= 2.39E 01	FVOL= 1.30E 02	UMAX= 3.37E 01	UEDG= 2.34E 01	LDEG= 81
CYCLE=154	ITER= 3	DELT= 1.48E-01	TIME= 2.41E 01	FVOL= 1.30E 02	UMAX= 3.27E 01	UEDG= 2.26E 01	LDEG= 82
CYCLE=155	ITER= 7	DELT= 1.53E-01	TIME= 2.42E 01	FVOL= 1.30E 02	UMAX= 3.27E 01	UEDG= 2.26E 01	LDEG= 82
CYCLE=156	ITER= 3	DELT= 1.53E-01	TIME= 2.44E 01	FVOL= 1.30E 02	UMAX= 3.17E 01	UEDG= 2.26E 01	LDEG= 82
CYCLE=157	ITER= 8	DELT= 1.58E-01	TIME= 2.46E 01	FVOL= 1.30E 02	UMAX= 3.17E 01	UEDG= 2.20E 01	LDEG= 83
CYCLE=158	ITER= 1	DELT= 1.58E-01	TIME= 2.47E 01	FVOL= 1.30E 02	UMAX= 3.06E 01	UEDG= 2.20E 01	LDEG= 83
CYCLE=159	ITER= 2	DELT= 1.63E-01	TIME= 2.49E 01	FVOL= 1.30E 02	UMAX= 3.06E 01	UEDG= 2.20E 01	LDEG= 83
CYCLE=160	ITER= 6	DELT= 1.63E-01	TIME= 2.50E 01	FVOL= 1.30E 02	UMAX= 2.95E 01	UEDG= 2.09E 01	LDEG= 84
CYCLE=161	ITER= 1	DELT= 1.69E-01	TIME= 2.52E 01	FVOL= 1.30E 02	UMAX= 2.95E 01	UEDG= 2.09E 01	LDEG= 84
CYCLE=162	ITER= 6	DELT= 1.69E-01	TIME= 2.54E 01	FVOL= 1.30E 02	UMAX= 2.84E 01	UEDG= 2.09E 01	LDEG= 84
CYCLE=163	ITER= 1	DELT= 1.76E-01	TIME= 2.56E 01	FVOL= 1.30E 02	UMAX= 2.84E 01	UEDG= 2.09E 01	LDEG= 84
CYCLE=164	ITER= 9	DELT= 1.76E-01	TIME= 2.57E 01	FVOL= 1.30E 02	UMAX= 2.72E 01	UEDG= 1.47E 01	LDEG= 85
CYCLE=165	ITER= 4	DELT= 1.83E-01	TIME= 2.59E 01	FVOL= 1.30E 02	UMAX= 2.72E 01	UEDG= 1.47E 01	LDEG= 85
CYCLE=166	ITER= 1	DELT= 1.84E-01	TIME= 2.61E 01	FVOL= 1.29E 02	UMAX= 2.61E 01	UEDG= 1.47E 01	LDEG= 85
CYCLE=167	ITER= 6	DELT= 1.92E-01	TIME= 2.63E 01	FVOL= 1.30E 02	UMAX= 2.60E 01	UEDG= 1.47E 01	LDEG= 85
CYCLE=168	ITER= 4	DELT= 1.92E-01	TIME= 2.65E 01	FVOL= 1.29E 02	UMAX= 2.49E 01	UEDG= 1.47E 01	LDEG= 85
CYCLE=169	ITER= 10	DELT= 2.01E-01	TIME= 2.67E 01	FVOL= 1.29E 02	UMAX= 2.49E 01	UEDG= 1.08E 01	LDEG= 86
CYCLE=170	ITER= 1	DELT= 1.34E-01	TIME= 2.68E 01	FVOL= 1.30E 02	UMAX= 2.48E 01	UEDG= 1.08E 01	LDEG= 86
CYCLE=171	ITER= 2	DELT= 2.01E-01	TIME= 2.70E 01	FVOL= 1.29E 02	UMAX= 2.36E 01	UEDG= 1.08E 01	LDEG= 86
CYCLE=172	ITER= 7	DELT= 2.11E-01	TIME= 2.72E 01	FVOL= 1.29E 02	UMAX= 2.36E 01	UEDG= 1.08E 01	LDEG= 86
CYCLE=173	ITER= 1	DELT= 2.11E-01	TIME= 2.74E 01	FVOL= 1.28E 02	UMAX= 2.24E 01	UEDG= 1.08E 01	LDEG= 86
CYCLE=174	ITER= 9	DELT= 2.23E-01	TIME= 2.77E 01	FVOL= 1.29E 02	UMAX= 2.25E 01	UEDG= 1.04E 01	LDEG= 87
CYCLE=175	ITER= 4	DELT= 2.23E-01	TIME= 2.79E 01	FVOL= 1.29E 02	UMAX= 2.09E 01	UEDG= 1.04E 01	LDEG= 87

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CYCLE=176  ITER= 1  DELT= 2.39E-01  TIME= 2.81E 01  FVOL= 1.29E 02  UMAX= 2.12E 01  UEDG= 1.04E 01  LDEG= 87
CYCLE=177  ITER= 5  DELT= 2.36E-01  TIME= 2.84E 01  FVOL= 1.29E 02  UMAX= 2.13E 01  UEDG= 1.04E 01  LDEG= 87
CYCLE=178  ITER= 4  DELT= 2.35E-01  TIME= 2.86E 01  FVOL= 1.28E 02  UMAX= 1.97E 01  UEDG= 1.04E 01  LDEG= 87
CYCLE=179  ITER= 1  DELT= 2.54E-01  TIME= 2.88E 01  FVOL= 1.29E 02  UMAX= 2.00E 01  UEDG= 8.65E 00  LDEG= 88
CYCLE=180  ITER= 4  DELT= 2.50E-01  TIME= 2.91E 01  FVOL= 1.29E 02  UMAX= 2.01E 01  UEDG= 8.65E 00  LDEG= 88
CYCLE=181  ITER= 5  DELT= 2.49E-01  TIME= 2.93E 01  FVOL= 1.29E 02  UMAX= 1.84E 01  UEDG= 8.65E 00  LDEG= 88
CYCLE=182  ITER= 4  DELT= 2.72E-01  TIME= 2.96E 01  FVOL= 1.28E 02  UMAX= 1.87E 01  UEDG= 8.65E 00  LDEG= 88
CYCLE=183  ITER= 4  DELT= 2.67E-01  TIME= 2.99E 01  FVOL= 1.28E 02  UMAX= 1.73E 01  UEDG= 9.75E 00  LDEG= 89
CYCLE=184  ITER= 1  DELT= 2.89E-01  TIME= 3.02E 01  FVOL= 1.31E 02  UMAX= 1.68E 01  UEDG= 9.75E 00  LDEG= 89
CYCLE=185  ITER= 5  DELT= 2.73E-01  TIME= 3.04E 01  FVOL= 1.29E 02  UMAX= 1.72E 01  UEDG= 9.75E 00  LDEG= 89
CYCLE=186  ITER= 5  DELT= 2.90E-01  TIME= 3.07E 01  FVOL= 1.28E 02  UMAX= 1.75E 01  UEDG= 9.75E 00  LDEG= 89
CYCLE=187  ITER= 4  DELT= 2.86E-01  TIME= 3.10E 01  FVOL= 1.28E 02  UMAX= 1.55E 01  UEDG= 8.93E 00  LDEG= 90
CYCLE=188  ITER= 1  DELT= 2.96E-01  TIME= 3.13E 01  FVOL= 1.30E 02  UMAX= 1.60E 01  UEDG= 8.93E 00  LDEG= 90
CYCLE=189  ITER= 4  DELT= 2.94E-01  TIME= 3.16E 01  FVOL= 1.28E 02  UMAX= 1.62E 01  UEDG= 8.93E 00  LDEG= 90
CYCLE=190  ITER= 5  DELT= 3.08E-01  TIME= 3.19E 01  FVOL= 1.28E 02  UMAX= 1.41E 01  UEDG= 8.93E 00  LDEG= 90
CYCLE=191  ITER= 5  DELT= 3.53E-01  TIME= 3.23E 01  FVOL= 1.28E 02  UMAX= 1.48E 01  UEDG= 8.45E 00  LDEG= 91
CYCLE=192  ITER= 1  DELT= 2.14E-01  TIME= 3.25E 01  FVOL= 1.30E 02  UMAX= 1.50E 01  UEDG= 8.45E 00  LDEG= 91
CYCLE=193  ITER= 4  DELT= 3.16E-01  TIME= 3.28E 01  FVOL= 1.28E 02  UMAX= 1.22E 01  UEDG= 8.45E 00  LDEG= 91
CYCLE=194  ITER= 4  DELT= 3.28E-01  TIME= 3.31E 01  FVOL= 1.29E 02  UMAX= 1.26E 01  UEDG= 8.45E 00  LDEG= 91
CYCLE=195  ITER= 5  DELT= 3.49E-01  TIME= 3.35E 01  FVOL= 1.28E 02  UMAX= 1.33E 01  UEDG= 8.45E 00  LDEG= 91
CYCLE=196  ITER= 1  DELT= 3.76E-01  TIME= 3.39E 01  FVOL= 1.30E 02  UMAX= 1.38E 01  UEDG= 6.41E 00  LDEG= 92
CYCLE=197  ITER= 8  DELT= 1.80E-01  TIME= 3.40E 01  FVOL= 1.29E 02  UMAX= 1.05E 01  UEDG= 6.41E 00  LDEG= 92
CYCLE=198  ITER= 4  DELT= 3.74E-01  TIME= 3.44E 01  FVOL= 1.29E 02  UMAX= 1.10E 01  UEDG= 6.41E 00  LDEG= 92
CYCLE=199  ITER= 4  DELT= 2.77E-01  TIME= 3.47E 01  FVOL= 1.29E 02  UMAX= 1.13E 01  UEDG= 6.41E 00  LDEG= 92
CYCLE=200  ITER= 1  DELT= 3.99E-01  TIME= 3.51E 01  FVOL= 1.31E 02  UMAX= 1.16E 01  UEDG= 6.41E 00  LDEG= 92
CYCLE=201  ITER= 4  DELT= 3.09E-01  TIME= 3.54E 01  FVOL= 1.28E 02  UMAX= 1.21E 01  UEDG= 6.23E 00  LDEG= 93
CYCLE=202  ITER= 3  DELT= 2.06E-01  TIME= 3.56E 01  FVOL= 1.29E 02  UMAX= 8.96E 00  UEDG= 6.23E 00  LDEG= 93
CYCLE=203  ITER= 6  DELT= 3.61E-01  TIME= 3.60E 01  FVOL= 1.30E 02  UMAX= 9.39E 00  UEDG= 6.23E 00  LDEG= 93
CYCLE=204  ITER= 1  DELT= 2.70E-01  TIME= 3.62E 01  FVOL= 1.28E 02  UMAX= 9.40E 00  UEDG= 6.23E 00  LDEG= 93
CYCLE=205  ITER= 4  DELT= 3.73E-01  TIME= 3.66E 01  FVOL= 1.29E 02  UMAX= 9.44E 00  UEDG= 6.23E 00  LDEG= 93
CYCLE=206  ITER= 4  DELT= 2.92E-01  TIME= 3.69E 01  FVOL= 1.29E 02  UMAX= 9.75E 00  UEDG= 6.23E 00  LDEG= 93
CYCLE=207  ITER= 1  DELT= 4.42E-01  TIME= 3.73E 01  FVOL= 1.29E 02  UMAX= 1.04E 01  UEDG= 5.52E 00  LDEG= 94
CYCLE=208  ITER= 3  DELT= 1.65E-01  TIME= 3.75E 01  FVOL= 1.30E 02  UMAX= 1.06E 01  UEDG= 5.52E 00  LDEG= 94
CYCLE=209  ITER= 5  DELT= 3.96E-01  TIME= 3.79E 01  FVOL= 1.30E 02  UMAX= 8.70E 00  UEDG= 5.52E 00  LDEG= 94
CYCLE=210  ITER= 1  DELT= 2.55E-01  TIME= 3.82E 01  FVOL= 1.29E 02  UMAX= 8.56E 00  UEDG= 5.52E 00  LDEG= 94
CYCLE=211  ITER= 3  DELT= 3.99E-01  TIME= 3.86E 01  FVOL= 1.29E 02  UMAX= 8.26E 00  UEDG= 5.52E 00  LDEG= 94
CYCLE=212  ITER= 3  DELT= 2.76E-01  TIME= 3.88E 01  FVOL= 1.29E 02  UMAX= 7.87E 00  UEDG= 5.52E 00  LDEG= 94
CYCLE=213  ITER= 1  DELT= 4.50E-01  TIME= 3.93E 01  FVOL= 1.32E 02  UMAX= 8.18E 00  UEDG= 5.17E 00  LDEG= 95
CYCLE=214  ITER= 3  DELT= 1.64E-01  TIME= 3.94E 01  FVOL= 1.30E 02  UMAX= 8.23E 00  UEDG= 5.17E 00  LDEG= 95
CYCLE=215  ITER= 6  DELT= 3.95E-01  TIME= 3.98E 01  FVOL= 1.29E 02  UMAX= 8.59E 00  UEDG= 5.17E 00  LDEG= 95
CYCLE=216  ITER= 1  DELT= 2.53E-01  TIME= 4.01E 01  FVOL= 1.29E 02  UMAX= 8.87E 00  UEDG= 5.17E 00  LDEG= 95
CYCLE=217  ITER= 3  DELT= 3.86E-01  TIME= 4.05E 01  FVOL= 1.29E 02  UMAX= 7.56E 00  UEDG= 5.17E 00  LDEG= 95
CYCLE=218  ITER= 3  DELT= 2.78E-01  TIME= 4.08E 01  FVOL= 1.30E 02  UMAX= 7.25E 00  UEDG= 5.17E 00  LDEG= 95
CYCLE=219  ITER= 1  DELT= 4.18E-01  TIME= 4.12E 01  FVOL= 1.31E 02  UMAX= 6.76E 00  UEDG= 5.19E 00  LDEG= 96
CYCLE=220  ITER= 3  DELT= 1.77E-01  TIME= 4.14E 01  FVOL= 1.30E 02  UMAX= 6.69E 00  UEDG= 5.19E 00  LDEG= 96
CYCLE=221  ITER= 3  DELT= 3.74E-01  TIME= 4.17E 01  FVOL= 1.30E 02  UMAX= 6.80E 00  UEDG= 5.19E 00  LDEG= 96
CYCLE=222  ITER= 5  DELT= 2.56E-01  TIME= 4.20E 01  FVOL= 1.30E 02  UMAX= 6.91E 00  UEDG= 5.19E 00  LDEG= 96
CYCLE=223  ITER= 4  DELT= 3.48E-01  TIME= 4.23E 01  FVOL= 1.30E 02  UMAX= 6.83E 00  UEDG= 5.19E 00  LDEG= 96
CYCLE=224  ITER= 1  DELT= 2.95E-01  TIME= 4.26E 01  FVOL= 1.31E 02  UMAX= 6.90E 00  UEDG= 5.19E 00  LDEG= 96
CYCLE=225  ITER= 5  DELT= 3.53E-01  TIME= 4.30E 01  FVOL= 1.29E 02  UMAX= 6.93E 00  UEDG= 5.19E 00  LDEG= 96
CYCLE=226  ITER= 4  DELT= 3.05E-01  TIME= 4.33E 01  FVOL= 1.29E 02  UMAX= 7.39E 00  UEDG= 5.19E 00  LDEG= 96
CYCLE=227  ITER= 1  DELT= 3.64E-01  TIME= 4.37E 01  FVOL= 1.31E 02  UMAX= 7.85E 00  UEDG= 3.96E 00  LDEG= 97
CYCLE=228  ITER= 3  DELT= 2.00E-01  TIME= 4.39E 01  FVOL= 1.30E 02  UMAX= 8.03E 00  UEDG= 3.96E 00  LDEG= 97
CYCLE=229  ITER= 3  DELT= 3.61E-01  TIME= 4.42E 01  FVOL= 1.31E 02  UMAX= 5.90E 00  UEDG= 3.96E 00  LDEG= 97
CYCLE=230  ITER= 8  DELT= 2.62E-01  TIME= 4.45E 01  FVOL= 1.31E 02  UMAX= 5.98E 00  UEDG= 3.96E 00  LDEG= 97
CYCLE=231  ITER= 1  DELT= 3.36E-01  TIME= 4.48E 01  FVOL= 1.31E 02  UMAX= 5.87E 00  UEDG= 3.96E 00  LDEG= 97
CYCLE=232  ITER= 4  DELT= 2.93E-01  TIME= 4.51E 01  FVOL= 1.31E 02  UMAX= 5.66E 00  UEDG= 3.96E 00  LDEG= 97
CYCLE=233  ITER= 5  DELT= 3.32E-01  TIME= 4.54E 01  FVOL= 1.30E 02  UMAX= 5.69E 00  UEDG= 3.96E 00  LDEG= 97
CYCLE=234  ITER= 1  DELT= 3.16E-01  TIME= 4.58E 01  FVOL= 1.31E 02  UMAX= 5.48E 00  UEDG= 3.96E 00  LDEG= 97
CYCLE=235  ITER= 3  DELT= 3.33E-01  TIME= 4.61E 01  FVOL= 1.30E 02  UMAX= 5.32E 00  UEDG= 3.96E 00  LDEG= 97
CYCLE=236  ITER= 5  DELT= 3.17E-01  TIME= 4.64E 01  FVOL= 1.30E 02  UMAX= 5.15E 00  UEDG= 3.96E 00  LDEG= 97
CYCLE=237  ITER= 4  DELT= 3.30E-01  TIME= 4.67E 01  FVOL= 1.30E 02  UMAX= 5.03E 00  UEDG= 3.21E 00  LDEG= 98
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I	J	U	V	P	H	SUR CELL
1	1	.000E 00	.000E 00	.000E 00	2.000E 00	2
1	2	.000E 00	-2.009E 00	.000E 00	2.000E 00	2
1	3	.000E 00	-5.531E 00	.000E 00	2.000E 00	2
2	1	-1.423E 00	.000E 00	.000E 00	.000E 00	2
2	2	1.004E 01	-2.009E 00	.000E 00	.000E 00	2
2	3	1.004E 01	-5.531E 00	-6.251E 00	.000E 00	2
3	1	-1.926E 00	.000E 00	.000E 00	.000E 00	2
3	2	1.359E 01	-7.097E-01	.000E 00	.000E 00	2
3	3	1.359E 01	-3.288E 00	-7.286E 00	.000E 00	2
4	1	-2.291E 00	.000E 00	.000E 00	.000E 00	2
4	2	1.617E 01	-5.152E-01	.000E 00	.000E 00	2
4	3	1.617E 01	-2.329E 00	-7.607E 00	.000E 00	2
5	1	-2.577E 00	.000E 00	.000E 00	.000E 00	2
5	2	1.819E 01	-4.042E-01	.000E 00	.000E 00	2
5	3	1.819E 01	-2.129E 00	-7.575E 00	.000E 00	2
6	1	-2.845E 00	.000E 00	.000E 00	.000E 00	2
6	2	2.008E 01	-3.783E-01	.000E 00	.000E 00	2
6	3	2.008E 01	-2.005E 00	-7.257E 00	.000E 00	2
7	1	-3.054E 00	.000E 00	.000E 00	.000E 00	2
7	2	2.155E 01	-2.947E-01	.000E 00	.000E 00	2
7	3	2.155E 01	-2.026E 00	-7.351E 00	.000E 00	2
8	1	-3.239E 00	.000E 00	.000E 00	.000E 00	2
8	2	2.286E 01	-2.614E-01	.000E 00	.000E 00	2
8	3	2.286E 01	-4.194E 00	.000E 00	.000E 00	2

9	1	-3.402E 00	.000E 00	.000E 00	.000E 00	2
9	2	2.401E 01	-2.296E-01	.000E 00	.000E 00	2
9	3	2.401E 01	-4.094E 00	.000E 00	.000E 00	2
10	1	-3.567E 00	.000E 00	.000E 00	.000E 00	2
10	2	2.518E 01	-2.339E-01	.000E 00	.000E 00	2
10	3	2.518E 01	-3.870E 00	.000E 00	.000E 00	2
11	1	-3.720E 00	.000E 00	.000E 00	.000E 00	2
11	2	2.626E 01	-2.162E-01	.000E 00	.000E 00	2
11	3	2.626E 01	-3.865E 00	.000E 00	.000E 00	2
12	1	-3.848E 00	.000E 00	.000E 00	.000E 00	2
12	2	2.716E 01	-1.802E-01	.000E 00	.000E 00	2
12	3	2.716E 01	-3.988E 00	.000E 00	.000E 00	2
13	1	-3.941E 00	.000E 00	.000E 00	.000E 00	2
13	2	2.782E 01	-1.317E-01	.000E 00	.000E 00	2
13	3	2.782E 01	-4.086E 00	.000E 00	.000E 00	2
14	1	-4.041E 00	.000E 00	.000E 00	.000E 00	2
14	2	2.852E 01	-1.412E-01	.000E 00	.000E 00	2
14	3	2.852E 01	-3.911E 00	.000E 00	.000E 00	2
15	1	-4.126E 00	.000E 00	.000E 00	.000E 00	2
15	2	2.912E 01	-1.197E-01	.000E 00	.000E 00	2
15	3	2.912E 01	-4.017E 00	.000E 00	.000E 00	2
16	1	-4.195E 00	.000E 00	.000E 00	.000E 00	2
16	2	2.961E 01	-9.672E-02	.000E 00	.000E 00	2
16	3	2.961E 01	-4.053E 00	.000E 00	.000E 00	2
17	1	-4.263E 00	.000E 00	.000E 00	.000E 00	2
17	2	3.009E 01	-9.571E-02	.000E 00	.000E 00	2
17	3	3.009E 01	-4.019E 00	.000E 00	.000E 00	2
18	1	-4.311E 00	.000E 00	.000E 00	.000E 00	2
18	2	3.043E 01	-6.871E-02	.000E 00	.000E 00	2
18	3	3.043E 01	-4.194E 00	.000E 00	.000E 00	2
19	1	-4.331E 00	.000E 00	.000E 00	.000E 00	2
19	2	3.057E 01	-2.737E-02	.000E 00	.000E 00	2
19	3	3.057E 01	-4.361E 00	.000E 00	.000E 00	2
20	1	-4.329E 00	.000E 00	.000E 00	.000E 00	2
20	2	3.056E 01	1.599E-03	.000E 00	.000E 00	2
20	3	3.056E 01	-4.391E 00	.000E 00	.000E 00	2
21	1	-4.326E 00	.000E 00	.000E 00	.000E 00	2
21	2	3.054E 01	4.300E-03	.000E 00	.000E 00	2
21	3	3.054E 01	-4.317E 00	.000E 00	.000E 00	2
22	1	-4.338E 00	.000E 00	.000E 00	.000E 00	2
22	2	3.062E 01	-1.624E-02	.000E 00	.000E 00	2
22	3	3.062E 01	-4.166E 00	.000E 00	.000E 00	2
23	1	-4.386E 00	.000E 00	.000E 00	.000E 00	2
23	2	3.096E 01	-6.769E-02	.000E 00	.000E 00	2
23	3	3.096E 01	-4.036E 00	.000E 00	.000E 00	2
24	1	-4.400E 00	.000E 00	.000E 00	.000E 00	2
24	2	3.105E 01	-1.947E-02	.000E 00	.000E 00	2
24	3	3.105E 01	-4.334E 00	.000E 00	.000E 00	2
25	1	-4.422E 00	.000E 00	.000E 00	.000E 00	2
25	2	3.121E 01	-3.152E-02	.000E 00	.000E 00	2
25	3	3.121E 01	-4.161E 00	.000E 00	.000E 00	2
26	1	-4.452E 00	.000E 00	.000E 00	.000E 00	2
26	2	3.142E 01	-4.276E-02	.000E 00	.000E 00	2
26	3	3.142E 01	-4.108E 00	.000E 00	.000E 00	2
27	1	-4.490E 00	.000E 00	.000E 00	.000E 00	2
27	2	3.169E 01	-5.281E-02	.000E 00	.000E 00	2
27	3	3.169E 01	-4.048E 00	.000E 00	.000E 00	2
28	1	-4.533E 00	.000E 00	.000E 00	.000E 00	2
28	2	3.200E 01	-6.150E-02	.000E 00	.000E 00	2
28	3	3.200E 01	-3.982E 00	.000E 00	.000E 00	2
29	1	-4.583E 00	.000E 00	.000E 00	.000E 00	2
29	2	3.235E 01	-7.023E-02	.000E 00	.000E 00	2
29	3	3.235E 01	-3.912E 00	.000E 00	.000E 00	2
30	1	-4.636E 00	.000E 00	.000E 00	.000E 00	2
30	2	3.272E 01	-7.532E-02	.000E 00	.000E 00	2
30	3	3.272E 01	-3.827E 00	.000E 00	.000E 00	2
31	1	-4.706E 00	.000E 00	.000E 00	.000E 00	2
31	2	3.322E 01	-9.850E-02	.000E 00	.000E 00	2
31	3	3.322E 01	-3.654E 00	.000E 00	.000E 00	2
32	1	-4.772E 00	.000E 00	.000E 00	.000E 00	2
32	2	3.368E 01	-9.293E-02	.000E 00	.000E 00	2
32	3	3.368E 01	-3.694E 00	.000E 00	.000E 00	2
33	1	-4.835E 00	.000E 00	.000E 00	.000E 00	2
33	2	3.412E 01	-8.851E-02	.000E 00	.000E 00	2
33	3	3.412E 01	-3.683E 00	.000E 00	.000E 00	2
34	1	-4.892E 00	.000E 00	.000E 00	.000E 00	2
34	2	3.453E 01	-8.079E-02	.000E 00	.000E 00	2
34	3	3.453E 01	-3.662E 00	.000E 00	.000E 00	2
35	1	-4.958E 00	.000E 00	.000E 00	.000E 00	2
35	2	3.500E 01	-9.378E-02	.000E 00	.000E 00	2
35	3	3.500E 01	-3.492E 00	.000E 00	.000E 00	2
36	1	-5.029E 00	.000E 00	.000E 00	.000E 00	2
36	2	3.550E 01	-1.003E-01	.000E 00	.000E 00	2
36	3	3.550E 01	-3.337E 00	.000E 00	.000E 00	2
37	1	-5.125E 00	.000E 00	.000E 00	.000E 00	2
37	2	3.617E 01	-1.345E-01	.000E 00	.000E 00	2
37	3	3.617E 01	-3.012E 00	.000E 00	.000E 00	2

38	1	-5.206E 00	.000E 00	.000E 00	.000E 00	2
38	2	3.674E 01	-1.146E-01	.000E 00	.000E 00	2
38	3	3.674E 01	-3.192E 00	.000E 00	.000E 00	2
39	1	-5.284E 00	.000E 00	.000E 00	.000E 00	2
39	2	3.729E 01	-1.101E-01	.000E 00	.000E 00	2
39	3	3.729E 01	-3.157E 00	.000E 00	.000E 00	2
40	1	-5.355E 00	.000E 00	.000E 00	.000E 00	2
40	2	3.780E 01	-1.002E-01	.000E 00	.000E 00	2
40	3	3.780E 01	-3.208E 00	.000E 00	.000E 00	2
41	1	-5.418E 00	.000E 00	.000E 00	.000E 00	2
41	2	3.824E 01	-8.955E-02	.000E 00	.000E 00	2
41	3	3.824E 01	-3.244E 00	.000E 00	.000E 00	2
42	1	-5.478E 00	.000E 00	.000E 00	.000E 00	2
42	2	3.867E 01	-8.441E-02	.000E 00	.000E 00	2
42	3	3.867E 01	-3.220E 00	.000E 00	.000E 00	2
43	1	-5.538E 00	.000E 00	.000E 00	.000E 00	2
43	2	3.909E 01	-8.475E-02	.000E 00	.000E 00	2
43	3	3.909E 01	-3.220E 00	.000E 00	.000E 00	2
44	1	-5.584E 00	.000E 00	.000E 00	.000E 00	2
44	2	3.941E 01	-6.448E-02	.000E 00	.000E 00	2
44	3	3.941E 01	-3.450E 00	.000E 00	.000E 00	2
45	1	-5.611E 00	.000E 00	.000E 00	.000E 00	2
45	2	3.960E 01	-3.823E-02	.000E 00	.000E 00	2
45	3	3.960E 01	-3.599E 00	.000E 00	.000E 00	2
46	1	-5.633E 00	.000E 00	.000E 00	.000E 00	2
46	2	3.976E 01	-3.168E-02	.000E 00	.000E 00	2
46	3	3.976E 01	-3.542E 00	.000E 00	.000E 00	2
47	1	-5.640E 00	.000E 00	.000E 00	.000E 00	2
47	2	3.981E 01	-9.665E-03	.000E 00	.000E 00	2
47	3	3.981E 01	-3.639E 00	.000E 00	.000E 00	2
48	1	-5.654E 00	.000E 00	.000E 00	.000E 00	2
48	2	3.991E 01	-1.945E-02	.000E 00	.000E 00	2
48	3	3.991E 01	-3.642E 00	.000E 00	.000E 00	2
49	1	-5.679E 00	.000E 00	.000E 00	.000E 00	2
49	2	4.008E 01	-3.525E-02	.000E 00	.000E 00	2
49	3	4.008E 01	-3.871E 00	.000E 00	.000E 00	2
50	1	-5.716E 00	.000E 00	.000E 00	.000E 00	2
50	2	4.034E 01	-5.193E-02	.000E 00	.000E 00	2
50	3	4.034E 01	-3.980E 00	.000E 00	.000E 00	2
51	1	-5.737E 00	.000E 00	.000E 00	.000E 00	2
51	2	4.049E 01	-2.971E-02	.000E 00	.000E 00	2
51	3	4.049E 01	-3.639E 00	.000E 00	.000E 00	2
52	1	-5.649E 00	.000E 00	.000E 00	.000E 00	2
52	2	3.987E 01	1.234E-01	.000E 00	.000E 00	2
52	3	3.987E 01	-3.793E 00	.000E 00	.000E 00	2
53	1	-5.417E 00	.000E 00	.000E 00	.000E 00	2
53	2	3.823E 01	3.282E-01	.000E 00	.000E 00	2
53	3	3.823E 01	-3.976E 00	.000E 00	.000E 00	2
54	1	-5.254E 00	.000E 00	.000E 00	.000E 00	2
54	2	3.708E 01	2.302E-01	.000E 00	.000E 00	2
54	3	3.708E 01	-4.537E 00	.000E 00	.000E 00	2
55	1	-5.654E 00	.000E 00	.000E 00	.000E 00	2
55	2	3.990E 01	-5.645E-01	.000E 00	.000E 00	2
55	3	3.990E 01	-5.043E 00	.000E 00	.000E 00	2
56	1	-6.430E 00	.000E 00	.000E 00	.000E 00	2
56	2	4.538E 01	-1.095E 00	.000E 00	.000E 00	2
56	3	4.538E 01	-4.641E 00	.000E 00	.000E 00	2
57	1	-5.829E 00	.000E 00	.000E 00	.000E 00	2
57	2	4.114E 01	8.484E-01	.000E 00	.000E 00	2
57	3	4.114E 01	-2.209E 00	.000E 00	.000E 00	2
58	1	-5.841E 00	.000E 00	.000E 00	.000E 00	2
58	2	2.711E 01	2.806E 00	.000E 00	.000E 00	2
58	3	2.711E 01	-3.699E 00	.000E 00	.000E 00	2
59	1	-2.874E 00	.000E 00	.000E 00	.000E 00	2
59	2	2.028E 01	1.365E 00	.000E 00	.000E 00	2
59	3	2.028E 01	-9.730E 00	.000E 00	.000E 00	2
60	1	-5.405E 00	.000E 00	.000E 00	.000E 00	2
60	2	3.815E 01	-3.573E 00	.000E 00	.000E 00	2
60	3	3.815E 01	-1.214E 01	.000E 00	.000E 00	2
61	1	-1.038E 01	.000E 00	.000E 00	.000E 00	2
61	2	7.328E 01	-7.026E 00	.000E 00	.000E 00	2
61	3	7.328E 01	-8.137E 00	.000E 00	.000E 00	2
62	1	-2.666E 00	.000E 00	.000E 00	.000E 00	2
62	2	1.881E 01	1.089E 01	.000E 00	.000E 00	2
62	3	1.881E 01	-2.558E 01	.000E 00	.000E 00	2
63	1	-6.887E-01	.000E 00	.000E 00	.000E 00	2
63	2	4.861E 00	2.790E 00	.000E 00	.000E 00	2
63	3	4.861E 00	-1.535E 01	.000E 00	.000E 00	2
64	1	2.080E 00	.000E 00	.000E 00	.000E 00	2
64	2	-1.468E 01	3.908E 00	.000E 00	.000E 00	2
64	3	-1.468E 01	-1.236E 01	.000E 00	.000E 00	2
65	1	3.369E 00	.000E 00	.000E 00	.000E 00	2
65	2	-2.378E 01	1.820E 00	.000E 00	.000E 00	2
65	3	-2.378E 01	.000E 00	.000E 00	.000E 00	2
66	1	1.056E 01	.000E 00	.000E 00	.000E 00	2
66	2	-7.450E 01	1.014E 01	.000E 00	.000E 00	2
66	3	-7.450E 01	-2.740E 03	.000E 00	.000E 00	2

67	1	1.544E 02	.000E 00	.000E 00	.000E 00	2
67	2	-1.090E 03	2.030E 02	.000E 00	.000E 00	2
67	3	-1.090E 03	2.925E 01	.000E 00	.000E 00	2
68	1	3.940E 02	.000E 00	.000E 00	.000E 00	2
68	2	-2.781E 03	3.383E 02	.000E 00	.000E 00	2
68	3	-2.781E 03	-1.815E 03	.000E 00	.000E 00	2
69	1	4.929E 02	.000E 00	.000E 00	.000E 00	2
69	2	-3.479E 03	1.396E 02	.000E 00	.000E 00	2
69	3	-3.479E 03	-6.194E 03	.000E 00	.000E 00	2
70	1	1.260E 03	.000E 00	.000E 00	.000E 00	2
70	2	-8.891E 03	1.082E 03	.000E 00	.000E 00	2
70	3	-8.891E 03	.000E 00	.000E 00	.000E 00	2
71	1	-2.357E 03	.000E 00	.000E 00	.000E 00	2
71	2	.000E 00	-5.106E 03	.000E 00	.000E 00	2
71	3	.000E 00	.000E 00	.000E 00	.000E 00	2
72	1	2.421E-01	.000E 00	.000E 00	.000E 00	2
72	2	-1.709E 00	3.328E 03	.000E 00	.000E 00	2
72	3	-1.709E 00	3.904E 01	.000E 00	.000E 00	2
73	1	2.039E 00	.000E 00	.000E 00	.000E 00	2
73	2	-1.439E 01	2.537E 00	.000E 00	.000E 00	2
73	3	-1.439E 01	-2.543E 00	.000E 00	.000E 00	2
74	1	9.794E 00	.000E 00	.000E 00	.000E 00	2
74	2	-6.913E 01	1.095E 01	.000E 00	.000E 00	2
74	3	-6.913E 01	-2.468E 01	.000E 00	.000E 00	2
75	1	1.436E 01	.000E 00	.000E 00	.000E 00	2
75	2	-1.014E 02	6.448E 00	.000E 00	.000E 00	2
75	3	-1.014E 02	-1.367E 02	-8.413E 00	.000E 00	2
76	1	-4.431E 01	.000E 00	.000E 00	.000E 00	2
76	2	3.128E 02	-8.282E 01	.000E 00	.000E 00	2
76	3	3.128E 02	-1.421E 02	-9.824E 00	.000E 00	2
77	1	-2.413E 00	.000E 00	.000E 00	.000E 00	2
77	2	1.703E 01	5.915E 01	.000E 00	.000E 00	2
77	3	1.703E 01	6.673E 00	-8.744E 00	.000E 00	2
78	1	-3.533E 00	.000E 00	.000E 00	.000E 00	2
78	2	2.494E 01	-1.582E 00	.000E 00	.000E 00	2
78	3	2.494E 01	-4.751E 00	-8.764E 00	.000E 00	2
79	1	-4.172E 00	.000E 00	.000E 00	.000E 00	2
79	2	2.945E 01	-9.023E-01	.000E 00	.000E 00	2
79	3	2.945E 01	-2.832E 00	-8.946E 00	.000E 00	2
80	1	-3.068E 00	.000E 00	.000E 00	.000E 00	2
80	2	2.166E 01	1.558E 00	.000E 00	.000E 00	2
80	3	2.166E 01	-3.199E-01	-8.960E 00	.000E 00	2
81	1	-2.656E 00	.000E 00	.000E 00	.000E 00	2
81	2	1.875E 01	5.816E-01	.000E 00	.000E 00	2
81	3	1.875E 01	-1.477E 00	-9.650E 00	.000E 00	2
82	1	-2.589E 00	.000E 00	.000E 00	.000E 00	2
82	2	1.827E 01	9.567E-02	.000E 00	.000E 00	2
82	3	1.827E 01	-1.820E 00	-9.035E 00	.000E 00	2
83	1	-2.316E 00	.000E 00	.000E 00	.000E 00	2
83	2	1.635E 01	3.844E-01	.000E 00	.000E 00	2
83	3	1.635E 01	-1.287E 00	-1.028E 01	.000E 00	2
84	1	-2.101E 00	.000E 00	.000E 00	.000E 00	2
84	2	1.483E 01	3.039E-01	.000E 00	.000E 00	2
84	3	1.483E 01	-1.622E 00	-9.358E 00	.000E 00	2
85	1	-1.939E 00	.000E 00	.000E 00	.000E 00	2
85	2	1.369E 01	2.285E-01	.000E 00	.000E 00	2
85	3	1.369E 01	-1.672E 00	-9.406E 00	.000E 00	2
86	1	-1.767E 00	.000E 00	.000E 00	.000E 00	2
86	2	1.247E 01	2.436E-01	.000E 00	.000E 00	2
86	3	1.247E 01	-1.709E 00	-9.152E 00	.000E 00	2
87	1	-1.599E 00	.000E 00	.000E 00	.000E 00	2
87	2	1.128E 01	2.372E-01	.000E 00	.000E 00	2
87	3	1.128E 01	-1.883E 00	-8.439E 00	.000E 00	2
88	1	-1.439E 00	.000E 00	.000E 00	.000E 00	2
88	2	1.015E 01	2.260E-01	.000E 00	.000E 00	2
88	3	1.015E 01	-1.308E 00	-1.118E 01	.000E 00	2
89	1	-1.273E 00	.000E 00	.000E 00	.000E 00	2
89	2	9.027E 00	2.252E-01	.000E 00	.000E 00	2
89	3	9.027E 00	-2.089E 00	-7.609E 00	.000E 00	2
90	1	-1.165E 00	.000E 00	.000E 00	.000E 00	2
90	2	8.223E 00	1.606E-01	.000E 00	.000E 00	2
90	3	8.223E 00	-1.916E 00	-8.828E 00	.000E 00	2
91	1	-7.098E-01	.000E 00	.000E 00	7.938E-01	2
91	2	5.010E 00	6.427E-01	2.193E-12	7.938E-01	2
91	3	5.010E 00	-1.321E 00	-8.574E 00	7.938E-01	2
92	1	-4.757E-01	.000E 00	.000E 00	2.046E 00	3
92	2	3.357E 00	3.176E-01	1.060E 01	2.046E 00	3
92	3	4.191E 00	4.813E-01	-8.719E 00	2.046E 00	3
92	4	4.191E 00	.000E 00	.000E 00	2.046E 00	3
93	1	-4.359E-01	.000E 00	.000E 00	2.226E 00	3
93	2	3.077E 00	5.680E-02	1.199E 01	2.226E 00	3
93	3	4.438E 00	7.499E-03	-7.533E 00	2.226E 00	3
93	4	4.438E 00	.000E 00	.000E 00	2.226E 00	3
94	1	-4.635E-01	.000E 00	.000E 00	2.204E 00	3
94	2	3.271E 00	-4.633E-02	1.194E 01	2.204E 00	3
94	3	5.016E 00	-1.620E-01	-7.596E 00	2.204E 00	3
94	4	5.016E 00	.000E 00	.000E 00	2.204E 00	3

95	1	-4.838E-01	.000E 00	.000E 00	2.063E 00	3
95	2	3.415E 00	1.834E-02	1.026E 01	2.063E 00	3
95	3	5.027E 00	1.620E-02	-9.468E 00	2.063E 00	3
95	4	5.027E 00	.000E 00	.000E 00	2.063E 00	3
96	1	-7.060E-01	.000E 00	.000E 00	2.107E 00	3
96	2	4.983E 00	-3.261E-01	1.163E 01	2.107E 00	3
96	3	4.983E 00	-3.173E-01	-7.458E 00	2.107E 00	3
96	4	4.983E 00	.000E 00	.000E 00	2.107E 00	3
97	1	-2.186E-01	.000E 00	.000E 00	1.561E 00	2
97	2	1.543E 00	6.880E-01	-4.201E-03	1.561E 00	2
97	3	1.543E 00	-3.184E 00	.000E 00	1.561E 00	2
98	1	-7.898E-03	.000E 00	.000E 00	2.891E-02	2
98	2	5.575E-02	2.974E-01	5.575E-05	2.891E-02	2
98	3	5.575E-02	-4.429E 00	.000E 00	2.891E-02	2
99	1	-1.757E-05	.000E 00	.000E 00	.000E 00	2
99	2	1.240E-04	1.112E-02	8.604E-07	.000E 00	2
99	3	1.240E-04	-5.141E 00	.000E 00	.000E 00	2
100	1	5.890E-08	.000E 00	.000E 00	.000E 00	2
100	2	-4.157E-07	2.488E-05	-8.514E-09	.000E 00	2
100	3	-4.157E-07	-5.156E 00	.000E 00	.000E 00	2
101	1	5.888E-08	.000E 00	.000E 00	.000E 00	2
101	2	-4.156E-07	-1.811E-11	-1.031E-09	.000E 00	2
101	3	-4.156E-07	-5.182E 00	.000E 00	.000E 00	2
102	1	.000E 00	.000E 00	.000E 00	.000E 00	2
102	2	.000E 00	-5.182E 00	.000E 00	.000E 00	2
102	3	.000E 00	-5.182E 00	.000E 00	.000E 00	2

FLOW VELOCITY NEGLIGIBLE-CALCULATIONS TERMINATED

Appendix D
Listing of Program AVALNCH—Variable Width Option

```
C    PROGRAM AVALNCH.
*
C    EQUIVALENT HORIZONTAL GRID OPTION : VARIABLE WIDTH OPTION
*
C       THIS PROGRAM HAS BEEN DEVELOPED TO NUMERICALLY SOLVE (USING
C       FINITE DIFFERENCE TECHNIQUES) THE NAVIER - STOKES EQUATIONS
C       FOR TRANSIENT FLUID FLOW PROBLEMS.  IT WILL BE USED TO SIMULATE
C       THE PROBLEM OF SNOW AND ICE AVALANCHES ON SLOPES OF VARYING SLOPE.
        DIMENSION U(202,7),V(202,7),UN(202,7),VN(202,7),P(202,7),FR(202),
       1XPUT( 8),H(202),HN(202),JT(202),NAME(20),GX(202),GY(202),FRC(202),
       2W(202)
        REAL NU
        INTEGER CYCLE
        READ (105,45) NAME
        WRITE (108,35)
        WRITE (108,45) NAME
*
C * * READ AND PRINT INITIAL INPUT DATA
*
        READ(105,25) (XPUT(I),I=1,8)
        IBAR=XPUT(1) ; JBAR=XPUT(2) ; DELX=XPUT(3) ; DELY=XPUT(4)
        NU=XPUT(5)  ;  FRK=XPUT(6)  ;  TWFIN=XPUT(7)  ;  CWPRT=XPUT(8)
        WRITE (108,50) (XPUT(I),I=1,8)
     25 FORMAT(8F10.0)
     35 FORMAT(1H1)
     45 FORMAT(20A4)
     47 FORMAT(6X'I'7X'J'8X'U'13X'V'13X'P'13X'H'9X,'SUR CELL')
     48 FORMAT(4X,I3,5X,I3,4(4X,1PE10.3),6X,I2)
     49 FORMAT(2X'CYCLE='I3,2X'ITER='I3,2X'DELT='1PE9.2,2X'TIME='E9.2,2X,
       1'FVOL='E9.2,2X'UMAX='E9.2,2X'UEDG='E9.2,2X'LDEG='I3)
     50 FORMAT(1H ,1X'IBAR='F4.0,2X'JBAR='F3.0,2X'DELX='F6.2,2X'DELY='F5.2
       1,2X'NU='F4.2,2X'FRK='F4.2,2X'TWFIN='F5.0,2X'CWPRT='F5.0)
     60 FORMAT(8F10.0)
     61 FORMAT(8F10.3)
     70 FORMAT(1H0,35X,'FLOW HEIGHT')
     71 FORMAT(1H0,25X'ELEVATION CHANGE FOR EACH CELL')
     72 FORMAT(1H0,25X,'BOUNDARY FRICTION COEFFICIENTS')
     73 FORMAT(1H0,25X,'SLOPE-PARALLEL GRAVITY COMPONENT')
     74 FORMAT(1H0,25X,'SLOPE-NORMAL GRAVITY COMPONENT')
     75 FORMAT(1H0,30X,'END OF INPUT DATA'//)
     76 FORMAT(1H0,30X,'PER UNIT FLOW WIDTH')
     82 FORMAT(5X,'PROBLEM RUNNING TIME EXCEEDED-CALCULATIONS TERMINATED')
     83 FORMAT(5X,'AVALANCHE AT END OF GRID-CALCULATIONS TERMINATED')
     84 FORMAT(5X,'FLOW VELOCITY NEGLIGIBLE-CALCULATIONS TERMINATED')
*
C * * COMPUTE CONSTANT TERMS AND INITIALIZE NECESSARY VARIABLES
*
        IMAX=IBAR+2 ; JMAX=JBAR+2
        IM1=IMAX-1  ; JM1=JMAX-1
        RDX=1.0/DELX
        RDY=1.0/DELY
        DELM=DELY/100.
        DELT=1.0
        IM2=IMAX-2
        JM2=JMAX-2
        T=FLG=UEDG1=0.0
        CYCLE=ITER=IND=LDEG=0
        G=9.8 ; OMG=1.7 ; EPSI=.001 ; ALPHA=0.1 ; GAMMA=0.1 ; OZRO=1.0
```

```
      BETA= OMG/(2.*DELT*(RDX**2+RDY**2))
      ICPRT=INT(CWPRT)
      IF(ICPRT.EQ.1) ICPRT=2
      DO 100 I=1,IMAX
      H(I)=HN(I)=JT(I)=GX(I)=GY(I)=FRC(I)=W(I)=0.0
      DO 100 J=1,JMAX
  100 U(I,J)=V(I,J)=UN(I,J)=VN(I,J)=P(I,J)=0.0
*
C * * SPECIAL INPUT DATA
*
      READ(105,60)(H(I),I=2,IM1)
      READ(105,60)(HN(I),I=2,IM1)
      READ(105,60)(W(I),I=2,IM1)
      IF(FRK.GT.0.0) GO TO 120
      READ(105,60) (FRC(I),I=2,IM1)
      GO TO 130
  120 DO 125 I=2,IM1
  125 FRC(I)=FRK
  130 CONTINUE
      DO 150 I=2,IM1
      FR(I)=FRC(I)
      SP=HN(I)/DELX
      CP=SQRT(1.0-SP*SP)
      GX(I)=G*SP
  150 GY(I)=-G*CP
      WRITE(108,70)
      WRITE(108,61)(H(I),I=2,IM1)
      WRITE(108,71)
      WRITE(108,61)(HN(I),I=2,IM1)
      WRITE(108,72)
      WRITE(108,61) (FRC(I),I=2,IM1)
      WRITE(108,73)
      WRITE(108,61)(GX(I),I=2,IM1)
      WRITE(108,74)
      WRITE(108,61)(GY(I),I=2,IM1)
      WRITE(108,76)
      WRITE(108,61)(W(I),I=2,IM1)
      WRITE(108,75)
      DO 240 I=2,IM1
      JT(I)=INT(H(I)*RDY+1.E-6)+2
      IF(JT(I).GT.JM1) JT(I)=JM1
  240 HN(I)=0.0
      H(1)= H(2)
      W(1)=W(2)
      H(IMAX)= H(IM1)
      JT(1)= JT(2)
      JT(IMAX)= JT(IM1)
*
C * * CALCULATE HYDROSTATIC PRESSURE
*
      DO 280 I=2,IM1
      JT1=JT(I)
      DO 280 J=2,JT1
  280 P(I,J)=-GY(I)*(H(I)-(FLOAT(J)-1.5)*DELY)
      ASSIGN 4100 TO KRET
      GO TO 2000
*
C * * START CYCLE
*
 1000 CONTINUE
      ITER=0
      FLG=1.
      ASSIGN 3000 TO KRET
*
```

```
C * * COMPUTE TEMPORARY U AND V
*
      DO 1100 I=2,IM1
      JT1=JT(I)
      DO 1100 J=2,JT1
      FUX=((UN(I,J)+UN(I+1,J))*(UN(I,J)+UN(I+1,J))+ALPHA*ABS(UN(I,J)+UN(
     1I+1,J))*(UN(I,J)-UN(I+1,J))-(UN(I-1,J)+UN(I,J))*(UN(I-1,J)+UN(I,J)
     2)-ALPHA*ABS(UN(I-1,J)+UN(I,J))*(UN(I-1,J)-UN(I,J)))/(4.*DELX)
      FUY=((VN(I,J)+VN(I+1,J))*(UN(I,J)+UN(I,J+1))
     1+ALPHA*ABS(VN(I,J)+VN(I+1,J))*(UN(I,J)-UN(I,J+1))
     2-(VN(I,J-1)+VN(I+1,J-1))*(UN(I,J-1)+UN(I,J))
     3-ALPHA*ABS(VN(I,J-1)+VN(I+1,J-1))*(UN(I,J-1)-UN(I,J)))/(4.*DELY)
      FVX=((UN(I,J)+UN(I,J+1))*(VN(I,J)+VN(I+1,J))+ALPHA*ABS(UN(I,J)+UN(
     1I,J+1))*(VN(I,J)-VN(I+1,J))-(UN(I-1,J)+UN(I-1,J+1))*(VN(I-1,J)+VN(
     2I,J))-ALPHA*ABS(UN(I-1,J)+UN(I-1,J+1))*(VN(I-1,J)-VN(I,J)))/(4.*DE
     3LX)
      FVY=((VN(I,J)+VN(I,J+1))*(VN(I,J)+VN(I,J+1))+ALPHA*ABS(VN(I,J)+VN
     1(I,J+1))*(VN(I,J)-VN(I,J+1))-(VN(I,J-1)+VN(I,J))*(VN(I,J-1)+VN(I,J
     2))-ALPHA*ABS(VN(I,J-1)+VN(I,J))*(VN(I,J-1)-VN(I,J)))/(4.*DELY)
      VISX= NU*((UN(I+1,J)-2.*UN(I,J)+UN(I-1,J))/DELX**2+
     1          (UN(I,J+1)-2.*UN(I,J)+UN(I,J-1))/DELY**2)
      VISY= NU*((VN(I+1,J)-2.*VN(I,J)+VN(I-1,J))/DELX**2+
     1          (VN(I,J+1)-2.*VN(I,J)+VN(I,J-1))/DELY**2)
      U(I,J)= UN(I,J)+DELT*((P(I,J)-P(I+1,J))*RDX + GX(I)-FUX-FUY+VISX)
 1100 V(I,J)= VN(I,J)+DELT*((P(I,J)-P(I,J+1))*RDY + GY(I)-FVX-FVY+VISY)
*
C * * SET BOUNDARY CONDITIONS
*
 2000 CONTINUE
      HN(1)= HN(2)
      HN(IMAX)=HN(IM1)
      JT(1)=JT(2)
      JT(IMAX)=JT(IM1)
C   LEFT WALL RIGID AND SLIP FREE.
C   RIGHT WALL CONTINUOUS OUTFLOW.
      DO 2200 J=1,JMAX
      U(1,J)=0.0
      V(1,J)=V(2,J)
      IF(ITER.GT.0) GO TO 2200
      U(IM1,J)=U(IM2,J)
      V(IMAX,J)=V(IM1,J)
 2200 CONTINUE
C   TOP WALL CONTINUOUS OUTFLOW.
C   BOTTOM WALL RIGID - WITH FRICTION
      DO 2500 I=1,IMAX
      IF(ITER.GT.0) GO TO 2400
      V(I,JM1)=V(I,JM2)
      U(I,JMAX)=U(I,JM1)
 2400 V(I,1)=0.0
 2500 U(I,1)=U(I,2)*(1.0-2.0*FRC(I))
*
C * * FREE SURFACE BOUNDARY CONDITIONS
*
      DO 2650 I=2,IM1
      JT1=JT(I)
      IF(JT(I+1).LT.JT(I)) U(I,JT1)=U(I,JT1-1)
      V(I,JT1)= V(I,JT1-1)-DELY*RDX*(U(I,JT1)-U(I-1,JT1))
 2650 U(I,JT1+1)= U(I,JT1)
      GO TO KRET,(3000,4100,4280)
 3000 CONTINUE
*
C * * HAS CONVERGENCE BEEN REACHED
*
      IF(FLG.EQ.0.) GO TO 4000
```

```
      ITER=ITER+1
      IF(ITER.LT.500) GO TO 3050
      IF(CYCLE.LT.10) GO TO 4000
      T=1.E+10
      GO TO 4000
 3050 FLG=0.0
*
C * * COMPUTE UPDATED CELL PRESSURE AND VELOCITIES
*
      JB1=2
      DO 3500 I=2,IM1
      JT1=JT(I)
      DO 3500 J=2,JT1
      IF(JT1.EQ.JB1) GO TO 3060
      IF(J.NE.JB1 .AND. J.NE.JT1) GO TO 3200
      IF(J.EQ.JT1) GO TO 3100
      GO TO 3200
 3060 CONTINUE
      F=V(I,J)+DELY*RDX*(U(I,J)-U(I-1,J))
      DFDP=DELT*RDY*(1.0+2.0*DELY**2*RDX**2)
      DELP1=-F/DFDP
 3100 ETA=DELY/(HN(I)-(FLOAT(JT1)-2.5)*DELY)
      DELP=(1.0-ETA)*P(I,JT1-1)-P(I,JT1)
      IF(JB1.EQ.JT1) DELP=0.5*(DELP+DELP1)
      GO TO 3300
 3200 D=RDX*(U(I,J)-U(I-1,J))+RDY*(V(I,J)-V(I,J-1))
      IF(ABS(D/DZRO).GE.EPSI) FLG=1.0
      DELP= -BETA*D
 3300 P(I,J)=P(I,J)+DELP
      U(I,J)=U(I,J)+DELT*RDX*DELP
      U(I-1,J)=U(I-1,J)-DELT*RDX*DELP
      V(I,J)=V(I,J)+DELT*RDY*DELP
 3500 V(I,J-1)=V(I,J-1)-DELT*RDY*DELP
      GO TO 2000
 4000 CONTINUE
*
C * * COMPUTE NEW POSITION FOR TOP SURFACE
*
      DO 4100 I=2,IM1
      JT1=JT(I)
      HV= RDY*(HN(I)-FLOAT(JT1-2)*DELY)
      UAV= 0.5*(U(I-1,JT1) + U(I,JT1))
      H(I)=HN(I)*FVOL1/FVOL+DELT*(HV*V(I,JT1)+(1.0-HV)*V(I,JT1
     1-1)-0.5*RDX*(UAV*HN(I+1)+GAMMA*ABS(UAV)*(HN(I)-HN(I+1))
     2   -UAV*HN(I-1)-GAMMA*ABS(UAV)*(HN(I-1)-HN(I))))
 4100 CONTINUE
*
C * * FIND LEADING AND TRAILING EDGES OF AVALANCHE AND LD. EDGE VELOCITY
*
      LDEG1=LDEG
      I=IM2
 4400 IF(H(I).GT.DELM) GO TO 4500
      I=I-1
      GO TO 4400
 4500 LDEG=I
      I=2
 4600 IF(H(I).GT.DELM) GO TO 4700
      I=I+1
      GO TO 4600
 4700 KTEG=I
      IF(LDEG.EQ.LDEG1) GO TO 4800
      IF(CYCLE.GT.0) UEDG=DELX/TC
      IF(CYCLE.EQ.0) UEDG=5.0
      TC=DELT
```

```
      INFLO=1
      IF(UEDG.GT.UEDG1) UEDG1=UEDG
      DO 4750 I=KTEG,LDEG
 4750 H(I)=H(I)*W(I-1)/W(I)
      GO TO 4910
 4800 TC=TC+DELT
      INFLO=INFLO+1
 4910 CONTINUE
*
C * * CALCULATE CELL IN WHICH SURFACE IS LOCATED AND UPDATE ARRAY
*
      DO 4250 I=2,IM1
      IF(H(I).LT.DELM) H(I)=0.0
      JT(I)=INT(H(I)*RDY+1.0E-6)+2
      IF(JT(I).GT.JM1) JT(I)=JM1
 4250 CONTINUE
      ASSIGN 4280 TO KRET
      GO TO 2000
 4280 CONTINUE
*
C * * CALCULATE TOTAL FLUID VOLUME
*
      FVOL=0.0
      DO 4300 I=KTEG,LDEG
 4300 FVOL=FVOL+H(I)*DELX*W(I)
      IF(CYCLE.EQ.0) FVOL1=FVOL
*
C * * ADVANCE U,V,H ARRAYS.
*
      UMAX=VMAX=0.0
      DO 4900 I=1,IMAX
      DO 4900 J=1,JMAX
      IF(ABS(U(I,J)).GT.1.0E+04) U(I,J)=0.0
      UN(I,J)=U(I,J)
      IF(ABS(V(I,J)).GT.1.0E+04) V(I,J)=0.0
      VN(I,J)=V(I,J)
      IF(ABS(P(I,J)).LT.1.0E-16) P(I,J)=0.0
 4900 HN(I)=H(I)
      DO 4950 I=KTEG,LDEG
      DO 4950 J=2,JM1
      UT=ABS(UN(I,J))
      VT=ABS(VN(I,J))
      IF(UT.GT.UMAX) UMAX=UT
 4950 IF(VT.GT.VMAX) VMAX=VT
*
C * * LIST VELOCITY, PRESSURE, AND SURFACE POSITION
*
 5000   WRITE(108,49) CYCLE,ITER,DELT,T,FVOL,UMAX,UEDG,LDEG
      IF(CYCLE.NE.ICPRT) GO TO 6000
      IF(CYCLE.EQ.ICPRT) GO TO 5030
 5030 ICPRT=ICPRT + INT(CWPRT)
 5060 CONTINUE
      WRITE(108,47)
      DO 5250 I=1,IMAX
      JT1= JT(I)
      JT2=JT1+1
      DO 5250 J=1,JT2
      WRITE(108,48) I,J,U(I,J),V(I,J),P(I,J),H(I),JT1
 5250 CONTINUE
      IF(IND.EQ.2) GO TO 6520
      IF(IND.EQ.3) GO TO 6530
      IF(IND.EQ.4) GO TO 6540
*
C * * RECOMPUTE CONTROL PARAMETERS.
```

```
*
 6000 IF(CYCLE.EQ.0) GO TO 6300
      DTX=DELX/UMAX
      DTY=DELY/VMAX
      DELT=AMIN1(DTX,DTY)/3.0
      IF(ITER.LT.10) DELT=1.5*DELT
      IF(NU-1.E-6.LT.0.0) GO TO 6300
      DET=(DELX*DELY)**2/(2.*NU*(DELX**2+DELY**2))
      IF(DELT.LT.DET) GO TO 6300
      DELT=0.9*DET
 6300 T=T+DELT
      IF(CYCLE.EQ.0) GO TO 6400
      DAX=UMAX*DELT/DELX
      DAY=VMAX*DELT/DELY
      ALPHA=1.35*AMAX1(DAX,DAY)
      IF(ALPHA.GT.1.0) ALPHA=0.95
      GAMMA=ALPHA
      BETA=DMG/(2.*DELT*(RDX**2+RDY**2))
*
C * * TEST FOR PROGRAM TERMINATION.
*
 6400 IF(T.GT.TWFIN) IND=2
      IF(H(IM2).GT.DELM) IND=3
      IF(UEDG.LT.0.05*UEDG1) IND=4
      IF(INFLO.EQ.50) IND=4
      IF(IND.GT.1) GO TO 6500
      IF(CYCLE.LT.3) GO TO 6440
      AA=1.0+20.0*EXP(-1.25*UEDG)
      DO 6430 I=2,IM1
 6430 FRC(I)=AA*FR(I)
 6440 CYCLE=CYCLE+1
      GO TO 1000
 6500 T=T-DELT
      GO TO 5060
 6520 WRITE(108,82)
      GO TO 6600
 6530 WRITE(108,83)
      GO TO 6600
 6540 WRITE(108,84)
 6600 STOP
      END
```

```
01F0:   LANG8232,543   12/20/77   15:17
01F0:   LANG8232,543   12/20/77   15:17
01F0:   LANG8232,543   12/20/77   15:17
01F0:   LANG8232,543   12/20/77   15:17
01F0:   LANG8232,543   12/20/77   15:17
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1F0:	LANG8232,543	12/20/77	15:17
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1F0:	LANG8232,543	12/20/77	15:17
1F0:	LANG8232,543	12/20/77	15:17
1F0:	LANG8232,543	12/20/77	15:17
1F0:	LANG8232,543	12/20/77	15:17
1F0:	LANG8232,543	12/20/77	15:17
1F0:	LANG8232,543	12/20/77	15:17
1F0:	LANG8232,543	12/20/77	15:17
1F0:	LANG8232,543	12/20/77	15:17
1F0:	LANG8232,543	12/20/77	15:17
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1F0:	LANG8232,543	12/20/77	15:17
1F0:	LANG8232,543	12/20/77	15:17

Lang, T. E., K. L. Dawson, and M. Martinelli, Jr. 1978. Numerical simulation of snow avalanche flow. USDA For. Serv., Res. Pap. RM-205, 51 p. Rocky Mt. For. and Range Exp. Stn., For. Serv., U.S. Dep. Agric., Fort Collins, Colo. 80526.

A numerical, finite difference computer program based on the Navier-Stokes equations is modified to give avalanche runout distance, velocity of the leading edge of the avalanche, and depth of debris in the runout zone. The program requires a longitudinal profile of the avalanche path, thickness of the snow in the starting zone, and two friction coefficients. Kineomatic viscosity (or coefficient of internal friction) is expressed as an average for the entire avalanche path. Slope inclinations and coefficient of surface friction can be varied for every 10- to 20-m increment of the avalanche path. The program can be modified to allow for variable width of flow and for snow entrainment during flow. In test cases, the program predicted results consistent with observations for a number of avalanche events.

Keywords: Avalanche, avalanche runout distance, simulation modeling, avalanche dynamics.

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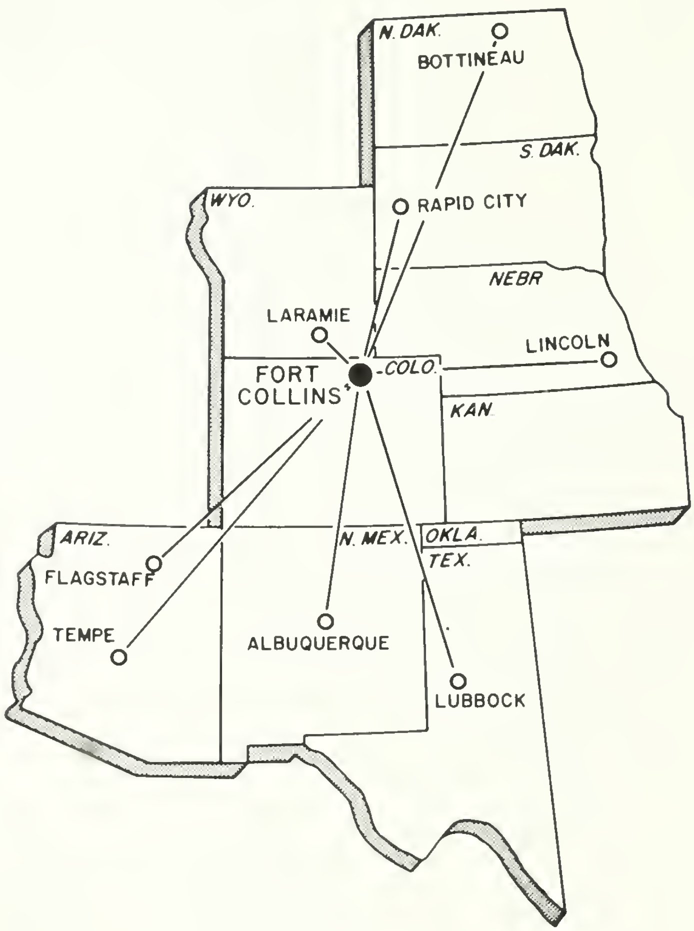
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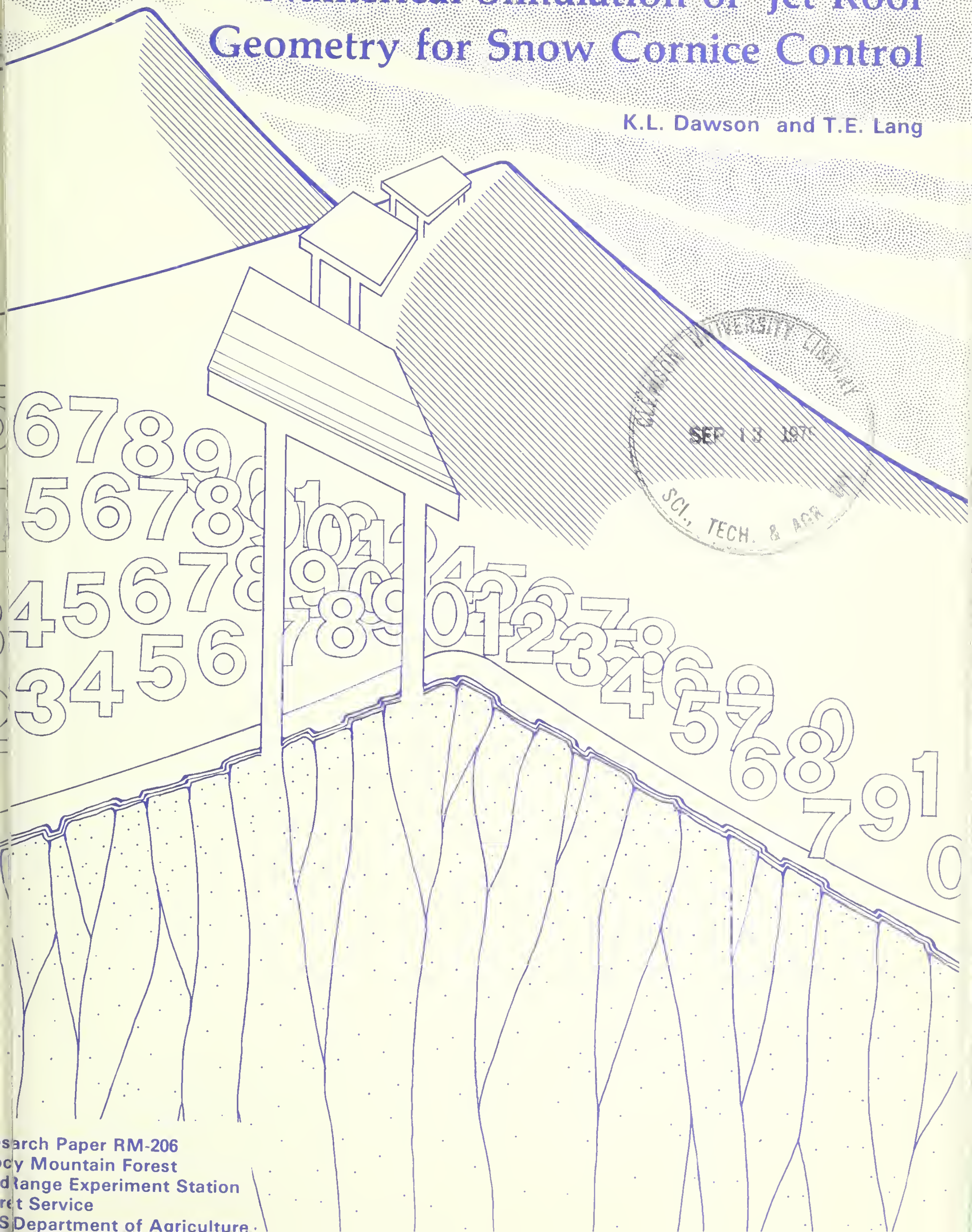
Numerical Simulation of Jet Roof Geometry for Snow Cornice Control

K.L. Dawson and T.E. Lang



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Abstract

A numerical solution algorithm is used to study the air flow over a mountain ridge with and without a jet roof located near the ridge crest. For the simple ridge geometry studied the roof should be parallel to the lee slope, the leading edge of the roof should be at or near the ridge crest, and the height of the leading edge above ground should be about the same dimension as the roof length from leading edge to trailing edge.

Research Paper RM-206 March 1979

Numerical Simulation of Jet Roof Geometry for Snow Cornice Control[1]

K.L. Dawson, Graduate Student[2]
Montana State University

T.E. Lang, Professor
Montana State University

[1]This research was conducted under Cooperative Agreement 16-627-CA between the Rocky Mountain Forest and Range Experiment Station, with central headquarters maintained at Fort Collins, in cooperation with Colorado State University, and Montana State University, Bozeman.

[2]Current affiliation: Research Engineer, Boeing Aircraft Company, Seattle, Wash.

Contents

Numerical Simulation of Jet Roof Geometry for Snow Cornice Control[1]

K.L. Dawson and T.E. Lang

Management Implications

In many areas, snow cornices and the snow cushion" that often forms downslope from them resent serious safety problems. Snow avalanches riggered by falling cornice blocks or by failure in the now cushion are common on such slopes. Strategic lacement of a simple wind deflector, called a jet oof, at the ridge crest will often alleviate the problem by deflecting the wind down the lee slope and reventing or reducing the formation of the cornice nd changing the snow deposition pattern on the lope. This paper gives information regarding the ocation and shape of such structures based on a omputer program modeling of wind flow patterns ver the ridge.

Introduction

In this report, we consider the flow of air and snow ver a simplified mountain ridge and the resulting accumulation and dispersion of snow on the downwind lope. The snow cornice (fig. 1) and its closely ssociated, downslope snow cushion often are important factors in avalanche release. Although jet oofs have been used to change the air flow and snow eposition patterns to try to prevent cornice development, no analytical studies have been made of the ptimum size and shape of these roofs.

The objective of the present research is to use a numerical solution algorithm to investigate the flow of air over a mountain ridge with a jet roof situated near the ridge crest (fig. 2). The effect the jet roof has on cornice development and the scoured region produced by the roof are evaluated. A comparison is made between the accumulation effects with and without the jet roof. Also considered is the optimization of the length and angular inclination of the jet roof with respect to the local geometry of the upper part of the lee slope. The uphill or leading edge of the jet roof is positioned relative to the crestline of the ridge, so that well defined flow is established above and beneath the roof surface, and roof angle and length are optimized. Then, using the optimum length-angle configuration of the roof, position of the roof on the slope is varied to assess its position effect on the flow.

The flow model that is used in the computer simulation is that of a laminar, rotational (or viscuous) fluid in two dimensions. In using a laminar flow model, it is assumed that steadiness of the flow is a more dominant characteristic in establishing scour and stagnation regions than possible turbulence of the flow.

This paper is intended to illustrate an analytical method for studying cornice control without getting into the specifics of particular ridge geometries.

igure 1.—A snow cornice formed where the wind decreases in the lee of a flat-topped ridge. Winds blow from right to left.

Figure 2.—A jet roof located above the lee slope. Winds trapped between the roof and the terrain are accelerated enough to prevent cornice formation.

Methodology

Since the jet roof problem involves the flow of a snow-air mixtuie at relatively low velocities, fluid flow is assumed incompressible. Therefore, the time-dependent fluid flow of the jet roof problem can be mathematically modeled using numerical techniques. A numerical solution algorithm (SOLA) for laminar, transient incompressible fluid flows, developed by Hirt et al. (1975), treats the problem of viscous and inviscid fluid flows in problems involving confined regions (SOLA), as well as free surfaces (SOLA-SURF). Program SOLA-SURF and its extension to admit free surfaces and curved rigid boundaries is used exclusiveley in the investigation of the jet-roof problem.

Equations of Motion

The mathematical techniques used in the SOLA-SURF code are identical to those utilized in the well-known Marker-And-Cell (MAC) method (Harlow et al. 1966). The technique uses a finite difference formulation in a two-dimensional Eulerian vector space in which the motion of the fluid particles is studied as they pass through a fixed coordinated system. The primary dependent variables are pressure and velocity.

The equations of motion which must be solved are the Navier-Stokes equations in two-dimensional Cartesian coordinates. These are written as,

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} = -\frac{\partial p}{\partial y} + g_x + \nu \nabla^2 u$$

$$\frac{\partial v}{\partial t} + \frac{\partial uv}{\partial x} + \frac{\partial v^2}{\partial y} = -\frac{\partial p}{\partial y} + g_y + \nu \nabla^2 v \qquad [1]$$

Also, the continuity-of-mass equation must be satisfied and is given by,

$$\underline{\nabla} \cdot \underline{V} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad [2]$$

The x- and y-components of velocity and body acceleration are u and v, and g_x and g_y, respectively. The ratio of pressure to constant density is p, and the constant ν is the coefficient of kinematic viscosity. The Laplacian operator is ∇^2, so that, for example

$$\nabla^2 u = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \qquad [3]$$

The Navier-Stokes equations (eq. [1]) form a relationship between the flux of momentum in a fluid flow and the accelerations and viscous forces applied to the fluid. The continuity-of-mass equation, for an incompressible fluid, simply states that there i to be no net inflow of fluid with respect to time.

Finite Difference Model

The finite difference mesh used to obtain numerical solution to equations [1] and [2] abov consists of a grid of rectangular cells each of width δx and height δy. The arrangement of the finite difference variables u, v, and p in a typical cell locate in the ith column and jth row is shown in figure 3.

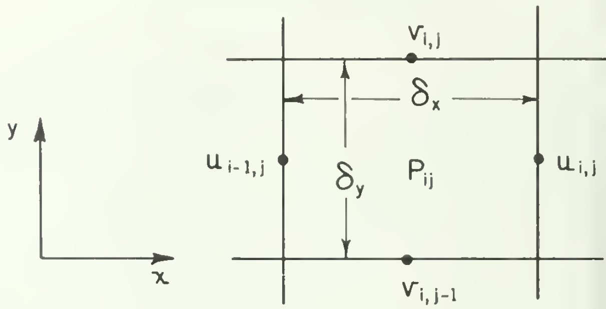


Figure 3.—Finite difference variables u, δ, and p in a typica cell in the ith column and the jth row.

The fluid flow region is divided into a gridwork o cells numbering IBAR in the x-direction and JBAR i the y-direction. The fluid flow region is surrounde by a layer of fictitious cells called phantom or boundary cells. This layer of fictitious cells is necessar when writing the finite difference equations and imposing boundary conditions. The arrangement of the overall finite difference grid is shown in figure 4 wit the boundary cells located around the periphery o the fluid flow region.

Eq. [1] and [2] are given in their finite differenc form by Hirt, et al. (1975). A coefficient, α, is used i the finite difference form of the Navier-Stokes equations to control the amount of upstream or "dono cell" differencing, referring to the amount of convective fluxing of momentum from an upstream cell (i-1,j) to its adjacent downstream cell (i,j). The choice of the parameter α is important when considering the numerical stability of the finite difference equations. The problem of numerical stability in the SOLA-SURF code is discussed in greater detail later.

Since finite differencing of nonlinear partial differential equations is an approximating technique, the velocities predicted by the finite difference form of the Navier-Stokes equations usually will not satisfy the continuity-of-mass equation (eq. [2]). The divergence of a cell, $\underline{\nabla} \cdot \underline{V}$, can be forced to be equal to zero by adjusting iteratively the pressure of a cell so there will be no net inflow or outflow of mass. For example, a negative divergence of a particular cell orresponds to a net flow of mass into the cell, and he cell pressure may be increased to eliminate this inlow. Because an iterative procedure is used to force he divergence of each cell in the computational mesh o zero, a user-specified parameter, ε, must be elected as an acceptable level of accuracy for the cell livergence. The parameter, ε, describes how close to ero we wish to force the cell divergence of equation 2].

oundary Conditions

Four types of boundary conditions are made vailable for use in the SOLA-SURF code. These are

1. Rigid free-slip boundary.
2. Rigid no-slip boundary.
3. Continuative boundary.
4. Periodic boundary.

Only the first and third are needed when modeling he jet roof problem. Consider the free-slip boundlary condition for the bottom boundary (fig. 4). For he free-slip boundary condition, the normal velocity t the bottom boundary is zero, and the tangential elocity will have no gradient normal to the surface. 'herefore,

$$u_{i,1} = u_{i,2}$$

$$v_{i,1} = 0$$

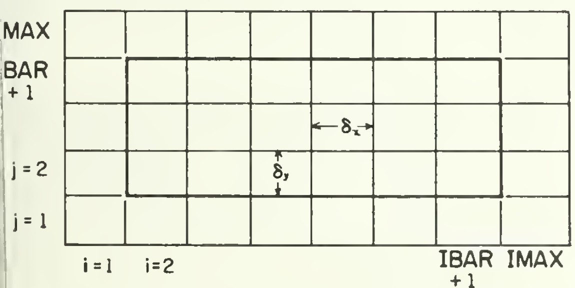
or all i.

Consider the continuative boundary condition at he right boundary (fig. 4). It is desirable to specify a ontinuative outflow condition at this boundary so hat there will be a minimum effect on the flow ›receding the boundary. We then write

$$u_{IM1,j} = u_{IM2,j}$$

$$v_{IMAX,j} = v_{IM1,j}$$

or all j, IM1 = IMAX-1, and IM2 = IMAX-2.



gure 4.—Finite difference grid arrangement and nomenclature.

Two other boundary conditions are introduced in ıe SOLA-SURF code, and are applied when updating the configuration of free surfaces or adjusting velocities at rigid boundaries. At a free surface, the pressure must be zero. At a no-slip, rigid boundary, the velocity parallel to the boundary is zero. A detailed discussion of these boundary conditions and the updating of free surface configurations is given in Hirt et al. 1975.

Numerical Stability

When performing numerical computations, the problem of numerical instability becomes extremely important. Instability arises when variables calculated from finite difference equations develop large, uncontrolled oscillations about a solution as the computations proceed. Generally, these oscillations lead to an exponentially growing instability. A finite difference equation, especially one that is written from a nonlinear differential equation, may yield an oscillating and growing solution that does not resemble the expected solution.

The solution algorithm used to consider the jet roof problem solves the nonlinear Navier-Stokes equations numerically. To maintain numerical stability of the finite difference form of these equations, care must be exercised in selecting the cell width, δx, and height, δy, by time increment, δt, and the donor cell differencing parameter, α, discussed previously.

The mesh increments, δx and δy, must be small enough to have acceptable spatial resolution to handle variations in all of the dependent variables (velocity, pressure, and free-surface height). Experience is a valuable asset when selecting values of δx and δy. Limits placed on the allowable computing time or available memory place restrictions on how small the mesh increments may be. However, if the mesh increments are too large, the accuracy of the results may be questionable.

The selection of the time increment, δt, is governed by two restrictions, both in the form of inequalities. The first is that fluid cannot flow through more than one cell in one time step. This is because the finite difference equations are written so that mass is exchanged between adjacent cells only in a single time step. Therefore, the time increment, δt, must satisfy the inequality,

$$\delta t < \min \left\{ \frac{\delta x}{|u|}, \frac{\delta y}{|v|} \right\} \qquad [4]$$

Usually, δt is chosen to be ⅓ to ½ of the minimum cell transition time predicted by equation [4]. The second restriction is used when the kinematic viscosity ν is nonzero. In this case, momentum cannot pass through more than one cell in one time step. It can be shown that this restriction implies that

$$\nu \delta t < \frac{1}{2} \quad \frac{\delta x^2 \delta y^2}{\delta x^2 + \delta y^2} \qquad [5]$$

Finally, the first restriction is used to predict a value for the upstream differencing parameter, α. This being the case, α is given by the inequality

$$1 \geqslant \alpha > \max \left\{ \left| \frac{u \delta t}{\delta x} \right| \quad \left| \frac{v \delta t}{\delta y} \right| \right\} \qquad [6]$$

Usually, α is taken to be 1.2 to 1.5 times the right-hand side of equation [6]. When α is taken to be zero, the finite difference equations for the Navier-Stokes equations are space centered and are numerically unstable, unless some nonzero value of kinematic viscosity, ν, is specified (Hirt 1968). When α is taken equal to 1.0, the finite difference equations reduce to the full donor cell form. These equations are stable, provided the restriction of equation [4] is satisfied.

The three inequalities given by equations [4], [5], and [6] have been added to the SOLA-SURF code, so that time, t, will be incremented automatically with the proper value of the time increment, δt, being computed each cycle. The upstream differencing parameter, α, is also adjusted accordingly. These modifications to the time advance section of the code ensure numerical stability, as far as the two restrictions placed on the flow of mass and momentum through cells are concerned. However, other problems regarding numerical instability arise when modeling the jet roof problem. These are discussed later.

Additionally, the SOLA-SURF code, which contains the options for free and curved rigid surfaces, imposes two other conditions in order to assure stability of the finite difference equations. First, the free or curved rigid surfaces, which are initially defined by the user, must remain single-valued functions $y=y(x,t)$ for all time. The second restriction is that the cell aspect ratio, $\delta y/\delta x$, may not exceed the slope of either the top or bottom surface.

The Jet Roof Problem and Its Mathematical Model

Mathematical Model

A finite difference grid is constructed in the local flow region using a two-dimensional rectangular Cartesian coordinate system. A number of simplifying refinements are made on how the jet roof flow problem is modeled to make the most effective and economic use of computer storage space and problem running time. These modifications are described below.

For simplicity, the mountain ridge geometry considered has a 45° inclination to either side of the crest (fig. 5). This simplification, although not normally physically realistic, allows the use of equal mesh increments, δx and δy which tends to speed up the convergence of the calculations, particularly during flow initiation. This simple geometry is used also to gain insight into the way flow patterns of the continuum change with respect to time when flowing past a projecting obstacle such as a mountain ridge. To represent the mountain, velocities in the cells occupied by the mountain are set equal to zero for all time in a section of the code set aside for special boundary conditions. Additionally, since the magnitude and direction of the corresponding velocity vectors for each cell are computed, these are also set equal to zero on each iteration for those cells occupied by the mountain. The same procedure is used to "zero-out" those cells occupied by the jet roof. The inclusion of both the upwind and downwind slopes in the finite difference model gives an overall picture of the development of flow patterns across the ridge. A velocity-vector plot showing the development of the flow for the "full-ridge" model is shown in figure 6.

From the results of figure 6, note that directly above the apex (or ridge crest) the velocity vectors are horizontal, as would be expected in laminar steady flow. This implies that the upwind geometry of the mountain has no influence on the flow pattern from the ridge crest downstream past the jet roof. Thus, the geometry of the mountain can be of any slope from horizontal to any angle (45° in fig. 6), and the results of the flow study past the jet roof will be the same. From the standpoint of flow continuity, upwind geometry of the mountain will affect the magnitude of the flow velocity at the ridge crest; however, in the present study this velocity is set at 20 m/s as a typical value.

The independence of solution of flow past the jet roof from upwind mountain geometry is further exemplified in a second refinement of simply shifting the ridge crest to the left-hand boundary, so that only the downwind portion of the ridge remains in the grid.

The primary advantage of this modification is a savings in computer storage space and program run time. The modifications to the code for this type of slope configuration are straightforward. The development of the flow for this "half-ridge" flow model and a jet roof length of 3.5 m is given in figure 7.

An additional refinement made to the finite difference model allows a closer look at the flow in the immediate vicinity of the jet roof. This modified form of the flow model yields a magnified view of the flow under and downslope from the jet roof, and is

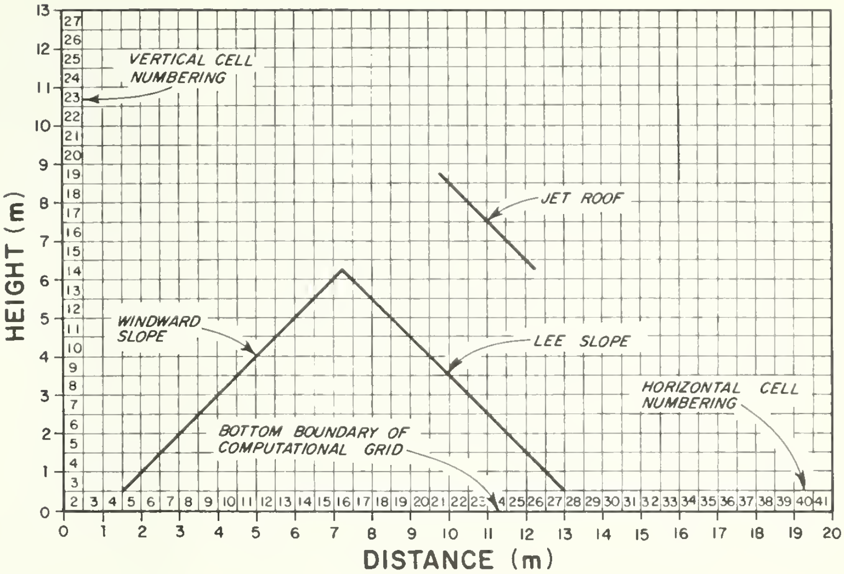
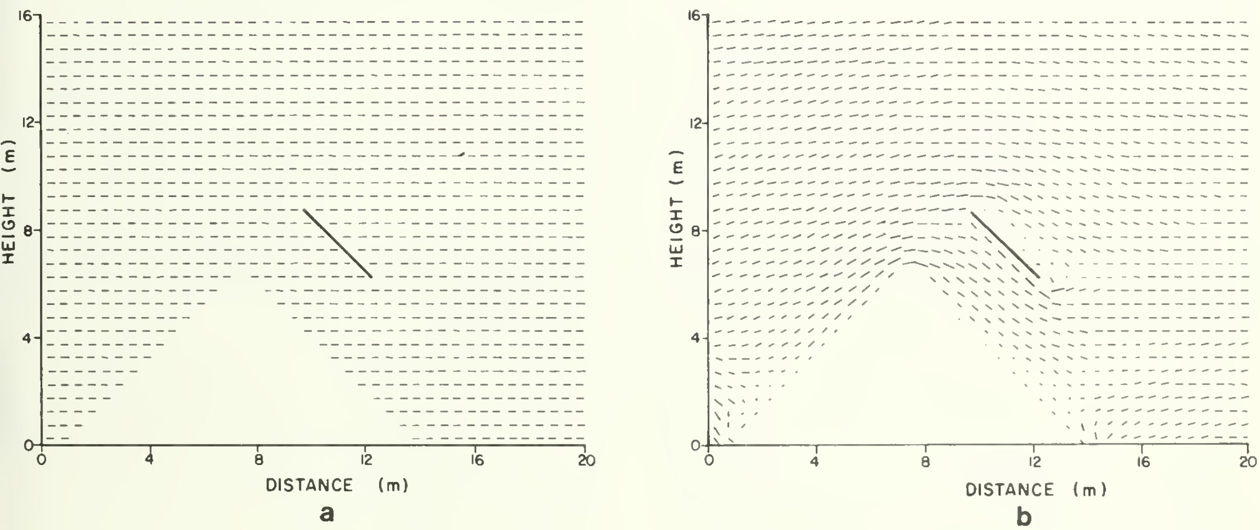


Figure 5.—Jet roof initial model (full ridge).



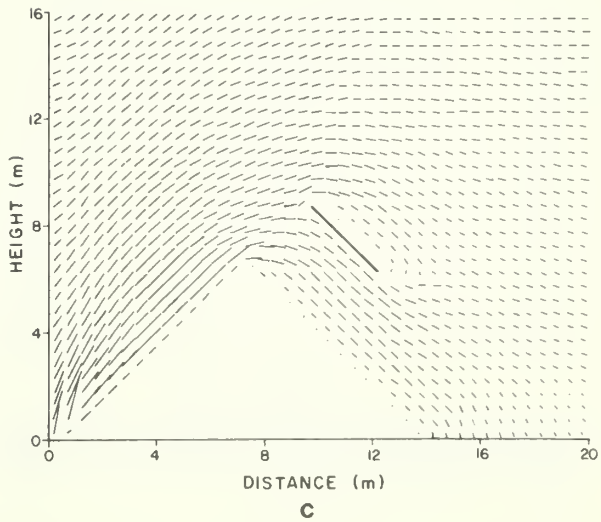


Figure 6.—Development of flow field for the full ridge model with a slope-parallel jet roof, 3.5-m characteristic length.
a. Cycle 0.
b. Cycle 1.
c. Cycle 20.

used to optimize the length and angular inclination of the jet roof. The modification involved requires a rotation of the mountain ridge through an angle within the grid such that the downwind slope is coincident with the bottom boundary of the mesh. The actual ridge crest coincides with the lower left corner of the mesh, so that only the jet roof itself is present within the grid. This final modification is shown in figure 8. For reference purposes, the development of the flow pattern in the "no-ridge model" without a jet roof is given in figure 9.

Required modifications to the SOLA-SURF code are in the sections for specifying and setting boundary conditions (2000 and 2600 sections). In the two previous models, a continuative flow boundary is specified at all boundaries, and a continuous inflow

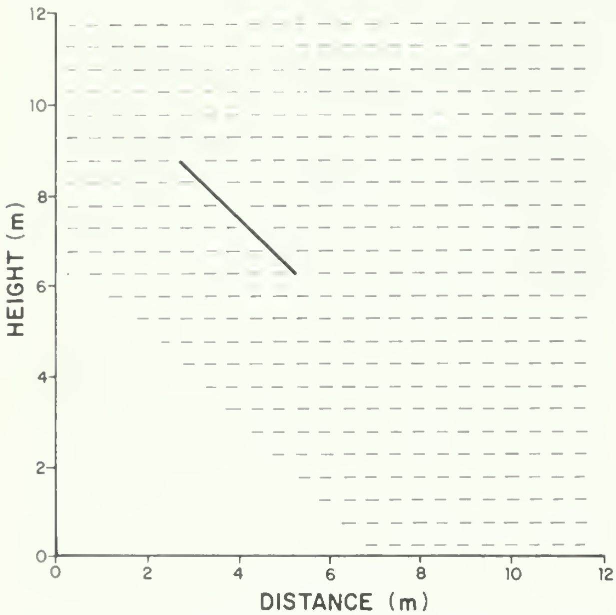


Figure 7a.—Development of flow field for the half ridge model with a slope-parallel jet roof, 3.5-m characteristic length, cycle 0.

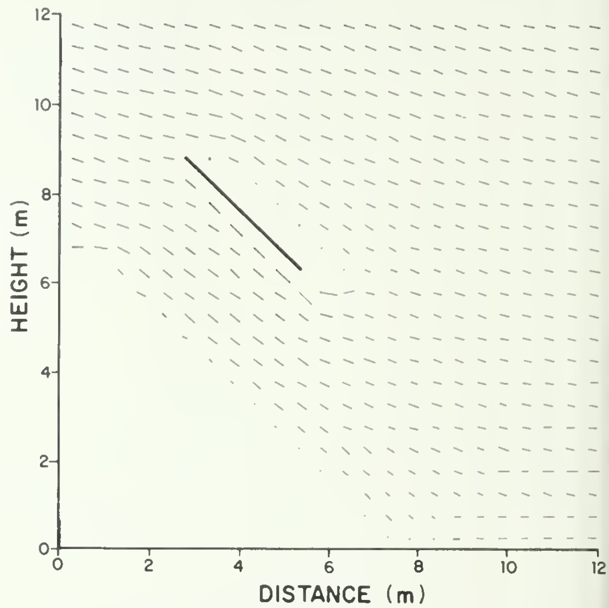


Figure 7b.—Development of flow field for the half ridge model with a slope-parallel jet roof, 3.5-m characteristic length, cycle 1.

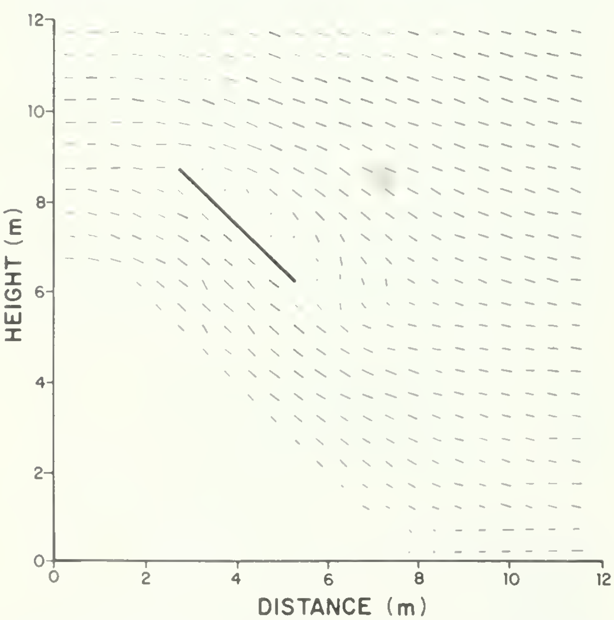


Figure 7c.—Development of flow field for the half ridge model with a slope-parallel jet roof, 3.5-m characteristic length, cycle 20.

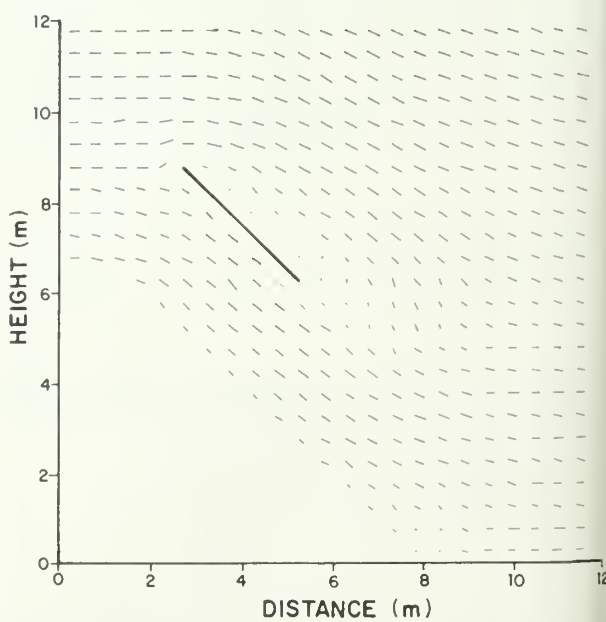
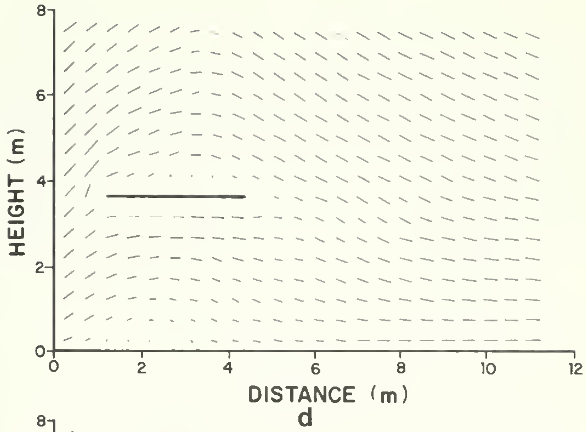


Figure 7d.—Development of flow field for the half ridge model with a slope-parallel jet roof, 3.5-m characteristic length, cycle 40.

Figure 8.—Development of flow field for the no-ridge model with a slope-parallel jet roof, 3.5-m characteristic length.
a. Cycle 0.
b. Cycle 1.
c. Cycle 20.
d. Cycle 40.
e. Cycle 60.
f. Cycle 80.
g. Cycle 100.



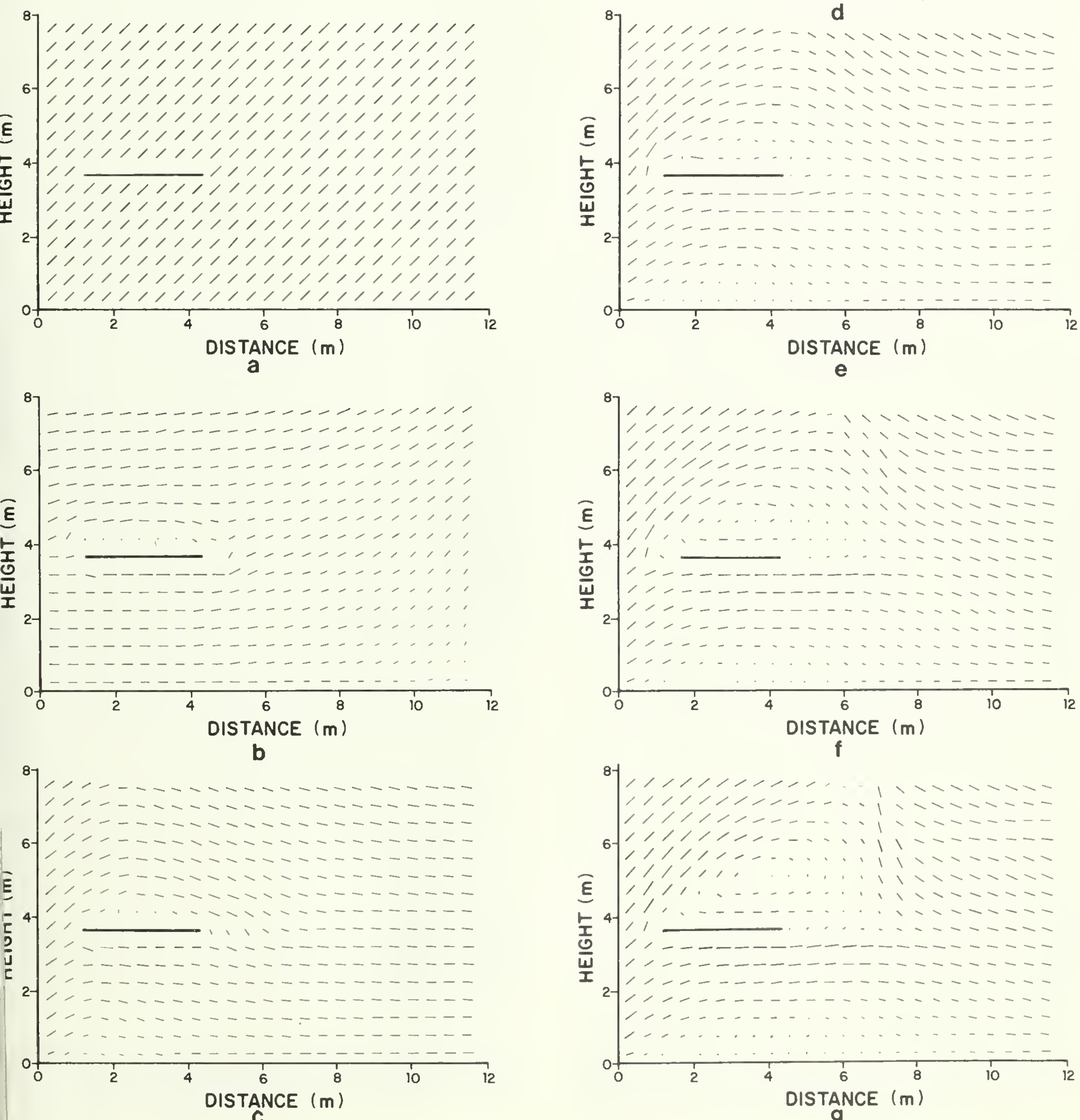
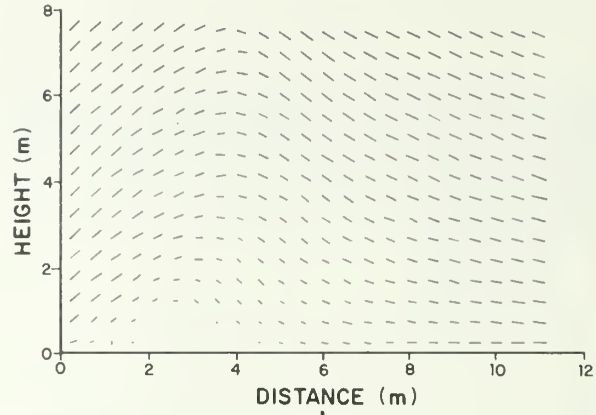
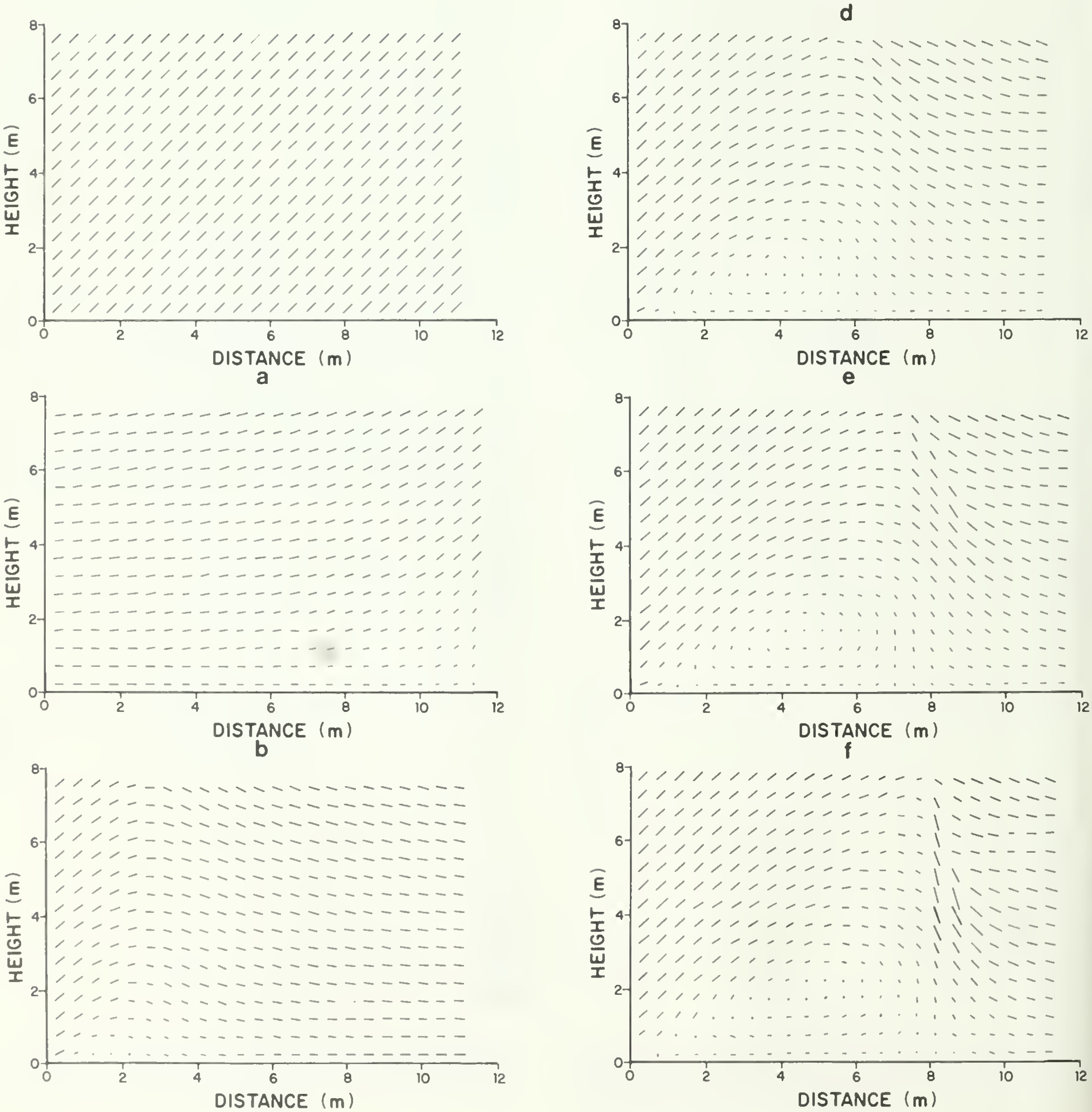


Figure 9.—Development of flow field in absence of a jet roof.
a. Cycle 0.
b. Cycle 1.
c. Cycle 20.
d. Cycle 40.
e. Cycle 60.
f. Cycle 80.
g. Cycle 100.





of fluid is specified along the left boundary. Whereas the full- and half-ridge peak models have only a u-component of velocity, UI, initially (VI = 0.0), and only a u-component of velocity specified in the continuous inflow condition along the left boundary, the "no-ridge" model has two components of velocity, UI and VI, specified initially along the left boundary. These velocities are functions of the angle through which the downwind slope is rotated, so that it will become coincident with the bottom of the mesh in the manner of figure 8. The primary advantages to this model are a savings in memory storage space requirements and program run-time, and the fact that we can make use of a more finely resolved grid (corresponding to selecting smaller mesh increments) for use in optimizing the angular inclination of the jet roof. A velocity vector plot showing the development of the flow is shown in figure 8.

The reason for using the modified flow model of figure 8 lies in the fact that dynamic similarity in the flows is noted between the full-, half-, and no-ridge[3] models, particularly in the location and magnitude of recirculating eddies and stagnation flow patterns.

Jet Roof Optimization

The characteristic length, angular inclination (relative to the downwind slope surface) and position on the slope of the jet roof are optimized so as to minimize the accumulation of snow in the vicinity of the jet roof and to have the greatest effect on maximizing the "scour region" along the slope.

Optimum length is that for which the least possible amount of stagnation exists underneath the roof and just beyond the trailing edge when the jet roof is parallel to the downwind slope. Stagnation occurs when the air flow comes to rest in isolated localities within the grid during the development of the flow patterns. In the areas of stagnation, a settling and resulting accumulation of snow is expected.

The development of regions of stagnation is usually noted on plots of the flow field as localized areas with low fluid velocities near the slope surface or in the form of recirculating eddies above and beyond the trailing edge of the jet roof.

The following notation is used in the JETROOF code to denote the location of the leading and trailing edge of the jet roof:

ILE = i index of the cell containing the leading edge
JLE = j index of the cell containing the leading edge
ITE = i index of the cell containing the trailing edge
JTE = j index of the cell containing the trailing edge

[3]Printouts of the full-ridge and no-ridge models are available upon request from the USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, 240 W. Prospect Street, Fort Collins, Colo. 80526.

The first criterion of optimization establishes a relationship between the velocity gradients between the slope surface and the jet roof at the leading and trailing edges. This relationship is described physically as how the ratio of the average velocity between the slope surface and the jet roof at the leading and trailing edges is changing with respect to time. This ratio is written in terms of the leading and trailing edge velocities at some t, as

$$\text{VELRA1} = \frac{\dfrac{1}{\text{JLE-2}} \sum_{j=2}^{\text{JLE-1}} [(u(\text{ILE}, j))^2+(v(\text{ILE}, j))^2]^{1/2}}{\dfrac{1}{\text{JTE-2}} \sum_{j=2}^{\text{JTE-1}} [(u(\text{ITE}, j))^2+(v(\text{ITE}, j))^2]^{1/2}} \qquad [7]$$

The development of the velocity ratio, VELRA1, as a function of time for a variety of slope-parallel jet roof lengths at a height of approximately 3.75 m above the slope surface are shown in figure 10. The plot for the 1.0-m jet roof length is the limiting case for the mesh increments selected (DELX = DELY = 0.5m). Figure 10 indicates that the flow transients under the jet roof decay rapidly at low real times. As a result the jet roof is an efficient device for control of air flows since the initial transients decay rapidly. The curves of figure 9 are generated from time and velocity ratio data computed up to cycle 100 at program termination. For exact steady-state flow prediction, computations beyond cycle 100 are necessary.

In view of the previous definition of the optimum jet roof length, the effect which the jet roof length has on the flow downslope from the trailing edge must also be considered. Figure 11 shows the development of the flow a distance downslope from the trailing edge (the "recovery distance") equal to the characteristic length of the jet roof, and indicates how the flow recovers from the effects of the jet roof at that distance. The velocity ratio, VELRA2, is plotted as a function of time, where VELRA2 is the ratio of the average velocities between the slope surface and trailing edge and at the same height at the recovery distance. The velocity ratio, VELRA2, is computed in a manner analogous to that of the first velocity ratio, VELRA1, given by equation [7].

Ideally, the transition from transient to steady flow conditions should occur in minimal time. The velocity ratio, VELRA1, should converge to a value which is relatively close to unity, which indicates approximately equal velocities at the leading and trailing edges of the jet roof. Plots of the velocity vector field show that there is a definite relationship between the velocity ratio, VELRA1, the height and position of stagnation under the jet roof, and the characteristic length of the roof. Following a similar argument, it is also desirable that the recovery distance velocity ratio, VELRA2, converge to a constant value as quickly as possible after the flow begins. The steady-state value of VELRA2 should be greater than that of VELRA1, for effective scouring, but still in the vicinity of unity. This indicates a state of flow in which the velocities at the beginning of the recovery distance are somewhat greater than those at the end of the recovery distance. This condition minimizes the accumulation of snow at the trailing edge of the jet roof and effectively maintains the desired scouring action throughout the recovery distance. The velocity vector plots show that a continuous flow is present throughout the recovery distance. Considering all of these criteria, a choice of

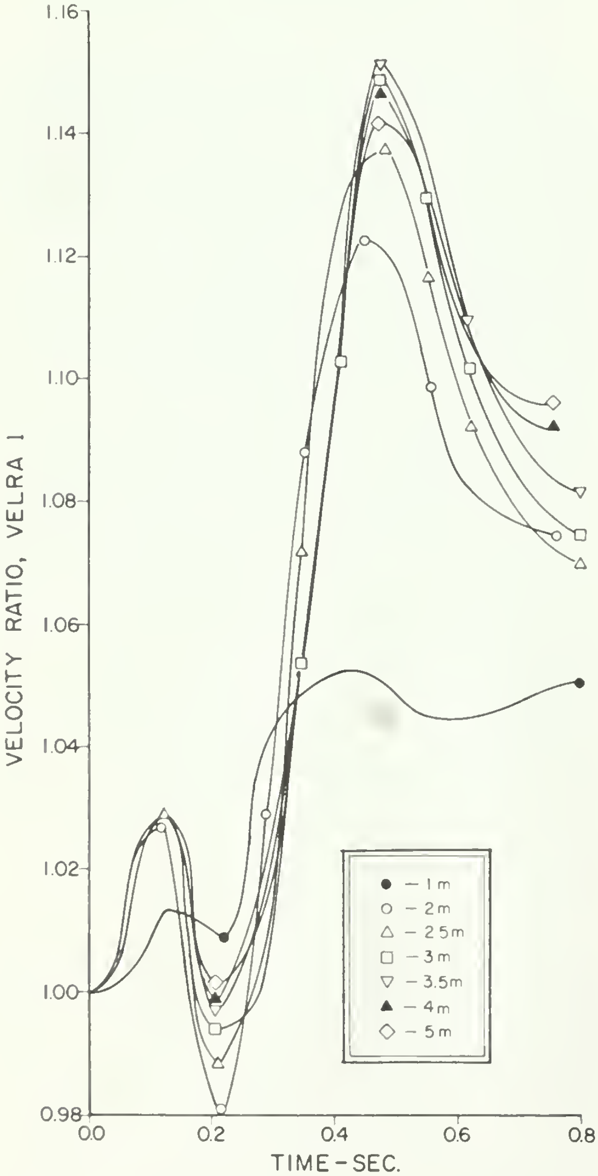


Figure 10.—Ratio of average trailing edge to recovery distance velocities for the jet roof parallel to surface.

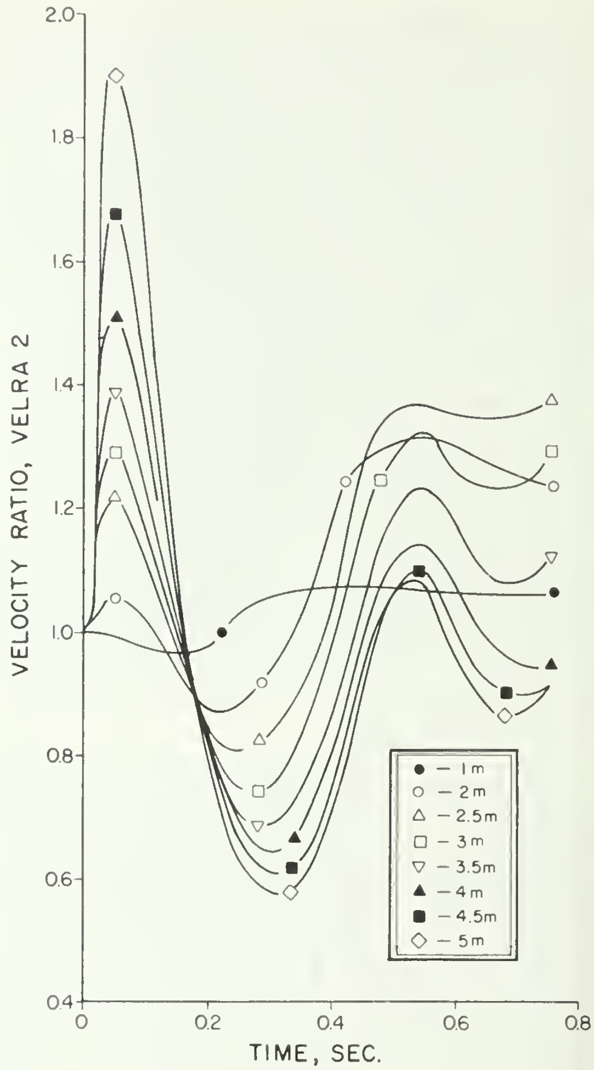


Figure 11.—Ratio of average trailing edge to recovery distance velocities for the jet roof parallel to surface.

a jet roof length of 3.0 m appears to be optimum (figs. 10, 11).

The development of the flow field for a slope-parallel jet roof 3.0 m long, as shown in figure 12, indicates a region of stagnation approximately 1.0 m high and 4.0 m long under the jet roof. A variety of runs using slope-parallel jet roofs varying in length from 1.0 m to 5.0 m show that the length of the stagnation region is less sensitive to jet roof length variations than is the height of the region. Within constraints of the finite difference model, stagnation height can be reduced by positioning the jet roof closer to the surface.

In initial studies using coarser mesh increments of DELX = DELY = 1.0 m, the stagnation under the jet roof could be eliminated by positioning the roof closer to the surface. However, this does not represent the true physical situation for two reasons. First, most jet roofs now in use are situated parallel to the downwind slope and from 2.44 to 4.27 m above the slope (Montagne et al. 1968). Second, when coarse mesh increments are used, a serious loss of spatial resolution and computational accuracy is noted as the jet roof is moved closer to the slope surface. As fewer cells are maintained between the slope surface and the jet roof, the flow under the roof is forced to assume a nonrotational pattern since there is only one set of spatial variables (two components of velocity and one pressure) per cell.

Consider next the effect that inclining the jet roof has on reducing stagnation under the roof, and on scouring the downslope region. The angular inclination of the jet roof relative to the slope surface is optimized in a manner similar to that of determining the optimum jet roof length. The optimum jet roof inclination is the angular inclination relative to the surface of the downwind slope, which has the greatest effect on reducing the height and length of the region of stagnation.

The inclination of the jet roof is handled as shown in figure 13, in which the velocities of the corresponding cells are set equal to zero. Figure 13 shows a jet roof inclination of $\Phi = -9.5°$ relative to the downwind slope surface. A number of jet roof inclinations were considered including Φ = -45°, -22.6°, -9.5°, -4.8°, 4.8°, 9.5°, 22.6°, and 45°. The values of VELRA1 and VELRA2 are plotted for increasing time in figures 14 and 15 in a manner similar to that for the parallel jet roof in figures 10 and 11, respectively.

Ideally, the velocity ratio plots of figures 14 and 15 for the inclined jet roof will exhibit characteristics similar to those desirable for the slope-parallel jet roof. It is also important to consider the velocity vector plots showing the development of the flow field for jet roofs of both positive and negative inclinations. Jet roofs with negative inclinations (inclined downward) have a pronounced effect in reducing the stagnation under the jet roof. Jet roof inclinations which are positive (inclined upward) result in an increased stagnation near the surface toward the trailing edge of the roof. Therefore, an undesirable deposition of snow can be expected to occur in this area. Thus, the jet roof should be inclined downward to have the greatest effect in reducing stagnation under the jet roof and to allow the flow to return to its normal pattern as soon as possible after passing the jet roof.

Additionally, as noted from the velocity vector plots, any inclination of the jet roof causes a large recirculating eddy to be formed just above its trailing edge. As the angle of inclination increases, so does the size of the recirculating eddy. The presence of this recirculating eddy tends to cause two problems. First, snow may be deposited on the trailing edge of the jet roof which will load the structure and change the flow characteristics. Second, the possibility exists of an accumulation further downslope that the flow next to the surface can not eliminate. This snow accumulation is not indicated on the velocity vector plots for the inclined jet roofs examined, but was noted by Montagne et al. 1968 in field experiments using jet roofs erected to control cornice development in the Bridger Range of southwestern Montana.

Using the above discussion as a guideline and considering the velocity ratio plots of figures 14 and 15 and the velocity vector plots for the jet roofs of 3.0 m length and inclined at angles of Φ = -4.8°, -9.5°, -22.6°, -45°, 4.8°, 9.5°, 22.6°, and 45°, respectively, a jet roof which is inclined at an angle of $\Phi = -9.5°$ was selected as the optimized design for which the stagnation region and the recirculating eddy above the trailing edge are both minimal. The development of the flow field for the optimized jet roof (jet roof length = 3.0 m, $\Phi = 9.5°$) is shown in figure 16.

Final consideration is given to placement of the jet roof relative to the ridge of the mountain. Using a jet roof configuration of length 3.0 m and relative slope angle to the lee slope of $\Phi = 0°$, consider four positions of the roof. The four configurations are indicated in figures 17a,b,c,d and will be designated as Cases A,B,C,D, respectively, in the following discussions. The quasi-steady-state flow patterns shown in figure 17 qualitatively depict the properties of the four geometric cases, in which trends in the recirculation and stagnation regions can be defined. To further appraise these cases, the average velocity at the trailing edge of the jet roof, and the volume flow rate per unit width of jet roof are computed and summarized in table 1.

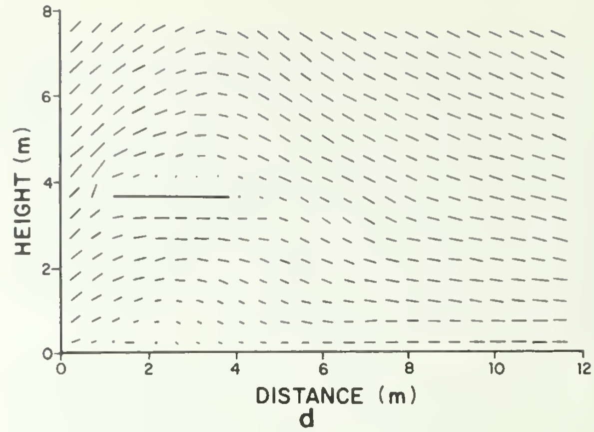
Table 1.—Average velocity and volume flow rate at the vertical cross section at the trailing edge of the jet roof

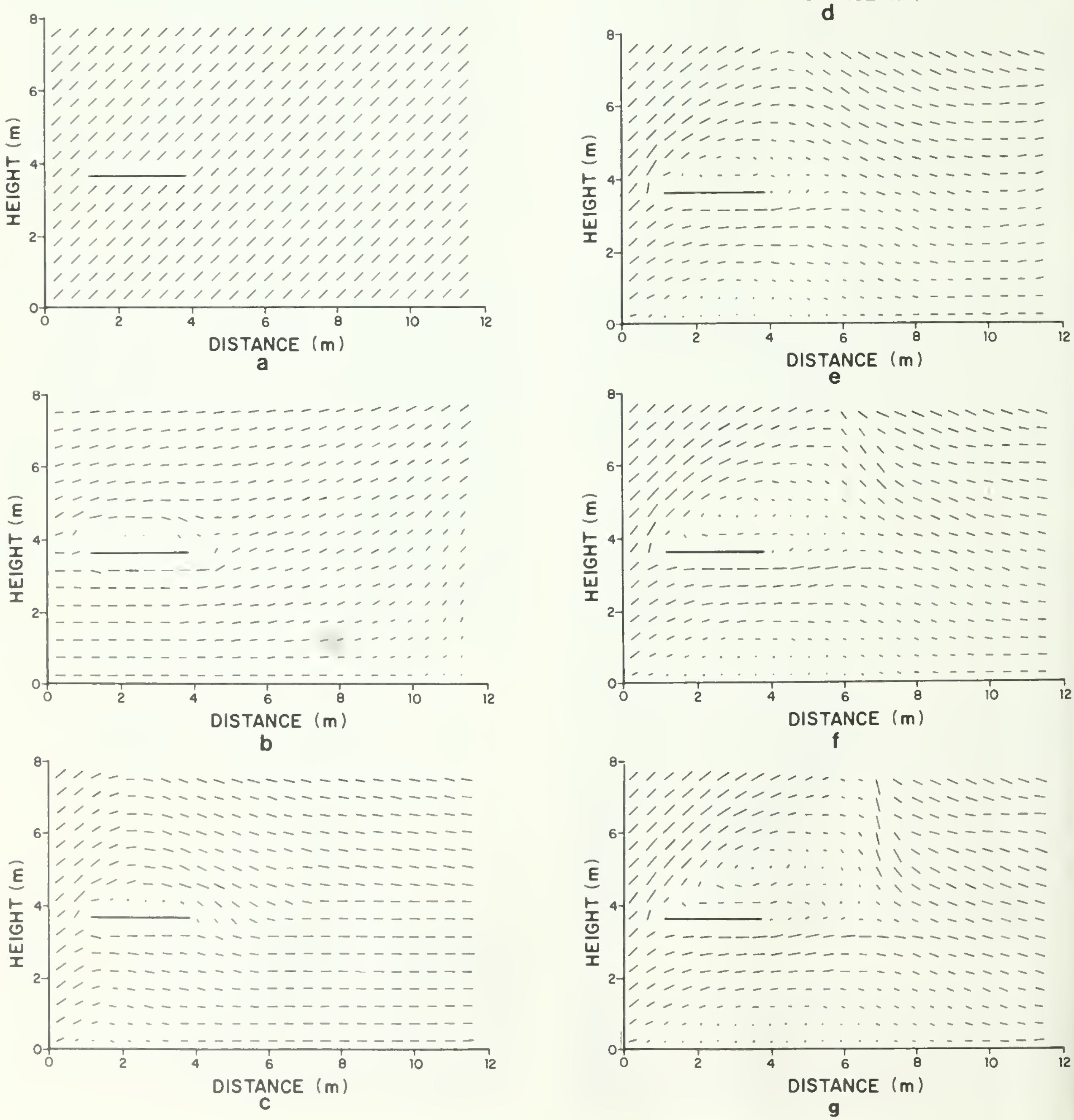
Case	Average Velocity (m/s)	Volume Flow Rate (m^3/s)
A	13.9	48.8
B	18.6	43.3
C	19.9	30.4
D	20.2	15.9

The low average velocity of Case A is one design condition that is conducive to jet roof jamming by excessive snow deposition. In Case D, a second design condition is exemplified of low volume flow rate, a condition for limited scour region effectiveness. Excluding these cases, Cases B and C remain, for which further evaluation is considered in the conclusions section.

Figure 12.—Development of flow field for optimum slope-parallel jet roof, 3.0-m characteristic length.

a. Cycle 0.
b. Cycle 1.
c. Cycle 20.
d. Cycle 40.
e. Cycle 60.
f. Cycle 80.
g. Cycle 100.





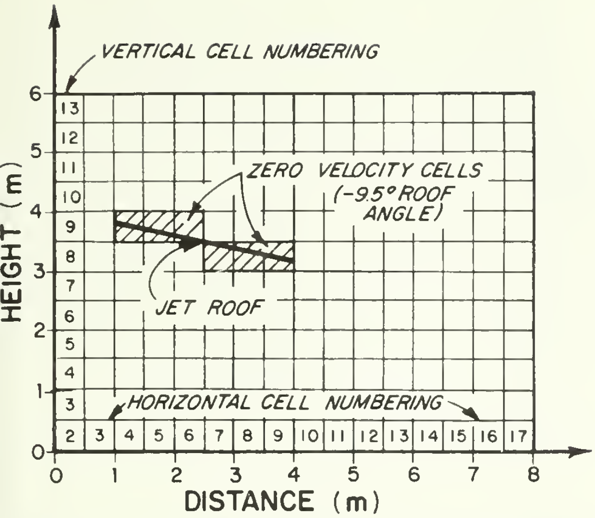


Figure 13.—Jet roof with location of cells for finite difference approximation of jet roof inclination relative to mean slope surface ϕ=-9.5°.

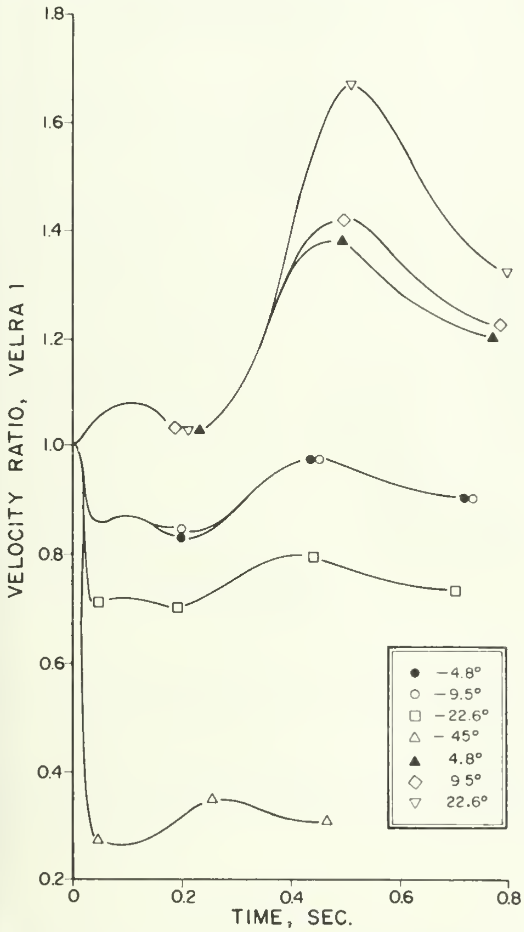


Figure 14.—Ratio of average leading to trailing edge velocities for the jet roof inclined relative to surface, jet roof length = 3.0 meters.

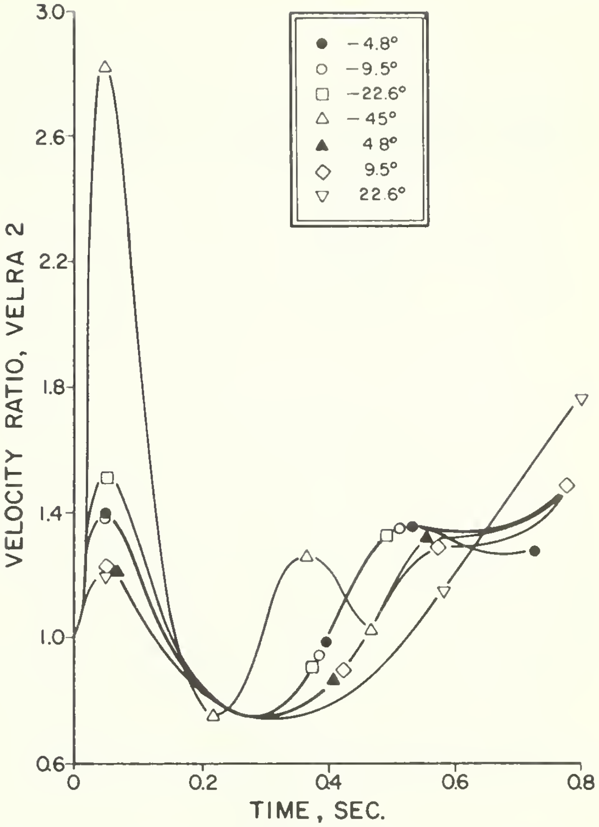


Figure 15.—Ratio of average trailing edge to recovery distance velocities for the jet roof inclined relative to surface, jet roof length = 3.0 meters.

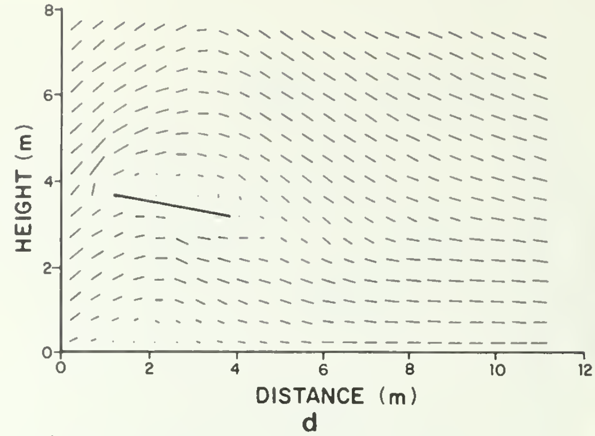
Output data and velocity vector plots for slope-parallel and roof-angle cases not reported herein are reported in a supplemental document that lists these data.[4]

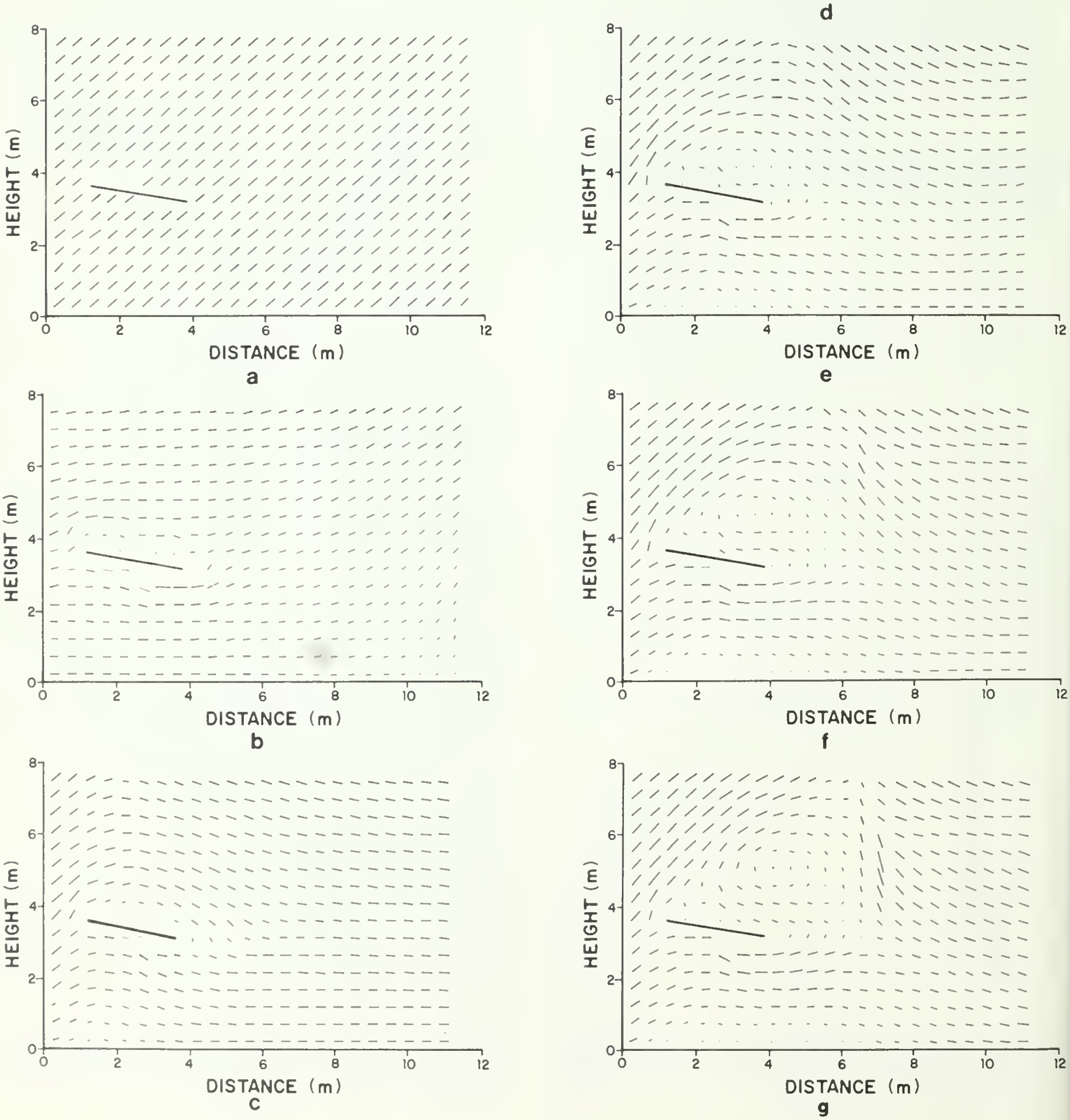
Certain conditions on numerical stability relate to all the jet roof models that have been evaluated. Referring to figure 17, the bottom boundary of the computational grid is specified as a slip-free rigid boundary. In earlier runs with the full-ridge and half-ridge models, a continuative inflow-outflow boundary was specified at the bottom, which did not affect the flow pattern at the jet roof, but resulted in a greater number of iterations for each cycle. Another numerical instability results when the number of cells vertically above the jet roof is reduced to one or two instead of five or more. For, say, two cells above the roof, the recirculation condition may result in adjacent cells having large equal and opposite vertical velocities, which lead to a rapidly developing numerical instability. This condition is eliminated in

[4]*Dawson, K.L. and T.E. Lang. "Listings of flow field plots from numerical simulation of air flow past jet roof geometries for snow cornice control," USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. 80526 (on file).*

Figure 16.—Development of flow field for optimum sloping jet roof, 3.0-m characteristic length, Φ = -9.5°.

a. Cycle 0.
b. Cycle 1.
c. Cycle 20.
d. Cycle 40.
e. Cycle 60.
f. Cycle 80.
g. Cycle 100.





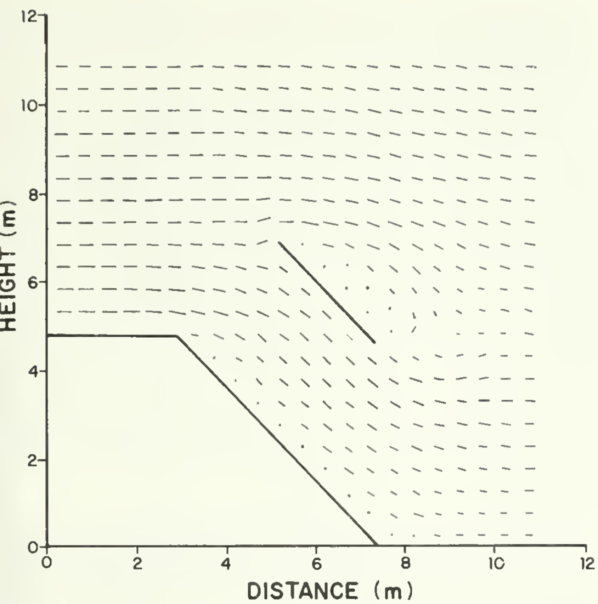


Figure 17a.—SOLA-SURF jet roof with vorticity flow mountain ridge flow, Case A.

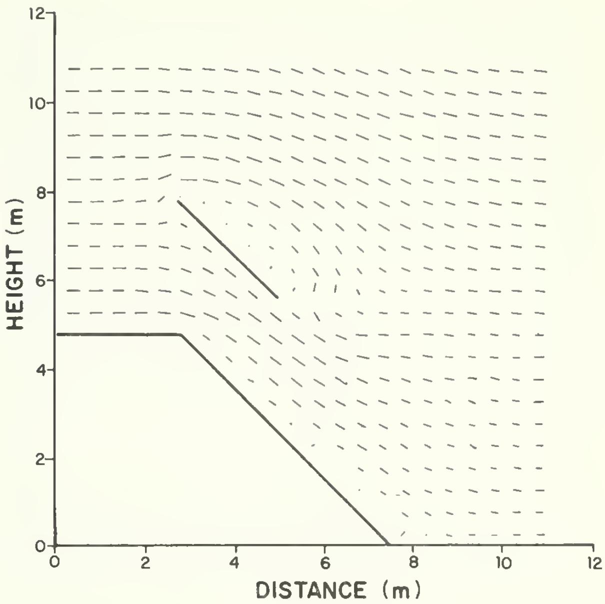


Figure 17b.—SOLA-SURF jet roof with vorticity flow mountain ridge flow, Case B.

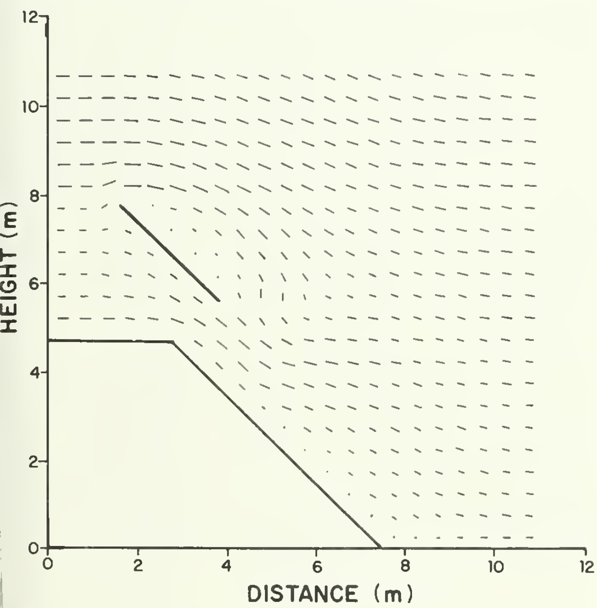


Figure 17c.—SOLA-SURF jet roof with vorticity flow mountain ridge flow, Case C.

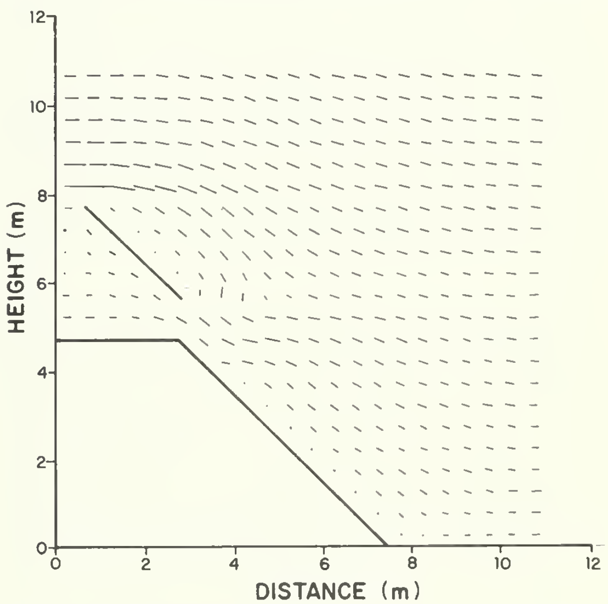


Figure 17d.—SOLA-SURF jet roof with vorticity flow mountain ridge flow, Case D.

xpanding the domain so that five or more cells are ised above the jet roof, depending upon the vertical xtent of the recirculation region.

Conclusions

The use of a jet roof as a flow spoiling device can e a valuable asset in controlling the development of now cornices (Montagne 1968). For a particular ridge geometry, prevailing winds, and fixed roof height, primary variables are the roof length, angular inclination, and roof orientation relative to the ridge in controlling stagnation region and recirculating eddy developments.

The three mathematical models, designated the full-ridge, half-ridge, and no-ridge models, are found to equally represent air flow past a jet roof on the downwind side of a ridge. The no-ridge version is a valid simplification of the other two models as a result of the dynamic similarity of the flow fields between each model. The no-ridge model also represents the most efficient and economic use of the JETROOF code. Additionally, the successive simplifications to the no-ridge model without disturbance to the flow field past the jet roof implies negligible dependence of the flow pattern on upwind geometry of the mountain. Thus, the results obtained are general for any upwind mountain geometry that does not exclude the jet roof from being considered as placed at a ridge. Turbulence, which is likely to be present in actual air flow at a ridge, is considered a secondary effect for steadiness of the flow in defining scour region and stagnation zones.

Considering the plots of the developing flow fields for both the slope-parallel (fig. 12) and inclined (fig. 16) jet roof, note that the characteristic length of the jet roof controls the height of the stagnation region. In contrast, the inclination of the roof controls the length, height and position of the stagnation region. These results are further verified in the summary plots of figures 18, 19, and 20 which show the basic stagnation and eddy regions for the different geometric configurations that have been evaluated. Figure 18 shows the changes as a function of jet roof length for the slope-parallel case. Figures 19 and 20 show the changes as a function of the angular inclination of the 3.0 m length jet roof. It is concluded that changing the length of the jet roof has little effect on the size of the stagnation region, and that angular inclination must be included in any design consideration.

Additionally, the velocity vector plots showing the developing flow fields without a jet roof present indicate that a large clockwise recirculating eddy is formed just downslope from the ridge (fig. 9). When a jet roof is introduced, the recirculation is located just above the trailing edge of the roof. The characteristic length of the jet roof affects the location of the recirculaton, whereas the angular inclination controls its size (compare figs. 18, 19, and 20). It is desirable to minimize the size of the recirculating eddy because of the possibility of deposition of snow on the trailing edge of the jet roof. Figure 20 indicates that any positive inclination of the jet roof is undesirable because it results in the formation of an enlarged stagnation region under the roof. Conversely, a negative inclination of the jet roof has a pronounced effect on reducing the stagnation under the roof (fig. 19).

An inclination angle of $\Phi = -45°$ (fig. 19) results in the smallest stagnation region of the jet roofs considered; however, the recirculating eddy is exceedingly large. It is concluded then, from the flow field plots for the inclined jet roof, that the slope-parallel jetroof or one with a small negative inclination ($-10° \leqslant \Phi \leqslant 0$) is the most efficient jet roof with respect to minimizing both the stagnation region and the recirculation.

With regard to the position of the jet roof relative to the mountain ridge, four configurations that are evaluated are shown in figure 21a and designated as Cases A,B,C,D. The developed flow fields for each of these cases are shown in figures 17a, b, c, d. The recirculation regions and the starting fronts of the stagnation regions for the four cases are shown in figure 21b. The recirculation regions show a trend toward smaller regions from Case A to Case D; however, this variation is not considered significant in selecting one configuration over another. From the standpoint of wanting the stagnation region to start as far down slope as possible, Cases B and C are preferred.

From results on average flow and volume flow rate in table 1, it is determined that although the average velocity for Case B is 7% lower than that of Case C, the volume flow rate for Case B is 33% greater than that of Case C. The greater flow rate for Case B is principally a function of the greater area of the opening at the trailing edge of the jet roof, which provides greater margin against possible snow blockage under the jet roof. In accounting for all aspects of the jet roof configurations evaluated, Case B, for which the leading edge of the jet roof is directly above the mountain ridge, has characteristics most desirable from a design standpoint. Since most jet roof configurations tested to date have been oriented as in Case D (Perla and Martinelli 1976), further experimental verification of the Case B configuration is warranted.

Based on the observation that the jet roof can control transients in the fluid flow over short time durations, long duration computer simulations are not necessary to accurately represent the state of the flow field as it approaches steady-state conditions. This would not be true in the case of mountain ridge flow models which consider the more realistic condition of variable input flow boundary conditions corresponding to wind fluctuations. This case can be modeled using the JETROOF code, wherein the input velocities at the entrance to the flow domain at the left boundary will change with respect to time, and consequently, produce a continuing transient state; however, the computer cost of this refinement is not presently justifiable.

The mesh increments DELX and DELY are user-specified parameters which control the spatial resolution of the finite difference grid, the program run time, and the accuracy of the results. The spatial resolution is an important consideration relative to the ability of the JETROOF program to detect regions of stagnation and recirculation. A coarsely resolved flow domain will reveal regions of stagnation as well

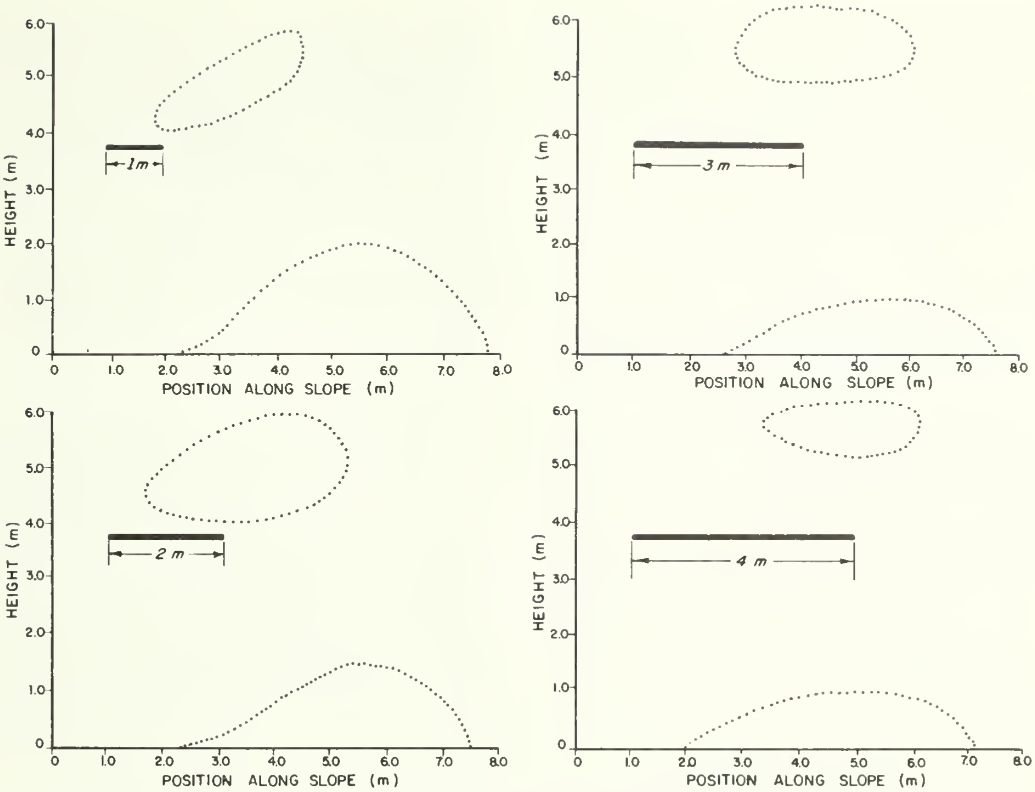


Figure 18.—Dependence of stagnation region and recirculaton eddy upon slope-parallel jet roof.

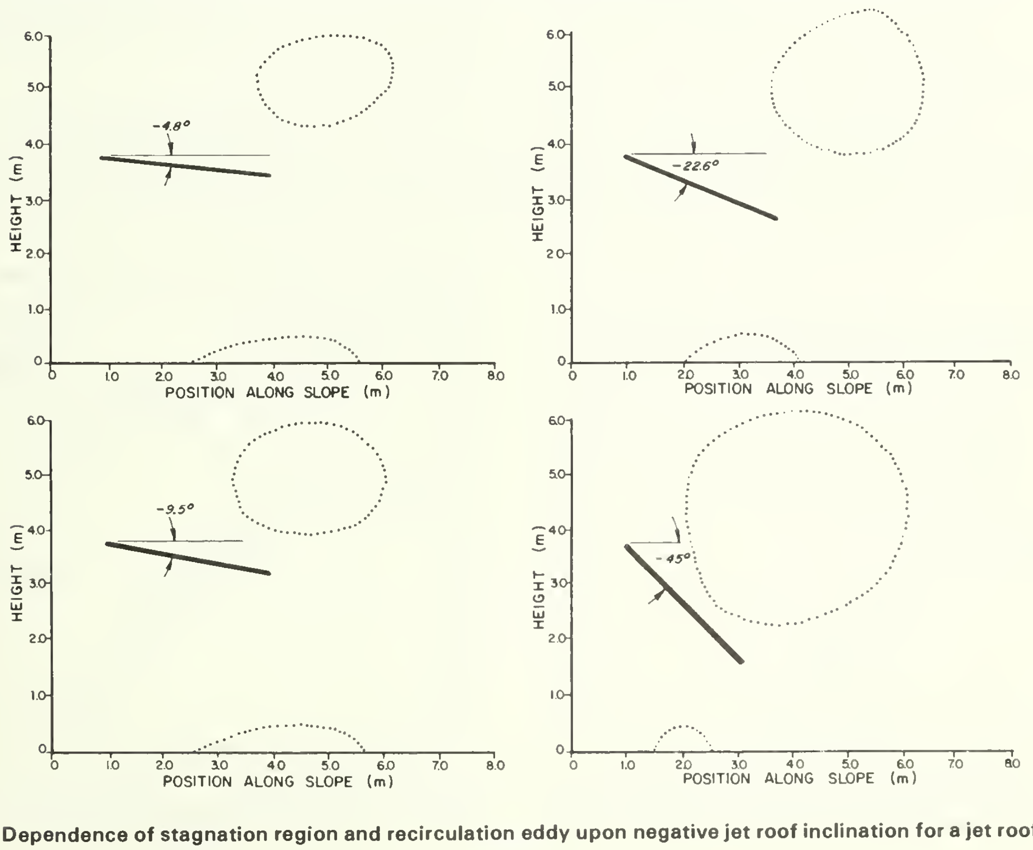


Figure 19.—Dependence of stagnation region and recirculation eddy upon negative jet roof inclination for a jet roof 3.0 m long.

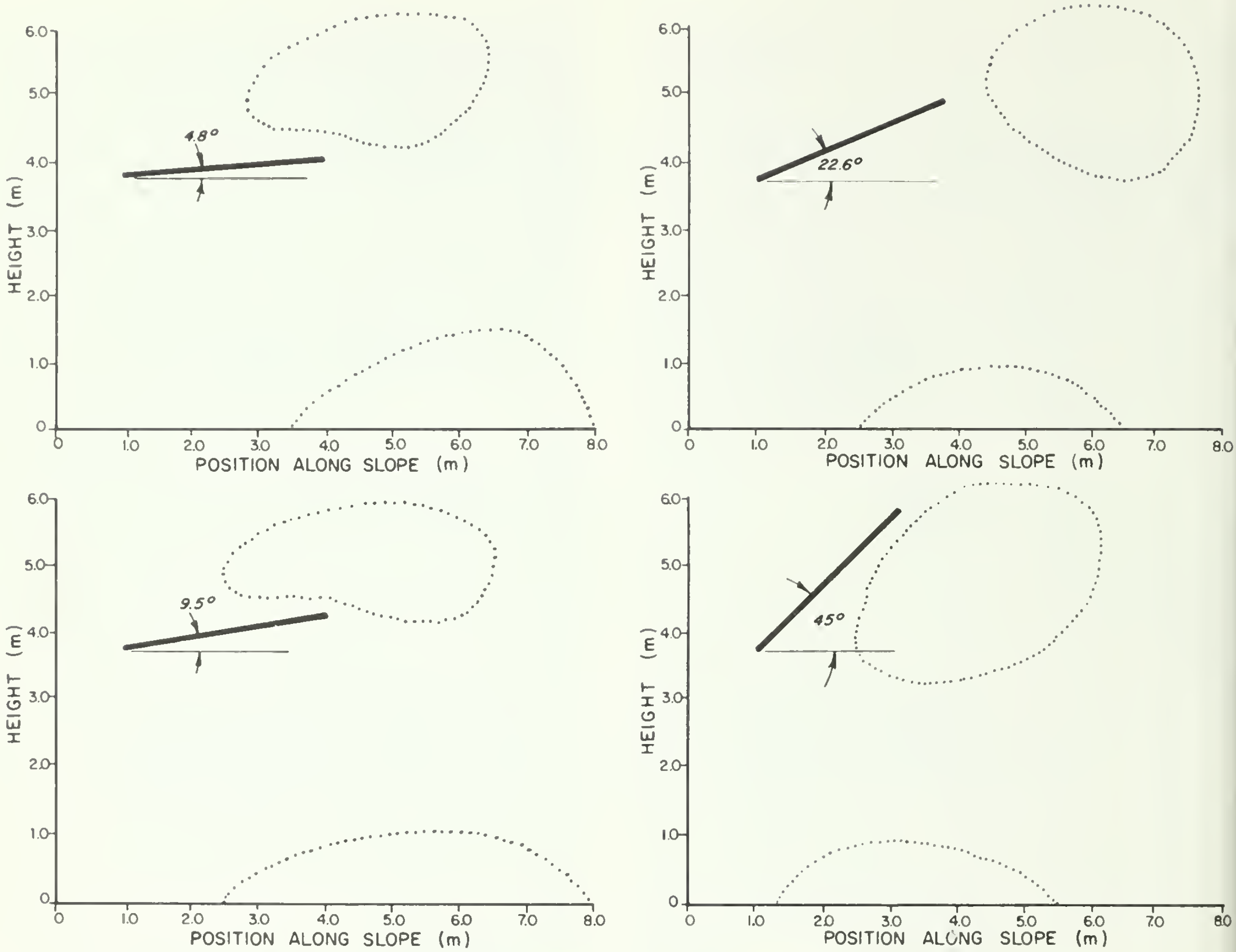


Figure 20.—Dependence of stagnation region and recirculation eddy upon positive jet roof inclination for a jet roof 3.0 m long.

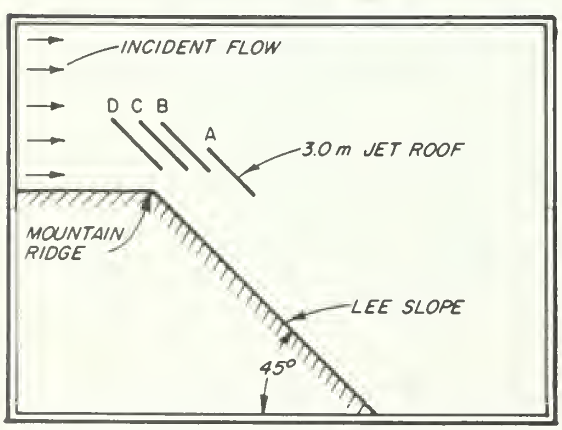


Figure 21a.—Definition of four jet roof geometries relative to the mountain ridge.

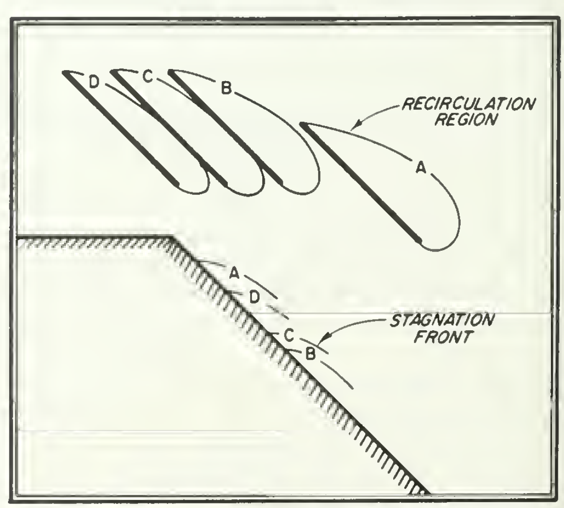


Figure 21b.—Stagnation regions and recirculation eddies for the four regions.

as a more finely resolved grid. The number of cells separating the jet roof and the ground surface should be great enough to accurately indicate the height of the stagnation region under the roof. Initial runs using a three- or four-cell separation (DELY = 1.0 m) did not correctly predict the stagnation which was shown to exist using a seven- or eight-cell separation (DELY = 0.5 m). It is concluded that a seven- to ten-cell separation between the jet roof and the ground surface provides a sufficient spatial resolution so that regions of stagnation under the roof will be correctly predicted.

Care must be exercised in using the continuative boundary condition for the upper boundary due to instabilities which may occur. The computational mesh must be of sufficient size to allow for any recirculation patterns to be detected. As the magnitude of the recirculating eddy increases, so must the height of the finite difference grid. Due to the boundary condition problems encountered as discussed earlier, the continuative boundary conditions used in the JETROOF code are difficult to satisfy when a recirculating flow containing diametrically opposed components of velocity in adjacent cells is present next to the boundary.

Program Availability

Printouts of the following computer programs for use with FORTRAN compilers are on file at the USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, 240 West Prospect Street, Fort Collins, Colo. 80526.

A . Full mountain ridge and jet roof model.

B . No mountain ridge and jet roof model.

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A numerical solution algorithm is used to study the air flow over a mountain ridge with and without a jet roof located near the ridge crest. For the simple ridge geometry studied the roof should be parallel to the lee slope, the leading edge of the roof should be at or near the ridge crest, and the height of the leading edge above ground should be about the same dimension as the roof length from leading edge to trailing edge.

Keywords: Avalanche control, mountain snow, jet roofs, cornice control.

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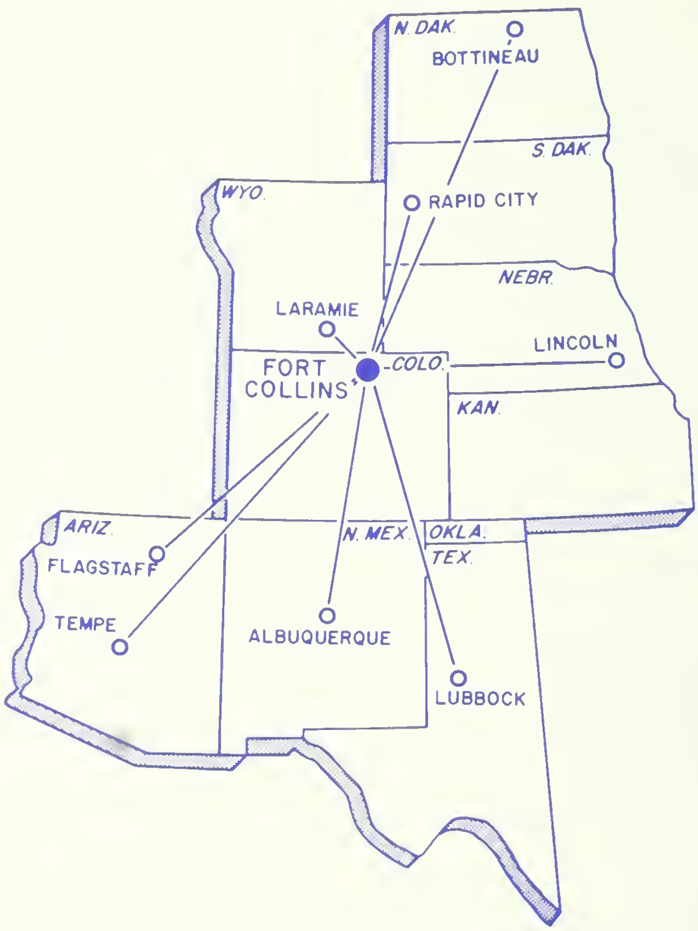
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OKLA.
TEX.
FLAGSTAFF
TEMPE
ALBUQUERQUE
LUBBOCK

A Classification of Spruce-fir and Mixed Conifer Habitat Types of Arizona and New Mexico

William H. Moir and John A. Ludwig

Research Paper RM-207
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U. S. Department of Agriculture

Abstract

Nineteen major forest habitat types (HT's) are described on the basis of extensive reconnaissance data throughout the major mountain ranges and plateaus of Arizona and New Mexico. Eight of these HT's are within spruce-fir forests where either *Picea engelmannii* or *Abies lasiocarpa* are the climax dominants; the remainder are within mixed conifer forests where *Abies concolor*, *Picea pungens*, and *Pseudotsuga menziesii* are climax dominants or codominants. Sixteen other HT's are briefly described based on limited data, usually from one geographic

A Classification of Spruce-fir and Mixed Conifer Habitat Types of Arizona and New Mexico[1]

William H. Moir, Consultant
Rodeo, New Mexico

John A. Ludwig, Associate Professor
New Mexico State University

[1]This work was performed under cooperative agreement with the Rocky Mountain Forest and Range Experiment Station with central headquarters maintained in Fort Collins in cooperation with Colorado State University. Supervision was provided by the Station's Research Work Unit at Flagstaff in cooperation with Northern Arizona University. This work was performed under contracts 16-326-CT and 16-362-CT and purchase order 588-R3-75 between the U.S. Department of Agriculture, Forest Service, and the authors. The authors are grateful to John W. Chambers, Gilbert H. Schubert, and John R. Jones for their continued support and encouragement during this study. Capable and enthusiastic assistance in field work was given by M. Alberico, C. J. Campbell, A. J. Dye, E. Lee Fitzhugh, J. P. Hanks, J. R. Jones, D. Lanning, H. Miller, D. Richards, and M. Richards.

Contents

A Classification of Spruce-fir and Mixed Conifer Habitat Types in Arizona and New Mexico

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INTRODUCTION

Spruce-fir forests occupy less than 0.5% of Arizona and about 2% of New Mexico. Despite this limited distribution, these high elevation forests are important and valuable resources, providing major snow catchement and watershed areas and serving as focal points for winter and summer recreation. The subtending mixed conifer forests, covering about 3% and 4% of Arizona and New Mexico, respectively, are intensively utilized for timber, range and wildlife production, watershed management, and recreation. These forest types respond in complex ways to many man-caused and natural impacts and treatments such as timber harvesting, fire, recreation usage, and foraging by livestock and game.

Scientists and land managers have recognized the need to classify these forests into units of like biological potential (Alexander 1974, Jones 1974, Layser 1974). This study gives a classification of the spruce-fir and mixed conifer forests based upon the concept of habitat types (Daubenmire and Daubenmire 1968). Each habitat type embraces a relatively narrow range of environmental variation and can be identified in old-growth forest stands (late seral to climax) by the dominant plants in each vegetation layer (canopy layer, tree regeneration, shrub, and herbaceous layers). The effects of management practices or natural impacts within a forest habitat type can be understood and predicted in terms of seral communities, growth rates and potentials for various tree species, and rates of succession. The biological potential and forest responses are more uniform within a habitat type than across different habitat types. By stratifying a forest region into habitat types, managers are given an ecological basis for predicting effects of forest treatments and attaining maximum productive potential (Layser 1974, Pfister 1974).

Existing knowledge of habitat types in spruce-fir and mixed conifer forests in Arizona and New Mexico is rudimentary. Regional vegetation maps are very generalized, usually including within a single mapping unit very different forest habitat types (New Mexico Agricultural Experiment Station 1957, Choate 1966, Kuchler 1964, Nichol 1937, Spencer 1966). Daubenmire (1943) reviewed generalized relationships of the elevational sequences of forests in the Rocky Mountains (including Arizona and New Mexico).

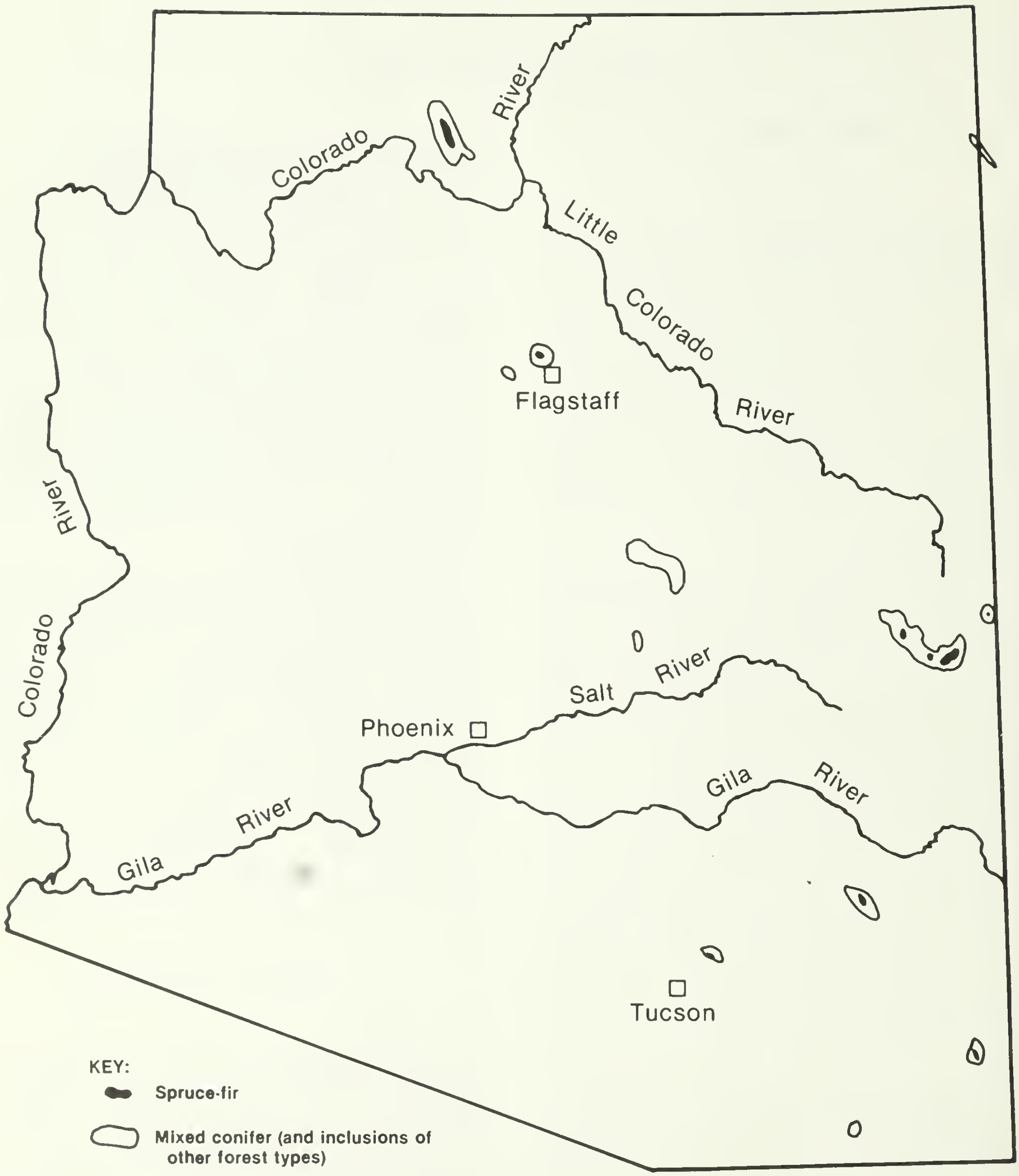
Spruce-fir forests generally have been recognized by dominance or regeneration potential of either or both *Picea engelmannii* and *Abies lasiocarpa.* The lower boundary of these forests has been confused when *Abies concolor, Pseudotsuga menziesii, Picea pungens,* or species of *Pinus* command significant portions of either the overstory or understory. These trees constitute mixed conifer forests when occurring purely or in mixture but to the exclusion (or only accidental presence) of *Picea engelmannii* or *Abies lasiocarpa.* The lower forest boundary of the mixed conifer region is also poorly defined, with conflicting definitions in the literature. Much of this confusion arises from insufficient knowledge of the successional rates of forest communities and from preoccupation with canopy dominance or cover type rather than habitat type.

Descriptions of high elevation forest communities have been published for the North Kaibab Plateau (Merkle 1954), the Sierra Ancha Range (Pase and Johnson 1968), and the Pinaleno and Santa Catalina Mountains (Whittaker and Niering 1965). In New Mexico, Hanks and Dick-Peddie (1974) studied forest succession after fire in the mixed conifer forests of the Sacramento Mountains, and at higher elevations Dye and Moir (1977) described a spruce-fir forest type. However, little is known about the homogeneity of these forests or their relationship and similarity to other high elevation forests in Arizona and New Mexico. The objective of this paper, therefore, is to present stratification by habitat type of spruce-fir and mixed conifer forests in both states.

STUDY AREAS

Stands of spruce-fir and mixed conifer forests were sampled in major mountain ranges and plateaus of Arizona and New Mexico except the Chuska Mountains and Black Range (table 1). Generally, the more extensive the forest distribution was, the greater the number of stands that were studied. The many isolated and minor coniferous stands in canyons or north-facing slopes of minor mountain ranges were not visited. Figure 1 shows the location of spruce-fir and

Arizona


Colorado
River
Little
Colorado
River
Flagstaff
River
Colorado
Salt
River
Phoenix
Gila
River
Gila
River
Tucson
KEY:
Spruce-fir
Mixed conifer (and inclusions of other forest types)

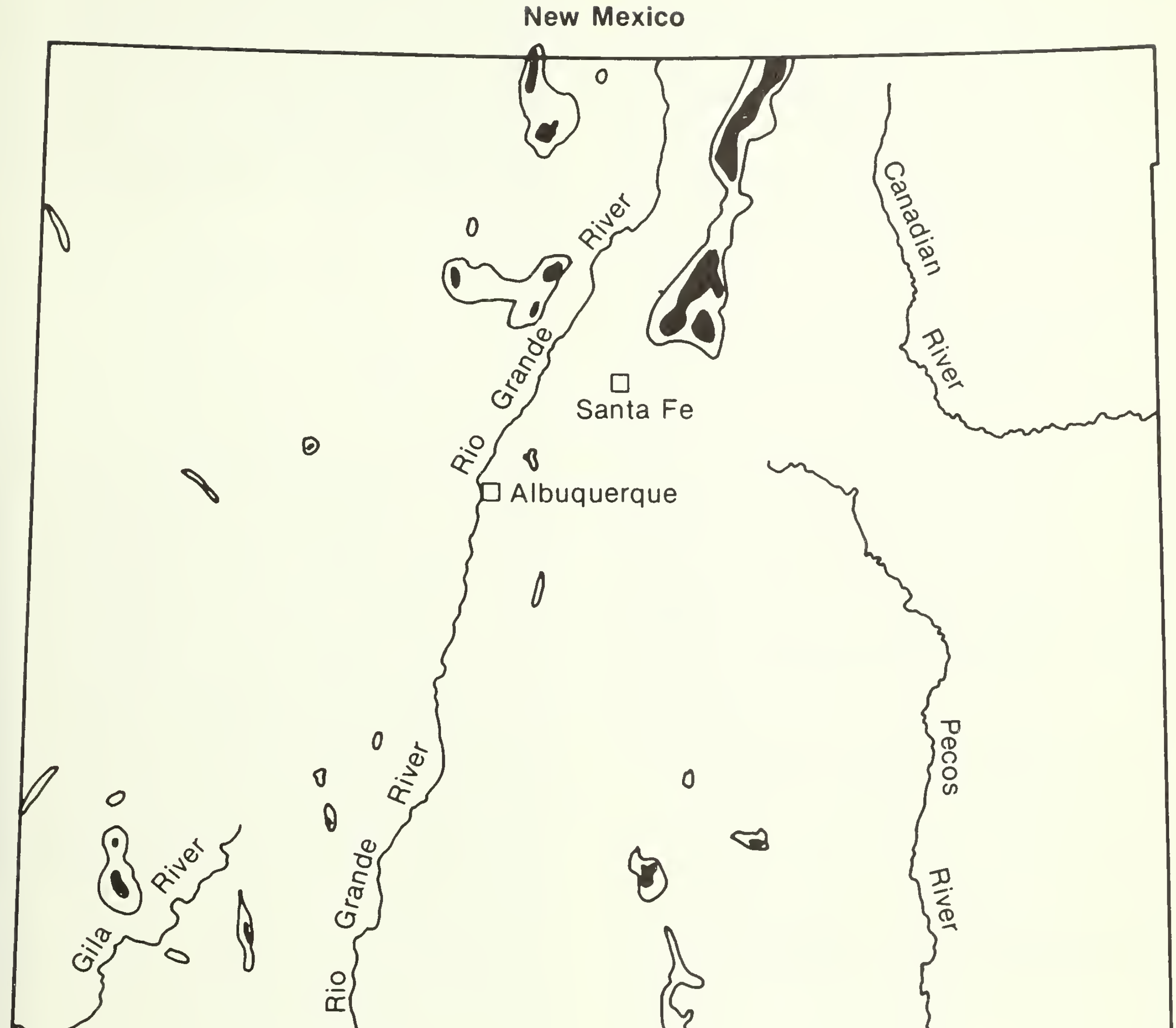


Figure 1.—Geographic location of spruce-fir and mixed conifer forests in Arizona and New Mexico (modified from Choate 1966 and Spencer 1964).

mixed conifer forests in the two states and identifies the sampled areas. Sampled stands vary in elevation from 7,100 feet (2,160 m) to 11,900 feet (3,630 m) with boundaries of spruce-fir and mixed conifer zones shifting with geographic locations (Daubenmire 1943).

The mountain ranges in table 1 occur over four physiographic provinces of Arizona and New Mexico recognized primarily as structural geological divisions (Wilson 1962). The Southern Rocky Mountain Cordilleran Province includes the Sangre de Cristo Range and San Juan Mountains, both extending into New Mexico from Colorado. The latter includes the San Pedro Mountains and Jemez Mountains. The Basin and Range Province includes many block faulted mountain ranges of southern New Mexico and southern Arizona. High elevation coniferous forests are found in the Capitan, Sacramento, and Black Ranges in New Mexico and Chiricahua, Pinaleno, Santa Catalina, and Sierra Ancha Mountains of Arizona.

The Mogollon Volcanic Province includes the high plateaus and summits of the Mogollon Plateau, White Mountains, and Mogollon Mountains. The Magdelena and San Mateo Mountains of central New Mexico are near the eastern border of this province. On the Mogollon Plateau, strata of basalt dip gently to the north and northeast; and in the White Mountains, volcanic ash covers the edge of the Plateau, and flows extend in tongues northward toward the Little Colorado Drainage (Wilson 1962). The Colorado Plateau Province includes the San Francisco Peaks and Bill Williams Mountain, both large central-type volcanic cones of the San Francisco volcanic field which lies on a broad structural dome in north-central Arizona. The North Kaibab Plateau, a system of uplifted sedimentary strata, is part of this dome. In New Mexico, the Chuska Mountains, Mount Taylor, and Zuni Mountains are part of the Colorado Plateau. At highest elevations and cooler, north-trending canyon drainages of these mountains, there are primarily mixed conifer forests not included in this study.[2]

Table 1.—Number of stands sampled in spruce-fir and mixed conifer forests as distributed by mountain ranges and plateaus in Arizona and New Mexico

	Spruce-fir	Mixed conifer
Arizona		
Chiricahua Mts.	1	18
Pinaleno Mts.	4	6
White Mts.	43	42
Mogollon Plateau	1	27
San Francisco Peaks	6	3
North Kaibab Plateau	7	20
Bill Williams Mt.	0	2
New Mexico		
Sangre de Cristo Mts.	69	36
San Juan Mts.	11	11
Sacramento Mts.	21	27
Capitan Mts.	4	5
Mogollon Mts.	18	13
Totals	185	210

Published climatological data for high elevation forests are very limited or generalized (Daubenmire 1943), except for the study by Beschta (1976). His studies in central Arizona suggest that most high elevation mixed conifer and spruce-fir forests occur where mean annual precipitation exceeds about 30 inches (762 mm), and mean snowfall depths exceed about 100 inches (2.5 m).

METHODS

FIELD SAMPLING

Forests eligible for study were those in which any of *Picea engelmannii, Abies lasiocarpa, A. concolor,* or *Picea pungens* exhibited at least some natural regeneration potential in relatively mature forest growth. Stands in late seral, near-climax, or climax condition (i.e., old growth relatively free of major disturbance effects) usually were sought. Often, however, judgments as to what constituted a "major" disturbance had to be compromised, especially in areas where man's influences were pervasive. Partial overstory cutting, grazing, long periods of fire suppression, and activities of early-day tie cutters (in the 1860's and 1870's) are examples of disturbances which may have altered the major dominance relationships of vegetation in each structural layer of the stand. In a few areas of intense utilization, we looked for least disturbed stands and then decided whether or not these revealed sufficient vegetation characteristics of the potential climax forest type.

To sample a large number of stands representing the spectrum of habitat types in Arizona and New Mexico, a relatively rapid reconnaissance method was used (Franklin et al. 1970). Circular plots, mostly 375 m^2, were located in areas of vegetation homogeneity (judged visually) and were surrounded by similar vegetation of the stand to ensure minimal edge effects. In each plot, all tree individuals from established seedlings (larger than about ankle height, or 1 dm tall) to the largest specimens were tallied by 2-inch (5-cm)

[2] A summary of the vegetation of Mount Taylor is given by N. L. Osborn, 1966. A comparative floristic study of Mount Taylor and Redondo Peak, New Mexico. Ph.D. Thesis, Univ. N.M., Albuquerque, 148 pp. See also W. C. Martin, C. R. Hutchins, R. G. Woodmansee, 1970. A flora of the Sandia Mountains, New Mexico, unpublished mimeo 319 pp., Dept. Bio., Univ. N.M., Albuquerque. Mixed conifer forests in the Chuska Mountains have been described by Wright et al. (1973).

diameter classes as measured at breast height (d.b.h). Trees under 2 inches d.b.h. were also tallied into height classes less than breast height (4.5 feet or 14 dm) and greater than or equal to breast height.

In each plot, visual estimates of canopy coverage were made (Daubenmire 1968) for each vascular species of understory shrubs and herbs. These estimates were made to the nearest percentage up to 10% cover and to the nearest 5% thereafter. The visual estimates occasionally were calibrated with the more precise mensuration technique of using forest macroplots 25 by 15 m in rectangular dimension and a grid of 50 microplots each 2 by 5 dm within the macroplot for measuring canopy coverage (Daubenmire 1968). Species of coverage less than 1% but of frequent occurrence were recorded as 0% and arbitarily assigned a cover value of 0.1% on summary sheets. Infrequent or rare species within the plots were recorded as -1 and assigned the cover value of 0.01%; species in the stand but outside the plot were recorded for presence by -2 but were not used in summary tables or analysis. About 350 taxa were involved in these tree and understory measurements (see appendix). Voucher specimens have been deposited at the USDA Forest Service Herbarium, Fort Collins, Colo., as primary depository, and at herbaria at New Mexico State University, University of Colorado, and University of Wyoming.

Site data recorded for each plot included elevation (from topographic maps), slope, aspect, and landform and position in the landscape (ridge, upper slope, midslope, lower slope, bench, streamside). Soil mapping units or profile features, if available for the site, were recorded. Soil surface characteristics of litter, exposed soil and rocks, cryptogams, and vascular plant basal area were visually estimated in such manner as to total 100%. Effects of fire, insects, erosion, browsing, or other disturbances were recorded if sufficiently apparent and thought to influence vegetation composition as either pertubation or sustained site influence.

Several trees in most plots were aged at breast height (by increment coring and counting rings in the field) and measured for height. Trees were selected to reveal site potential (optimal growth rates under field condition). Other individuals, usually of the larger sizes, were chosen to indicate stand age, or period since last major disturbance (usually fire). Recent stumps in logged stands were used for ring-count estimates of stand age, also.

DATA ANALYSIS

For purposes of forest classification, tree data for each plot were summarized into stem densities per 500 m² of young regeneration (d.b.h. less than 2 inches), advanced regeneration (d.b.h. 2-10 inches), and mature (d.b.h. greater than 10 inches). For *Populus tremuloides, Quercus gambelii, Robinia neomexicana,* and several other less common tree species, the size class data were summarized into two classes: regeneration (0-10 inches d.b.h.), and mature (d.b.h. greater than 10 inches).

The relative importance of understory shrubs and herbs was computed by multiplying percentage presence (number of plots of occurrence as percent of all plots) and cover index (the percent cover of each species summed over all plots of occurrence). Shrubs with importance greater than 250 and herbs with importance greater than 200 were used in subsequent analyses.

Plot data were sorted into groups based on similarities in the tree, shrub, and herb layers (Shimwell 1971). Emphasis of the tree regeneration and survivorship data was used in grouping the plots, since reproductive success of a species is a factor of great importance in judging the seral status of vegetation types (Daubenmire and Daubenmire 1968). An agglomerative-hierachial classification method also was used to further clarify the groupings (Lance and Williams 1967). The grouping of plots thus obtained were then analyzed by generating plot tables. However, there were instances where the computed groupings were overriden or modified based on ecological judgments. The final habitat type plot tables[3] reflect both computational methodology and ecological judgments.

RESULTS AND DISCUSSION

A listing of all forest habitats defined in this study and grouped into series (Hoffman and Alexander 1976) is given in table 2. The following sections contain brief, synoptic descriptions of each habitat type. The descriptions are essentially summaries and abstractions from the final habitat type plot tables. Diagnostic vegetation consists of only those vegetative features of the habitat type that are essential for field identification and distinction from other habitat types. The geography encompasses our knowledge of geographic range in Arizona and New Mexico either from actual location of plots or from literature, field notes, and miscellaneous sources of information. Topography summarizes the physical site features from the stand tables. Information on soils are primarily references to Soil Resource Inventories of the Southwestern Region, USDA (Carleton 1971, Dunstan and Johnson 1972, Gass 1972). However,

[3] These plot tables along with a list of the species used in the data analysis are deposited at the USDA Forest Service data depository at Flagstaff, Ariz.

Table 2. Spruce-fir and mixed conifer forest habitat types of Arizona and New Mexico. Habitat types are listed by series, with name abbreviations and the number of plots representing each type given

Forests	Abbreviation	No. plots
Picea engelmannii Series		
1. *Picea engelmannii/Vaccinium scoparium/Polemonium delicatum* HT	PIEN/VASC/PODE HT	14
2. *Picea engelmannii/Moss* HT	PIEN/MOSS HT	13
Abies lasiocarpa Series		
3. *Abies lasiocarpa/Vaccinium scoparium* HT	ABLA/VASC HT	46
4. *Abies lasiocarpa/Vaccinium scoparium/Linnea borealis* HT	ABLA/VASC/LIBO HT	10
5. *Abies lasiocarpa/Rubus parviflorus* HT	ABLA/RUPA HT	7
Vaccinium myrtillus Phase	VAMY Phase	
Acer glabrum Phase	ACGL Phase	
6. *Abies lasiocarpa/Erigeron superbus* HT	ABLA/ERSU HT	35
7. *Abies lasiocarpa/Juniperus communis* HT	ABLA/JUCO HT	8
8. *Abies lasiocarpa/Senecio sanguisorboides* HT	ABLA/SESA HT	10
Picea pungens Series		
9. *Picea pungens-Picea engelmannii/Senecio cardamine* HT	PIPU-PIEN/SECA HT	23
Abies lasiocarpa Phase	ABLA Phase	
Abies concolor Phase	ABCO Phase	
10. *Picea pungens-Picea engelmannii/Erigeron superbus* HT	PIPU-PIEN/ERSU HT	5
11. *Picea pungens/Poa pratensis* HT	PIPU/POPR HT	3
12. *Picea pungens/Carex foenea* HT	PIPU/CAFO HT	18
Pseudotsuga menziesii Phase	PSME Phase	
Pinus ponderosa Phase	PIPO Phase	
13. *Picea pungens-Pseudotsuga menziesii* HT	PIPU-PSME HT	10
Arctostaphylos uva-ursi Phase	ARUV Phase	
Valeriana acutiloba Phase	VAAC Phase	
Linnaea borealis Phase	LIBO Phase	
Juniperous communis Phase	JUCO Phase	
Abies concolor Series		
14. *Abies concolor-Pseudotsuga menziesii/Acer glabrum* HT	ABCO-PSME/ACGL HT	41
Berberis repens Phase	BERE Phase	
Holodiscus dumosus Phase	HODU Phase	
15. *Abies concolor-Pseudotsuga menziesii/Quercus gambelii* HT	ABCO-PSME/QUGA HT	62
Typical Phase	typical Phase	
Muhlenbergia virescens Phase	MUVI Phase	
Festuca arizonica Phase	FEAR Phase	
16. *Abies concolor-Pseudotsuga menziesii* HT	ABCO-PSME HT	37
Berberis repens Phase	BERE Phase	
Robinia neomexicana Phase	RONE Phase	
17. *Abies concolor/Acer grandidentatum* HT	ABCO/ACGR HT	5
18. *Abies concolor/Festuca arizonica* HT	ABCO/FEAR HT	7
Pseudotsuga menziesii Series		
19. *Pseudotsuga menziesii-Pinus strobiformis/Muhlenbergia virescens* HT	PSME-PIST/MUVI HT	11

field notes, unpublished soil profile descriptions, and miscellaneous sources of information are included when available.

A section on ecotones and related habitats follows the soils summary. Descriptions of ecotones for each habitat type are based upon field reconnaissance for forest habitats adjoining stands where plots were described. Related habitats extend our knowledge of these habitat types to other geographic locations, including other western states. A discussion includes general comments and observations within each habitat type from field notes. We also survey existing literature pertinent to the habitat type, describe our observations (or those from the literature) on succession or other ecological dynamics, and comment about tree growth potential for commercial species and other land use practices that appear of major importance within the habitat.

The entire synoptic description of each habitat type is intended to be only preliminary familiarization or state-of-knowledge. Data necessary for in-depth understanding of ecological processes and management prescriptions in these habitat types are often lacking. Also, this study is primarily a classificatory stratification of the spruce-fir and mixed conifer forest types.

DESCRIPTION OF SPRUCE-FIR HABITAT TYPES

Picea engelmannii Series

1. *Picea engelmannii/Vaccinium scoparium/Polemonium delicatum* HT

Diagnostic vegetation.—At least moderate (more than 300 stems/ha) and sometimes heavy (more than 1,000 stems/ha) regeneration of *Picea engelmannii*. Regeneration of *Abies lasiocarpa* varies from light (fewer than 100 stems/ha) to heavy. Crown dominance usually by *Picea*; less commonly *Abies lasiocarpa* is codominant. No *Pseudotsuga menziesii* is present. *Vaccinium scoparium* is the understory dominant, ranging from 10%-95% cover (mean 53%) in the plots.

A well developed herbaceous layer can be dominated by any of several species: *Polemonium delicatum, Senecio amplectens,* or *Senecio sanguisorboides*. Species characteristic of tundras or forest-tundra ecotones are usually present: *Deschampsia caespitosa, Poa reflexa, Sibbaldia procumbens, Trifolium dasyphyllum,* and *Podistera eastwoodae*.

Geography.—Sangre de Cristo Mountains.

Topography.—High elevation forested slopes to timberline. Our 14 plots varied between 10,900 feet (3,320 m) and 11,900 feet (3,630 m) at all exposures. Landforms included cirque basins, moraines, alluvial streamsides, gentle upland ridges, and a variety of talus slopes.

Soils.—Soil mapping units included Angostura, Latir, and Nambe Cobbly Loams, Alpine Rockland, Stony Lands, and glacial outwash complexes.

Ecotones and related habitat types.—The *Picea engelmannii/Vaccinium scoparium/Polemonium delicatum* HT has ecotones with tundra at higher elevation and with *Abies lasiocarpa/Vaccinium* HT at lower elevation. This habitat type probably extends northward along the Sangre de Cristo Mountains at timberlines into Colorado. Langenheim (1962) describes a spruce-fir community type in the Crested Butte area of high floristic similarity (including dominance by *Vaccinium* and appreciable cover in certain plots of *Polemonium delicatum, Senecio amplectens,* etc.). Steen and Dix[4] describe a high elevation forest in Colorado dominated by *Picea engelmannii* (their *Picea-Abies/Polemonium delicatum-Polygonum bistortoides* type) with good representation of *Deschampsia caespitosa* and other tundra or high elevation subalpine herbs.

Discussion.—This habitat is restricted to glaciated recesses and slopes of New Mexico's highest peaks. Many stands occur in the Pecos and Wheeler Peak Wildernesses. A few areas are used for skiing and other winter recreation. The forests, therefore, have high scenic and recreation values. They are also important habitat for such wildlife of the forest-tundra ecotone as Rocky Mountain bighorn sheep and ptarmigan.

Aspen is absent from all plots, and some stands near the heads of sheltered cirque basins seem very old (ring counts on *Picea engelmannii* exceeding 500 years). Although fires can sweep up to timberline, many stands of this habitat have escaped serious fire for centuries. The watershed value of this forest, principally for snow and water storage, may be highly variable. Steen and Dix suggested that sites in Colorado where spruce occurs to the exclusion of *Abies lasiocarpa* may represent the drier of timberline conditions. There is no evidence that the same can be said for such stands where *Abies lasiocarpa* is minor or absent in this HT in New Mexico. The high coverage of both *Vaccinium scoparium* and herbs in most plots and the infrequent occurrence of fire suggest well watered (or deep snowpack) conditions. But snow blowoff and redesposition from tundra slopes into lower, sheltered forests can be highly variable, and snow hydrology patterns as related to this and other spruce-fir habitat types need much clarification.

2. *Picea engelmannii/Moss* HT

Diagnostic vegetation.—All sizes of *Picea engelmannii;* usually moderate or heavy regeneration of *Abies lasiocarpa* but mature sizes sometimes less common than *Picea*. Very sparse shrubs and herbs in the understory. Mosses and lichens dominate.

Geography.—Sangre de Cristo and San Juan Mountains, Pinaleno Mountains, San Francisco Peaks.

[4] *Unpublished manuscript.*

Topography.—Dry, high elevation sites. Ridges, upper slopes, southerly exposures, and saddles from 10,000-11,500 feet elevation (3,000-3,500 m).

Soils.—Excessively drained, often lithic and skeletal profiles.

Ecotones and related habitats.—In northern New Mexico, ecotones occur with *Picea/Vaccinium/Polemonium* and *Abies/Vaccinium* HT's and with dry meadows. In the San Francisco Peaks, the *Picea engelmannii/Geum rossii* HT occurs on wetter sites of the same or higher elevations, and the *Abies lasiocarpa/Lathyrus arizonicus* HT is found at lower elevations. In the Pinaleno Mountains are ecotones with *Abies/Vaccinium, Picea engelmannii/Carex foenea,* and dry meadow habitats.

The *Picea engelmannii/Moss* HT is probably related to the *Abies lasiocarpa-Picea engelmannii/Moss* and *Abies-Picea/Vaccinium/Moss* types of Colorado as classified by Steen and Dix.

Discussion.—Considerable geographic variation is found within this HT. In northern New Mexico, *Vaccinium caespitosum* is a rather diagnostic species of the sparse understory and may be common in cobbly meadow openings and aspen fringes which border the coniferous type. Cryptogamic cover is highly variable, depending upon litter accumulation, soil stoniness, and other factors. Perhaps the most reliable habitat indicator is the sparsity of understory vascular plant cover, including only meager representation of *Vaccinium scoparium* (ranging from a trace to 19% cover in our plots). In the Pinaleno Mountains, the sparsity of understory cover is again the best criterion of this habitat. This flora may include trace amounts of *Muhlenbergia montana, Carex hoodii, Potentilla subviscosa, Vaccinium myrtillus,* and *Erigeron formossissimus.* In some stands *Picea engelmannii* may be considerably more important than *Abies lasiocarpa.* In the San Francisco Peaks, the cover of cryptogams is mostly greater than total cover of herbs and shrubs (fig. 2), but local patches of *Lathyrus arizonicus* may exist in small openings. *Ribes montigenum* and *R. pinetorum* are usually present but infrequent. Both *Picea* and *Abies* are climax species, at least in our plots.

Site quality for Engelmann spruce is usually very poor to poor. Five trees between 100 and 165 years old were 50-60 feet (15-18 m) tall; three 130-160-year-old trees were 70-75 feet (21-23 m) tall. More favorable microsites, however, may have trees 90-100 feet (27-30 m) tall at about 140 years of age.

The principal seral tree is *Populus tremuloides,* but all plots occurred in stands which displayed only sporadic distribution of mature aspen stems. It is also likely that both *Picea* and *Abies lasiocarpa* are their own seral predecessors on these lithic, skeletal soils. Neither *Pseudotsuga menziesii* or *Pinus strobiformis* are important seral species, although a few individuals are sometimes found on high ridges (in New Mexico and the Pinaleno Mountains of Arizona.)

Figure 2.—***Picea engelmannii/Moss*** **HT, San Francisco Peaks. Sparse understory vascular plant vegetation at high elevations (here 3,160 m) is characteristic of the type. The meter stick banded into five 2-dm segments is used for scale.**

The warm, dry sites of this habitat may also be favored bedding and shelter areas (from storms) for game. There were abundant signs of elk, for example, in several plots in the Sangre de Cristo Mountains. The presence of numerous large browsing animals may contribute to the lack of understory vegetation, since many of these plants are important browse.

Abies lasiocarpa Series

3. *Abies lasiocarpa/Vaccinium scoparium* HT

Diagnostic vegetation.—Usually moderate to heavy regeneration of both *Picea engelmannii* and *Abies lasiocarpa. Pseudotsuga menziesii* regeneration absent or minor, but mature trees sometimes common. Cover of species of *Vaccinium,* the understory dominant, ranged from 3% to 95% (mean 60%). In northern New Mexico, *Vaccinium scoparium* is important; in southwestern New Mexico and Arizona, *V. myrtillus* is the only *Vaccinium.* Herbs are mostly of few species with low canopy coverage, considerably less than *Vaccinium.*

Geography.—Sangre de Cristo and San Juan Mountains, Mogollon Mountains, Pinaleno Mountains, and Mount Baldy (Arizona).

Topography.—Gentle to steep, smooth to dissected mountain and canyon sideslopes, upland slopes and ridges, narrow to broad valley bottoms at elevations of 9,800 -11,200 feet (2,400-3,400 m). All exposures, but south-facing slopes are mostly burned and in aspen or other seral stages.

Soils.—In northern New Mexico, soils may or may not exhibit weak spodic horizons, and sometimes show a well-developed, thick paleo-A2 horizon.[5] Soil map-

[5] Similar soils have been described in Colorado by Moir (1969) and Johnson and Cline (1965). The latter call profiles with thick eluvial horizon as Gray Wooded. Also see Madole (1969).

ping units include Angostura, Nambe, Latir, Jarosa, and Mallette Cobbly loams, Granite and rhyolite rock land, Greenie Loam. Elsewhere soils have not been described.

Ecotones and related habitats.—On upper slopes, the *Abies lasiocarpa/Vaccinium scoparium* HT is bounded by the *Picea engelmannii/Vaccinium scoparium/Polemonium delicatum* HT or on dry sites by the *Picea engelmannii/Moss* HT. On lower slopes, there may be ecotones with the *Abies lasiocarpa/Vaccinium scoparium–Linnaea borealis* HT or with the *Abies lasiocarpa/Erigeron superbus* HT. This latter may also adjoin the *Abies lasiocarpa/Vaccinium scoparium* HT on benches, minor drainage areas, or wherever variations in soil moisture and drainage or snowpack conditions cause shifts from one HT to the other.

Our *Abies lasiocarpa/Vaccinium scoparium* HT can be readily identified with other *Abies/Vaccinium* types of western North America, particularly in the Rocky Mountain Cordillera (Langenheim 1962, Oosting and Reed 1952, McLean 1970, Daubenmire and Daubenmire 1968). The *Abies lasiocarpa/Vaccinium scoparium* HT of Utah (Pfister 1972) appears to be nearly identical with ours. The mountains of southern Colorado probably contain extensive areas of the *Abies lasiocarpa/Vaccinium scoparium* HT.

There is a close relationship between our *Abies/Vaccinium scoparium* and *Abies/Erigeron superbus* HT's. It is uncertain just what environmental factors produce shifts from *Vaccinium* dominated to herb dominated understories. Possibly the latter occupy sites that are warmer, but well watered and well drained. One plot in the San Juan Mountains (Chicoma Peak) is an example of intergrading between these two habitat types. Here, both *Erigeron superbus* and low, evergreen shrubs (*Vaccinium myrtillus* and *Pachistima myrsinites*) are codominant.

Discussion.—As Langenheim (1962) pointed out, this habitat type has a high floristic homogeneity based upon an apparent repetitive pattern, not only of the dominant understory species, but also among many subdominant and minor plants. Shrubs of high constancy include *Ribes montigenum, Lonicera involucrata,* and in southern geographic areas *Lonicera utahensis.* Commonly encountered herbs include *Pedicularis racemosa (P. angustissima* in the Mogollon Mountains), *Epilobium angustifolium, Fragaria virginiana* var. *glauca, Haplopappus parryi, Erigeron superbus*, and *Bromus ciliatus* (fig. 3). However, the range of environmental variation within this habitat type can be seen as understory differences in comparatively wet and comparatively dry sites. The former, along streamsides or lower slopes, may exhibit (sometimes with high cover values) such species as *Trautvetteria grandis, Senecio sanguisorboides, S. bigelovii* or *Mertensia fransicana* and may have a rich complement of shrub and herb species. Dry upper slopes and ridges can be floristically impoverished (fewer than 10 species) and have cover values well below the mean.

Figure 3.—*Abies lasiocarpa/Vaccinium scoparium* HT, Mogollon Mountains. Broad high ridges (elevation here is 3,130 m) in this area may contain *Pedicularis angustissima* as an understory dominant.

Although *Picea engelmannii* and *Abies lasiocarpa* seem to occur as co-climax species in most of our plots, there is a very wide range of site quality ranging generally from moderate to poor. The growth potential for trees is better predicted by physical site features (exposure, position in the landscape) than by understory vegetation. There is little evidence to support the suggestion by some workers that *Abies lasiocarpa* would eventually replace *Picea engelmannii* in the absence of fire. Although young regeneration of *Abies* may be significantly greater than *Picea* in many plots, the latter survives better and often exhibits greater abundance of older regeneration.

Logging and fires are the principal causes of succession. Large areas of commercial forest land occur within this HT. Natural regeneration after clearing may be highly variable. In the vicinity of Cerro Vista (Penasco Ranger District, Carson National Forest), extensive herb meadows dominated by species of *Carex* have become established after clearing, and there is very little sign of natural restocking by conifers. Elsewhere, however, either or both *Picea engelmannii* and *Abies lasiocarpa* become reestablished, and occasional *Pseudotsuga menziesii* can be found. On some sites, particularly the warmer, south-facing slopes of the Sangre de Cristo Mountains, *Pinus aristata* is a major seral species. Other pine species, however, demonstrate little or no success as seral species within this habitat type. The most prevalent seral tree, especially after fire, is *Populus tremuloides.* Aspen, either as pure stands or with mixtures of conifers, is the most common seral species of this habitat type. Fire intensities are extremely variable and probably determine the proportion of aspen and conifers (Jones 1974). The composition of the stand at the time of fire is also a determinant.

The composition of understory vegetation and rates of coniferous succession under aspen dominated canopies are highly variable. Dominant herbs can include *Lathyrus arizonicus, Stellaria jamesiana, Geranium* *richardsonii, Bromus ciliatus,* species of *Castilleja, Fragaria vesca, Carex foenea,* or *Pseudocymopteris montanus.* The presence of *Vaccinium scoparium* or *V. myrtillus* is often a reliable clue, despite herb dominance, to the *Abies/Vaccinium scoparium* HT.

4. *Abies lasiocarpa/Vaccinium scoparium-Linnaea borealis* HT

Diagnostic vegetation.—Moderate to heavy regeneration by either or both *Picea engelmannii* and *Abies lasiocarpa. Pseudotsuga menziesii* and *Abies concolor* are both seral, and regeneration of the species may be light to heavy. *Pseudotsuga menziesii* is mostly dominant and sometimes codominant with *Picea engelmannii* in the canopy overstory. A low shrub layer is codominated by *Vaccinium scoparium* and *Linnaea borealis. Pachistima myrsinities* may also be codominant in this layer. A rich assortment of herbaceous species is found. Species of high constancy include *Aguilegia elegantula, Clematis pseudoalpina, Erigeron superbus, Fragaria virginiana* var. *glauca, Haplopappus parryi, Oryzopsis asperifolia, Bromus ciliatus,* and *Pyrola asarifolia.*

Geography.—Sangre de Cristo Mountains.

Topography.—Lower, north-facing canyon slopes, benches, and alluvial terraces between 8,800-9,800 feet (2,700-3,000 m) elevation.

Soil mapping units.—The mapping units include Jaroso-Encebado-Mascarenas complex, Mallette-Granite-Stony Land complex, Mallette Cobbly Loam, Mallette-Rhyolite-Granite Stony Land complex, and Shale and Sandstone Stony Land Complex.

Ecotones and related habitats.—At higher elevation or midslopes, this HT adjoins *Abies/Vaccinium scoparium* or *Abies/Erigeron superbus* HT's. At lower elevations of similar topography, there may be an ecotone with *Picea pungens-Pseudotsuga* HT, *Linnaea borealis* phase. Along adjoining streamsides is usually found the *Picea pungens/Poa pratensis* HT.

The *Abies lasiocarpa/Vaccinium scoparium-Linnaea borealis* HT is clearly most closely related to the *Abies/Vaccinium scoparium* HT but is found on lower, wetter slopes. The principal distinctions from the *Abies/Vaccinium scoparium* HT include greater regeneration densities of *Pseudotsuga* and *Abies concolor,* marked dominance of *Linnaea,* in the understory and the richer complement of herbaceous species. There is also a similarity between the *Abies/Vaccinium-Linnaea* HT and the *Abies/Erigeron superbus* HT as suggested by the expression of a tall shrub stratum (*Acer glabrum, Amelanchier alnifolia, Salix scouleriana*).

Habitats related to the *Abies/Vaccinium-Linnaea* HT are also found on similar topograpy in other geographic areas. In the Mogollon Mountains, the *Abies/Rubus parviflorus* HT is analogous. In Colorado, Steen and Dix[6] classify an *Abies lasiocarpa-Picea engelmannii/Vaccinium-Linnaea borealis* type on north-facing mesic slopes.

Discussion.—Successional stages of this habitat are generally similar to the *Abies/Vaccinium scoparium* HT. In both, aspen is the most common seral dominant. However, *Pseudotsuga menziesii, Abies concolor,* and occasional *Picea pungens* are also important seral and late seral trees. This habitat has a widespread history of disturbance by fire and logging. Virtually all plots exhibited generous proportions of *Pseudotsuga menziesii* and *Populus tremuloides.* But the generally moderate and heavy regeneration densities of *Abies lasiocarpa* and *Picea engelmannii* are evidence of the climax status of these shade tolerant species.

Douglas fir is the most important commercial tree of this habitat. Nevertheless, the site quality is poor: four trees at 80 years breast height age averaged only 57 feet (17 m) in height (range 49-66 feet); a fifth, at 89 years old was only 63 feet (19 m) tall. Growth rates for Engelmann spruce appear similar, but our data are very limited.

5. *Abies lasiocarpa/Rubus parviflorus* HT

Diagnostic vegetation.—Both *Abies lasiocarpa* and *Picea engelmannii* are climax dominants with moderate to heavy regeneration of *Abies* and light to moderate regeneration of *Picea. Pseudotsuga menziesii* is a major seral species. *Rubus parviflorus* is a conspicuous dominant of a well developed shrub layer. There is also a good coverage by herbaceous species, including *Geranium richardsonii, Haplopappus parryi, Ligusticum porteri, Erigeron superbus,* or *Senecio cardamine.*

We recognize two phases of this HT. The first is characterized by the low shrub *Vaccinium myrtillus* being codominant with *Rubus parviflorus.* The second is characterized by the consistent occurrence of *Acer glabrum* in the tall shrub stratum, and absence of *Vaccinium myrtillus* in the low shrub stratum. In the *Vaccinium myrtillus* phase, *Abies concolor* is minor or accidental, whereas in the *Acer glabrum* phase, *Abies concolor* is a major seral species.

Geography.—Mogollon Mountains.

Topography.—Moderate and steep, well watered mid- and lower slopes, and benches from 8,500-10,300 feet (2,600-3,100 m) elevation. Exposures are north, west and east.

Soils.—One plot of our *Acer glabrum* phase of this HT is mapped as Corner Stony Loam; however, most soils of this basaltic and rhyolitic area along Whitewater Creek and Whitewater Baldy have not been described.

Ecotones and related habitats.—The *Abies lasiocarpa/Rubus parviflorus* HT, *Vaccinium myrtillus* phase ecotones with the *Abies lasiocarpa/Vaccinium scoparium* HT occurs on cooler sites with deeper snowpack. This phase may be analogous to the *Abies lasiocarpa/Vaccinium scoparium-Linnaea borealis* HT of rather similar

[6] *Unpublished manuscript.*

wet locations in the Sangre de Cristo Mountains. At lower elevations (warmer, drier sites) the phase ecotones with the *Acer glabrum* phase of this HT. Habitats on adjacent, drier sites include the *Pinus strobiformis/Festuca arizonica* HT (on opposite south-facing slopes) and extensive *Populus tremuloides* seral communities (with understory dominated by *Muhlenbergia virescens* in some stands) of unknown HT.

Plot 326 has generous regeneration of *Abies concolor* and rather sparse cover (2%) of *Rubus parviflorus*. This plot is probably an integrade to the *Abies concolor-Pseudotsuga menziesii/Acer glabrum* HT.

Discussion.—This habitat type is clearly at the lower boundary of the spruce-fir zone on wet sites. Although climatic data are not available, the profusion and richness of the understory flora (21-27 species) suggests that this HT is very well watered, with minimal growing season water stresses. This is an outstanding wildlife habitat by virtue of its wealth of forage and browse species. The plots are all in the vicinity of Whitewater Baldy in the heart of the Mogollon Mountains. Summer precipitation in this area may possibly be higher than normal for mountains of New Mexico and Arizona.

Site quality for spruce and subalpine fir appears moderate to good. *Picea engelmannii* specimens were 65 and 73 feet (29 and 22 m) at respective breast height ages of 55 and 59 years. *Abies lasiocarpa* at 126 years of age (two specimens) ranged from 80 to 100 feet (24-30 m). Site quality was moderate for Douglas fir, attaining about 100 feet (30 m) at about 110 years of age.

Plots for the *Vaccinium myrtillus* phase were seral. Plot 323 was dominated by large old-growth (about 235 years old) *Pseudotsuga menziesii*, with young and advanced regeneration of mostly *Abies lasiocarpa*. Plot 328 was a young pole stand of both spruce and subalpine fir. *Picea engelmannii, Abies lasiocarpa, Pseudotsuga menziesii*, and *Populus tremuloides* are all seral species, with the last forming pure canopy in some areas (such as just below plot 328). Plot 327 is typical of young burned forest along lower, north-facing slopes of Whitewater Creek. There is heavy stocking of young regeneration of both *Pseudotsuga menziesii* and *Abies lasiocarpa*, as well as moderate stocking of young regeneration by *Picea engelmannii*. Despite the young age of this stand, the ground vegetation characteristics of the habitat are well developed. *Vaccinium myrtillus* and *Rubus parviflorus* had 60% and 50% cover, respectively, and herbaceous cover, principally *Senecio cardamine, Geranium richardsonii*, and *Valeriana acutiloba*, totaled about 20%.

The three plots of the *Acer glabrum* phase were also all seral, dominated by *Pseudotsuga menziesii* of approximately 325 years old. Numerous aspen saplings (mostly 4-6 inches d.b.h., or 10-15 cm) also characterized two of the plots. Primeval wildfires were probably mostly light, burning irregularly in patchy distribution within this, and related, wet habitats (Jones 1974).

6. *Abies lasiocarpa/Erigeron superbus* HT

Diagnostic vegetation.—*Picea engelmannii* with light or moderate regeneration, or less commonly, absent or with heavy regeneration. *Abies lasiocarpa* with moderate to heavy regeneration, occasionally only light regeneration. *Pseudotsuga menziesii* and *Abies concolor* may also show light or moderate regeneration densities, but their combined density is usually less than *Picea engelmannii* and *Abies lasiocarpa* together. Species of *Vaccinium* are usually absent, but with cover not over 15% when present. The understory is characteristically herbaceous. Dominants include *Erigeron superbus, Haplopappus parryi, Geranium richardsonii, Bromus ciliatus*, or *Lathyrus arizonicus*. Species of high constancy also include *Viola canadensis, Osmorhiza obtusa, Fragaria virginiana*, and *Artemisia franseriodes*.

Geography.—Widespread. Sangre de Cristo and San Juan Mountains, Mogollon Mountains, Escudilla Mountain, White Mountains (Arizona), and San Francisco Peaks.

Topography.—Gentle to moderate slopes (4%-30%) of rolling uplands or canyon mid- and upper-slopes; moderate to steep (30%-70%) canyon sideslopes; gentle lower canyon slopes and benches; occasionally along streamsides. In Arizona at elevations from 9,000-9,900 feet (2,700-3,000 m); in New Mexico from 9,200-10,900 feet (2,800-3,300 m). All exposures.

Soils.—Numerous soil types are found in this HT. Parent materials range from basalts (Sponseller silt loam in Arizona) to granitics and sedimentaries. Mapping units in northern New Mexico include Angostura, Maes, and Latir Cobbly Loams and Jarosa-Encebado-Mascarenas Complex. In other areas, the soils are not mapped or described.

Ecotones and related habitats.—The principal ecotone at higher elevation or cooler sites is *Abies/Vaccinium scoparium* HT. Warmer sites or lower elevations contain a wide variety of mixed conifer forest habitats, depending on geographic location and site and soil conditions.

There appear to be no related habitats in Utah or Colorado. Pfister (1972) describes an *Abies lasiocarpa/Berberis repens* HT at low elevations bordering mixed conifer forests in Utah, but it has little similarity to our *Abies lasiocarpa/Erigeron superbus* HT. There is nothing similar in the spruce-fir region of Colorado as classified by Steen and Dix.[7]

Discussion.—Although this habitat is found on a diversity of sites, it generally appears on comparatively warm (for the spruce-fir region) and mesic sites, with deep, well drained soils. The herb dominated understory is characteristic of the habitat (fig. 4), but much variation in composition can be found. At wetter extremes, *Senecio sanguisorboides, S. triangularis, Smilacina*

[7] *Unpublished manuscript.*

stellata, and *Ligusticum porteri* may be conspicuous codominants. Such habitats, usually restricted to streamside terraces in northern New Mexico, are rather strikingly similar to the *Abies/Senecio sanguisorboides* HT of the Sacramento Mountains in southern New Mexico. It is also floristically related to a wetter variation of the *Abies/Erigeron superbus* HT. On drier upper slopes, the cover of forbs may be reduced well below the mean for the habitat type, and more xerophytic grasses such as *Festuca arizonica* and *Muhlenbergia montana* may appear as minor components of the herb layer. The modal sites are typically dominated by *Erigeron superbus* and lack herb species of the wetter or drier extremes.

Both *Picea engelmannii* and *Abies lasiocarpa* are considered to be potential climax species of this habitat. Our examination of the stand structure of 35 sites indicated the following successional trends:

Indicated climax	Number of sites
Picea engelmannii	4
Abies lasiocarpa	7
Picea + Abies	24

Abies has greater density of seedlings and young regeneration, but greater mortality and lower longevity than *Picea*. *Picea* may have rather episodic reproduction in certain sites.

Site quality for *Picea engelmannii* is moderate. Trees can attain heights of 95-100 feet (29-30 m) at breast height age of 100 years.

The most important seral trees are *Pseudotsuga menziesii* and *Populus tremuloides*. *Abies concolor* is mostly a minor seral tree as is *Picea pungens*. Several plots showed evidence of *Pinus strobiformis* and *P. ponderosa* being early seral trees, possibly after hot fires which might have created forest openings. Hot fires can also create seral communities dominated purely by aspen (Jones 1974). Plots 16 and 17 are paired on either side of a fire line on similar sites in the Sangre de Cristo Mountains. *Pseudotsuga menziesii* dominates plot 16; *Populus tremuloides* dominates plot 17.

The herb dominated vegetation under aspen consists of *Vicia americana, Geranium richardsonii, Achillea lanulosa, Fragaria virginiana, Bromus richardsonii,* and *Viola canadensis* (each in excess of 10% cover); but vegetation under Douglas-fir consisted only of *Erigeron superbus* and *Haplopappus parryi* (in excess of 10% cover), and species such as *Artemisia franseriodes* and *Pachistima myrsinites* not found in the paired aspen plot. Vegetation composition under aspen or Douglas-fir seral stages of this HT can differ considerably.

7. *Abies lasiocarpa/Juniperus communis* HT

Diagnostic vegetation.—Both *Picea engelmannii* and *Abies lasiocarpa* dominate the forest regeneration.

Figure 4.—*Abies lasiocarpa/Erigeron superbus* HT, Mogollon Mountains. Common forbs in this stand are *Erigeron superbus, Geranium richardsonii,* and *Smilacina stellata.*

Pseudotsuga menziesii and *Abies concolor* are seral, but of sparse regeneration in stands dominated by spruce or subalpine fir. Understory shrubs and herbs are sparse. The most constant species are *Juniperus communis* and *Pyrola secunda*. Herbaceous cover is usually less than 1%.

Geography.—North Kaibab Plateau and mountains of northern New Mexico.

Topography.—Mostly gentle north- or east-facing draws and upland slopes on the North Kaibab Plateau between 8,700-9,200 feet (2,600-2,800 m) elevation. Hot, dry slopes about 10,500 feet (3,200 m) in the Sangre de Cristo Mountains.

Soils.—Generally undescribed. The plot in the Sangre de Cristos on Mallette-Granite-Rhyolite Stony Land soil mapping unit.

Ecotones and related habitats.—The major ecotone of this HT is the *Abies concolor-Pseudotsuga menziesii* HT, *Berberis repens* phase on ridges and west-facing slopes of the North Kaibab Plateau and the Sangre de Cristo Mountains; however, the *Picea pungens/Carex foenea* HT is commonly found on lower slopes and adjoining parks. This HT is related to the *Abies lasiocarpa/Berberis repens* HT in Utah, especially the modal phase described by Pfister (1972). Plots in the North Kaibab Plateau, however, lack *Pachistima myrsinites* and other species of the *Berberis repens* union described by Pfister. The geographic isolation of plots at North Kaibab is probably a leading cause of floristic impoverishment (Merkel 1954).

Discussion.—The sparcity of the understory and the relatively low elevations suggest this to be one of the driest habitats within the spruce-fir region of Arizona and New Mexico (see also the *Picea engelmannii/Acer glabrum* HT at southernmost outliers of the spruce-fir region). The *Abies lasiocarpa/Juniperus communis* HT shares this feature of sparse understory with the *Picea engelmannii/Moss* HT of higher elevations in other mountain areas of Arizona and New Mexico.

Plot 64, at 10,500 feet (3,200 m) on a south-facing slope of the Sangre de Cristo Mountains, provides a link between those two comparatively dry habitats. This plot is included with those of the North Kaibab Plateau because the diagnostic vegetation features are those of the *Abies lasiocarpa/Juniperus communis* HT of that region. Unfortunately most intermediate and high elevation, south-facing slopes visited in northern New Mexico were in young, aspen-dominated stages of succession. Therefore, there are very few samples of mature forests on these hot, dry slopes within the spruce-fir types. Many aspen stands are probably representative of the *Abies lasiocarpa/Vaccinium scoparium* HT, but since aspen is also a seral feature of the *Abies lasiocarpa/Juniperus communis* HT, a broader geographical range of this latter HT might be expected on south-facing mid- and upper-slopes at intermediate to high elevations in mountains of northern New Mexico.

Examination of stand structure of the seven North Kaibab plots suggests both *Picea* and *Abies* as major co-climax trees in five stands, and *Abies* (with *Picea* minor) in two stands. Site quality for *Picea engelmannii* is moderate; heights from 80 to 95 feet (24-29 m) are attained at 100 years of age, and heights of 100 feet (30 m) or so from 106-140 years of age. Most of the plots suffered defoliation by spruce budworms in 1974.

This HT is limited in acreage on commercial forest lands of the North Kaibab Plateau. Its extent within the North Rim portion of the adjoining Grand Canyon National Park is uncertain. Since most visitors in this area are destined for the Park, this HT in the Kaibab National Forest has little recreational usage except for hunters.

8. *Abies lasiocarpa/Senecio sanguisorboides* HT

Diagnostic vegetation.—*Abies lasiocarpa* is in all sizes and classes, with moderate to heavy restocking of young and advanced regeneration. *Picea engelmannii* has light to moderate regeneration densities. Crown dominance is often by *Abies lasiocarpa,* but sometimes, *Picea* is codominant. No *Abies concolor; Pseudotsuga menziesii* is seral only at low elevations. The shrub layer is dominated by either or both *Ribes wolfii* (average cover 18%) and *R. montigenum* (average cover 3%). A rich, well expressed herbaceous layer is dominated by *Senecio sanguisorboides* (average cover 10%). Other common species are *Ligusticum porteri, Osmorhiza depauperata, Actaea arguta, Bromus ciliatus, Trisetum montanum, Festuca scoria, Pseudocymopteris montana,* and *Erigeron superbus.*

Geography.—Sacramento Mountains in vicinity of Sierra Blanca Peak.

Topography.—All slopes and exposures above 10,000 feet (3,000 m).

Soil.—Soils have mostly developed from Three Rivers stock of intrusive monzonite and granite. They are primarily coarse-loamy, pachic cryoborolls. Profiles are deep, well drained, and have A1-A3-C mineral horizon sequences. Cobbles may be very compact in the profile below about 30-40 cm.

Dye and Moir (1977) sampled the uppermost mineral horizon (A11) in stands along a successional sequence ranging from young burns (dominated by shrubs) to climax. In their A11 horizons, they found a general increase of extractable phosphorus and basic cations along this successional sequence, with the most nutrient-rich soils in old-growth stand types. This trend inversely reflected understory canopy coverage, for the most luxuriant growth was found in the shrub thickets where extractable nutrients were lowest.

Ecotones and related habitats.—Ecotones occur with tundra along high, windswept ridges (Moir and Smith 1970), and with meadows dominated by *Festuca thurberi* (Moir 1967). At lower elevations, mixed conifer forest is mostly of the *Abies concolor-Pseudotsuga menziesii/Acer glabrum* HT, *Holodiscus dumosus* phase.

There appear to be no related habitats in the central and northern Rocky Mountains (Dye and Moir 1977). Herb-dominated habitats lacking *Vaccinium* occur along streamsides in northern New Mexico's Sangre de Cristo Mountains at high elevations. We interpret these as variations of the *Abies lasiocarpa/Vaccinium scoparium* and *Picea engelmannii/Vaccinium scoparium/Polemonium delicatum* HT's.

There is high floristic similarity of understory vegetation with other herb dominated spruce-fir habitat types, namely the *Abies lasiocarpa/Erigeron superbus, Abies lasiocarpa/Rubus parviflorus* and *Picea pungens-Picea engelmannii/Senecio cardamine* HT's. These are all either of low elevation or southern geographical distribution and may have certain common climatic features such as long, warm (in comparison to other spruce-fir HT's) growing seasons and good soil water supply during the growth season.

Discussion.—There may be two phases of this habitat type, although they are not definitely separated here. The typical phase occurs on most sites and lacks *Pseudotsuga* as a seral tree. Fires severe enough to create large forest openings (often along upper slopes and ridges) result in shrub dominated communities. Thickets are dominated by *Ribes montigenum* and *R. wolfii.* Gradually both *Picea engelmannii* and *Abies lasiocarpa* reinvade. Aspen is often absent. On warmer sites and lower elevations, a *Pseudotsuga menziesii* phase of this habitat type may be present. Fires may bring about seral communities suggestive of the *Abies concolor-Pseudotsuga menziesii/Acer glabrum* HT, *Holodiscus dumosus* phase. *Ribes* have low coverage values, and *Populus tremuloides* seral communities may also be found at some locations. We are reluctant to separate these phases as distinct because of the overall homogeneity of vegetation in mature forests and the very limited distribution of these spruce-fir forests in the Sierra Blanca area (Dye and Moir 1977). Instead, we regard the *Pseudotsuga* phase as a warmer, drier variation of this HT.

This habitat at low and intermediate elevations is of high site quality for *Abies lasiocarpa* var. *arizonica.* Robust, long-lived ecotypes and the tallest known specimens occur here (fig. 5). Larger specimens are often older than 275 years. Such longevity may explain the higher density of mature *Abies* in this type than in most other spruce-fir habitat types in Arizona and New Mexico. Examination of stand structure of six mature stands indicates the major climax species in four stands is *Abies lasiocarpa* var. *arizonica,* and both *Abies* and *Picea engelmannii* in two.

The spruce-fir forest in the vicinity of Sierra Blanca Peak is extensively used for skiing, and numerous paths have been cut for lift-lines and downhill runs. These paths and related access and maintenance roads have seriously chopped this very limited forest by creating numerous edge effects, but effects on water yield and quality are not documented. Snow depths vary from year to year, and during years of low snowfall, snow-making machines may be used to provide a satisfactory base for the runs. The *Abies lasiocarpa/Senecio sanguisorboides* HT is the principal watershed for the towns of Ruidoso and Capitan.

Dye and Moir (1977) studied the relationship of this HT to adjoining *Festuca thurberi* meadows. There is no evidence that many of these meadows are fire-initiated precursors of spruce-fir forest. Seral communities of the *Abies lasiocarpa/Senecio sanguisorboides* HT typically show a wealth of plant species, most of which are entirely absent from *Festuca thurberi* meadows (Moir 1967). Tree invasion under present climatic conditions is mostly lacking, except possibly in old sheep camps. However, a few small aspen stands have understories of *Festuca* and associated meadow species. These sites mostly border more mature coniferous forest and are seral forest communities of the *Abies lasiocarpa/Senecio sanguisorboides* HT. Conceivably, these seral border communities originated by grass fires pushing into adjoining forests. The greatest extent of *Festuca thurberi* meadows appears to be an edaphic climax on soils more finely textured than forest soils (Moir 1967). The meadows may have originated during drier or warmer postglacial climates as forests generally retreated upward in elevation and steppic vegetation expanded.

Figure 5.—*Abies lasiocarpa/Senecio sanguisorboides* HT, Sacramento Mountains. The shrubs, *Ribes wolfii* and *R. montigenum,* are common in the understory. The large tree at the right is *Abies lasiocarpa var. arizonica.* (Photo courtesy A.J. Dye)

DESCRIPTION OF MIXED CONIFER HABITAT TYPES

Picea pungens Series

9. *Picea pungens-Picea engelmannii/ Senecio cardamine* HT

Diagnostic vegetation.—*Picea engelmannii* usually in all size classes with light or moderate densities of regeneration and *Picea pungens* characteristically present. A low shrub layer is sparse and inconspicuous with *Lonicera utahensis* and *Rubus parviflorus* the most constant species. The herbaceous layer is well developed and diverse. Patches of *Senecio cardamine* are often conspicuous. Other common plants are *Pteridium aquilinum, Helenium hoopsii, Viola canadensis, Senecio wootoni, Geranium richardsonii, Fragaria virginiana, Bromus ciliatus,* and *Carex* spp.

We recognize two phases—the *Abies lasiocarpa* phase when this species has light to moderate regeneration, and the *Abies concolor* phase when this species has light to moderate regeneration with *Abies lasiocarpa* sparse or absent. Young *Picea pungens* and *Pinus strobiformis* are absent or sparse in the *Abies lasiocarpa* phase, but both have light densities in the *Abies concolor* phase. *Pseudotsuga menziesii* occurs in most size classes in both phases. *Pinus ponderosa* is an infrequent seral tree in both phases.

Geography.—Hannagan and Thomas Creek drainages of the White Mountains, Arizona.

Topography.—Gentle upland slopes and drainages, 8,800-9,200 feet (2,700-2,800 m), fingering down intermittent streamsides and lower northerly slopes to about 8,800 feet (2,700 m). The *Abies lasiocarpa* phase is usually not found on south-facing exposures, otherwise no consistent microsite differences occur between these phases.

Soils.—Sponseller Loam and various textural phases.

Ecotones and related habitat types.—Lower elevations have *Abies concolor-Pseudotsuga menziesii/Quercus gambelii* and *Abies concolor-Pseudotsuga menziesii* HT's as ecotones. Plot 10 on very stony, rocky upper side slopes is an old growth *Pinus strobiformis* forest with moderate stocking of young *Abies concolor* and *Pseudotsuga menziesii* and a herbaceous understory (including 4% cover of *Senecio cardamine;* the plot could not be classified.

These habitats are mostly closely related to the *Abies lasiocarpa/Rubus parviflorus* HT of the Mogollon Mountain. The *Abies lasiocarpa/Erigeron superbus* HT is also related, but the sparse cover of *Erigeron superbus* suggests that both phases occupy somewhat drier sites. All these habitats at lower elevations of the spruce-fir forests are within a family of HT's characterized by herbaceous understories (see the *Picea pungens-Picea englemannii/Erigeron superbus* HT).

Discussion.—This habitat type forms mosaics on undulant upland topography of the Hannagan and Thomas Creek drainages. Our study of tree structure from plots of both phases suggests the following climax status (C = climax co-dominant, c = minor climax, S = seral co-dominant, s = minor seral species, a = absent):

Species	Climax status	Percent of plots in phase *A. lasiocarpa*	*A. concolor*
Picea engelmannii	C	44	57
	c	56	15
	a	0	15
Abies lasiocarpa	C	78	0
	c	22	36
	a	0	64
Picea pungens	C	11	21
	c	33	71
	a	56	8
Abies concolor	C	0	36
	c	0	21
	S	22	8
	s	33	21
	a	45	0
Pseudotsuga menziesii	C	0	64
	c	0	14
	S	100	22
Pinus strobiformis	S	0	50
	s	44	29
	a	56	21
Pinus ponderosa	s	44	36
	a	56	64

Picea engelmannii, Picea pungens, and *Abies lasiocarpa* all have major or minor climax status in this *Picea/Senecio cardamine* HT, *Abies lasiocarpa* phase, and *Pseudotsuga menziesii, Abies lasiocarpa* and the pines are always seral. But all conifer species, except the pines, exhibit at least some climax potential in the *Picea/Senecio cardamine* HT, *Abies concolor* phase—a remarkable phenomenon that we have never experienced in coniferous forest of North America.

Site quality for *Picea engelmannii* is excellent. Site index at base age of 100 years breast height is about 110, but some specimens may reach 120 feet (37 m) or more at 100 years. Similarly, both *Pseudotsuga menziesii* and *Picea pungens* have good growth potential in this habitat; annual height increments averaged about 1 foot (25 cm). These habitats are important commercial forests. Timber volume from species such as *Picea engelmannii, Pseudotsuga menziesii,* and *Pinus ponderosa* is high in many old growth stands which contain larger trees often

240-260 years old at breast height. Gentle terrain is favorable to many logging operations and reforestation.

The major seral species after fire is *Populus tremuloides,* but many conifers of the late seral or climax vegetation may also become quickly established after fire. We consider this habitat type to be very near the boundary between spruce-fir and mixed conifer forests.

10. *Picea pungens-Picea engelmannii/ Erigeron superbus* HT

Diagnostic vegetation.—*Pseudotsuga menziesii* occurs in all sizes, and in four of five plots, is the leading regeneration species. Both *Picea pungens* and *Picea engelmanii* are major or minor co-climax species and have light or moderate regeneration densities. A well developed assemblage of herb species is present, with dominants including *Erigeron superbus, Carex foenea, Fragaria virginiana,* and *Lathyrus arizonicus.* Grasses are sometimes important: *Festuca arizonica* (up to 20% cover), *Muhlenbergia virescens, Poa pratensis,* and *Bromus ciliatus.*

Geography.—White Mountains, generally in the vicinity of Big Lake.

Topography.—Gentle slopes and plateau summits and ridges mostly around 9,000 feet (2,740 m) elevation; but on Burro Mountain it occurs at 9,800 feet (3,000 m); on all exposures.

Soils.—Mostly Sponseller gravelly silt loam.

Ecotones and related habitats.—These forests may adjoin grassy meadows dominated by *Festuca arizonica.* The most common nearby forest habitat is the *Picea pungens/Carex foenea* HT. This habitat is also related to the *Picea engelmannii/Senecio cardamine* HT of mountains just to the east. The tree structures are similar in both habitats; both have herbaceous understories, and occupy sites of similar landform and soils.

Discussion.—Most plots consisted of old-growth trees (larger trees 250-300 years old at breast height), forming semi-open canopies (overstory cover from 10% to about 35%) of *Pseudotsuga menziesii* and *Pinus ponderosa.* Partial overstory cutting took place in stands sampled by plots 80 and 81, but tree removal was light and seemed to have little effect on the present understory species composition. The other plots are within unlogged stands. Cattle are grazed in this HT, but the influence upon composition of the herbaceous understory could not be assessed.

Examination of the tree structures in the five plots located in this HT suggests the following climax status of the conifers (C = major climax, c = minor climax, S = major seral, s = minor seral, a = accidental or absent):

Species	Climax status	No. plots
Picea engelmannii	C	1
	c	4
Abies lasiocarpa	c	1
	a	4
Picea pungens	C	3
	c	2
Abies concolor	c or s	1
	a	4
Pseudotsuga menziesii	C	4
	c	1
Pinus strobiformis	S or s	5
Pinus ponderosa	S or s	3
	a	2

This habitat, like the *Picea pungens-Picea engelmannii/Senecio cardamine* HT, has at least four major or minor co-climax species. However, *Abies lasiocarpa* is very minor, and the climax status of *Abies concolor* is uncertain.

Fire scars at bases of some of the larger trees indicated ground fires. Fires in dry seasons may have been carried along a herbaceous cover, and some of these may have originated as range fires in dry parklands bordering these stands. *Populus tremuloides* is the major tree of the fire sere, but the 200-300-year-old pines in plots, as well as *Pseudotsuga menziesii* of about the same age, also may have become established, mostly in forest openings.

Site quality is moderate to good for both *Picea* species and moderate for *Pseudotsuga menziesii.* Individual tree selection is a suitable harvesting method, since these stands are mostly within a major recreation area (Big Lake) and have scenic value. Much of the timber volume is from the 200-300-year age classes, but shorter rotations of Douglas fir and shade tolerant spruce seem feasible.

11. *Picea pungens/Poa pratensis* HT

Diagnostic vegetation.—*Picea pungens* in all sizes and dominant in regeneration. Species of *Salix* and *Alnus* in a tall shrub stratum; other species of this stratum may include *Amelanchier alnifolia, Prunus virginiana,* and *Acer glabrum.* Extremely rich and diverse herbaceous vegetation (34-49 species in the plots). Dominants include *Poa pratensis* (3%-70% cover), *Fragaria* spp., *Erigeron superbus, Geranium richardsonii, Equisetum* spp., *Viola nephrophylla, Schizachne purpurascens,* and *Heracleum lanatum.*

Geography.—Sangre de Cristo, San Juan, Sacramento, Mogollon, and San Mateo Mountains.

Topography.—Streamsides and well watered tributary draws, the plots between 8,000-9,100 feet (2,440-2,750 m) elevation.

Soils.—Mostly deep alluvial soils with black, mollic epipedon.

Ecotones and related habitats.—This HT strings for miles along alluvial terraces of major drainages. At higher elevations, it merges with *Abies lasiocarpa/Vaccinium scoparium* HT, and at lower elevations, with *Pseudotsuga-Pinus ponderosa* streamside habitats, outside the scope of this study. *Populus augustifolia* may occur as codominant in some of these streamside habitats near lower distributional limits of *Picea pungens.*

Closely related habitats exist in canyon drainages at mid-elevations in southern Colorado and along the Front Range as far north as Left Hand Canyon near Boulder. We know of no related habitat in Arizona, although the *Picea pungens/Carex foenea* HT is, perhaps, the closest analogue. Alluvial terraces of major mountain drainage systems probably are just not that common in Arizona at elevations generally between 8,000-9,000 feet (2,440-2,740 m).

The habitat types of adjoining canyon sideslopes are numerous and varied, depending upon geographic range and elevation. Over much of the elevational and geographic range of the blue spruce streamsides, are adjacent sideslopes within the range of mixed conifer forest habitats described in this paper. At lower elevations, however, south-facing slopes may exhibit forest types of the *Pinus ponderosa* region (such as *Pinus ponderosa* and *Juniperus scopulorum* or *Pinus edulis* mixtures) while opposite slopes are classifiable as mixed conifer habitats. At upper elevations are north-facing slopes of habitat types classified as spruce-fir types in this paper, while south-facing slopes are again within the mixed conifer forest region.

Discussion.—This habitat type is possibly the most intensively utilized of all forests in Arizona and New Mexico. The number of recreational forest campgrounds along rivers and streams exceeds that of any other HT. Recreational fishing is also heavy. Many stands have been logged at least once. The habitat is very important as summer pasturage for livestock, because the best forage and watering areas are on the gentle slopes with low erosion potential.

For these reasons, it has been almost impossible to find stands with minimum human disturbance. Nearly all stands displayed signs of moderate to extensive impacts from some combination of camping, fishing, logging, or grazing.

The value of this HT is enhanced, because *Picea pungens* is a valuable horticultural species. Thus, the habitat is a valued gene pool for this species. But many other species of plants are also more or less confined to this habitat. Among these are *Cypripedium calceolus,* a rare species. Other species of botanical interest within this HT include *Habenaria hyperborea* and *H. saccata, Viola nephrophylla, Carex capillaris, Schizachne purpurascens,* and *Dodecatheon ellisiae.*

Site quality for *Picea pungens* is high (average annual growth exceeding 1 foot (30 cm)) or sometimes moderate (under 1 foot per year). Grazing quality for cattle and horses is high. The abundance of *Poa pratensis* in plot 130 may reflect a history of livestock grazing. Experience from other grazed locations within this HT suggests that *Poa pratensis,* a hardy and grazing-tolerant grass, increases, while palatable forbs such as *Heracleum lanatum* or *Mertensia franciscana* decline. Many pastures along streamsides throughout New Mexico are dominated by *Poa pratensis* within this habitat, although plots 26 and 121, which were lightly grazed by livestock, had only about 3%-4% cover.

Browse plants are important for domestic and wildlife in this habitat. In addition to the dominants listed above, *Cornus stolonifera, Rubus parviflorus, Lonicera involucrata* (at higher elevations), *Pachistima myrsinites, Symphoricarpos oreophilus,* several species of *Ribes,* and *Sherperdia canadensis* also are found. This browse assemblage might also be simplified or reduced in cover under intensive livestock grazing.

Aspen is the principal tree of the fire sere. Fires are probably less frequent in this habitat than in adjoining sideslopes or hotter, drier environments, but we have no evidence. However, *Populus tremuloides* was present in all plots, and often forms rather pure copses along the streamsides. Other seral species are *Pinus ponderosa, Pseudotsuga menziesii,* and *Abies concolor.*

12. *Picea pungens/Carex foenea* HT

Diagnostic vegetation.—*Picea pungens* in all size classes and of moderate to heavy regeneration densities. A well developed, herbaceous understory is dominated by graminoid species (*Carex foenea*) and grasses (*Muhlenbergia montana, Festuca arizonica,* and *Bromus ciliatus*).

We recognize two phases: the *Pseudotsuga menziesii* phase which has a strong codominance of Douglas fir including good regeneration, and the *Pinus ponderosa* phase which has Douglas fir poorly represented, especially in regeneration. The *Pseudotsuga menziesii* phase has *Carex foenea* as a strong herbaceous dominant with grasses not as important. The *Pinus ponderosa* phase has *Muhlenbergia montana* and other grasses as dominant in the understory, but *Carex foenea* is often minor. *Festuca arizonica* may be codominant in either phase, or is often absent. Important forbs include *Fragaria virginiana, Antennaria* spp., *Achillea lanulosa, Lathyrus arizonicus,* and species of *Erigeron.*

Geography.—White Mountains, North Kaibab Plateau, and possible outliers in the Mogollon Mountains.

Topography.—Gentle lower slopes and drainages, streamsides, and forest borders of grassy parks. Elevations as low as 8,300 feet (2,500 m) along drainages, but mostly 8,600-9,100 feet (2,620-2,770 m), and all exposures for the *Pinus ponderosa* phase and to 9,400 feet (2,860 m) for the *Pseudotsuga menziesii* phase. Some plots of the *Pseudotsuga menziesii* phase are also on moderate to steep sideslopes.

Soils.—Sponseller gravelly silt loam (White Mountains), and deep valley fills and alluviums derived from limestone (Kaibab Plateau), along with some Sprucedale Cobbly soils.

Ecotones and related habitats.—The most conspicuous ecotone is the grassy parkland of lower elevations. Forest ecotones include the *Abies lasiocarpa/Juniperous communis* and the *Abies lasiocarpa/Erigeron superbus* HT's on cooler, wetter sites, and the *Abies concolor-Pseudotsuga menziesii/Acer glabrum* HT, *Berberis repens* phase, and the *Abies concolor/Festuca arizonica* HT on drier sites. We know of no closely related habitats of other geographic areas. The *Picea pungens/Poa pratensis* HT of streamsides in New Mexico are usually on alluvial soils along permanent streams and rivers, whereas drainages in Arizona are more commonly intermittent within the *Picea pungens/Carex foenea* HT.

Discussion.—This is a major forest habitat of central and northern Arizona. The codominance of *Picea pungens* and *Pinus ponderosa,* often with heavy mixture of *Populus tremuloides,* are striking features of the pine phase of this HT. This habitat appears to be the optimum environment in Arizona for *Picea pungens,* which we regard as the climatic climax tree. This HT has very high scenic quality, and is visible from roads throughout valleys and parklands. The high proportion of aspen and the juxtaposition of forests and parklands contributes to this scenic appeal. Most stands of this habitat type visited are within summer grazing allotments.

Many stands in this habitat type are in areas of cold air drainage or frost pockets. At frost pockets (along margins of De Motte Park, for example), both *Picea englemannii* and *Abies lasiocarpa* occur sporadically, and on gentle, north-facing slopes, stands intergrade into spruce-fir habitat types. Warm, south-facing slopes may feature open, savanna-like *Pinus ponderosa* forest with light regeneration of *Picea pungens* and *Pinus ponderosa* (drier variants of our *Pinus ponderosa* phase of this HT). Xeric herbs of such warm microsites include *Chrysopsis villosa* var *foliosa, Hymenoxys subintegra, Festuca arizonica, Erigeron flagellaris,* and *E. formosissimus.* This herb assortment is highly similar to that of *Abies concolor/Festuca arizonica* HT. The chief distinctions between the two HT's at the warmer margins of the *Picea pungens/Carex foenea* HT are the regeneration of *Picea pungens* and the lack of any strong suggestion that *Abies concolor* is climax.

The shifts from *Carex foenea* to grasses in the two phases are quite distinctive. The reason for this differentiation of dominance relationships is uncertain. The influences of livestock, the frequency and characteristics of fires, and the duration of coniferous dominance between fire intervals are all possible causes. Our experience in other forest habitats hints that *Carex foenea* and other rhizomatous sedges are more

Figure 6.—*Picea pungens/Carex foenea* HT, *Pinus ponderosa* phase, North Kaibab Plateau. Note saplings of *Picea pungens*, mature *Pinus ponderosa*, and understory turf of *Carex foenea*.

tolerant of shaded coniferous microenvironments than the *Festuca arizonica* and the associated grasses (Moir 1966).

Fires play a major role in the dynamics of vegetation in this HT. Abundance of both *Populus tremuloides* and *Pinus ponderosa* in stands throughout this HT indicates that fires must have occurred frequently and at many locations within the past 100 years. The fires may commonly be surface fires. All the larger pines of plot 354, for instance, were fire-scarred at the ground (fig. 6). An occasional *Picea pungens* was spared as fire pursued its erratic course where fuel accumulations permitted. Specimens of *Picea pungens* in plot 371 were 230 years old at breast height. But fires may also crown during dry years or where high fuel loads or dense canopies allow. Fire created forest openings, regardless of size, may create herb dominance for a few years (Moir 1966), but rapidly growing aspen suckers soon result in tree dominance again. At certain sites along gentle drainages, a heavy cover of *Picea pungens* may be quickly established under aspen after fire.

Selective cutting has taken place at several locations adjoining or within plots. Trees harvested are mostly old-growth, overstory *Pinus ponderosa* or occasionally *Pseudotsuga menziesii. Pinus ponderosa* is the most important commercial tree of this HT, but its growth is poor to moderate. Site index is generally 70-80 (at 100 years). For *Picea pungens,* site quality of this HT is good to moderate.

13. *Picea pungens-Pseudotsuga menziesii* HT

Diagnostic vegetation.—The most conspicuous feature of this HT is the codominance of both *Picea pungens* and *Pseudotsuga menziesii* as climax species on valley sideslopes (rather than alluvial terraces or valley bottoms). *Abies concolor* is usually accidental, but may be minor seral in some plots. We are uncertain of its successional status in this HT.

We recognize four phases of this HT differing primarily in the following understory vegetative characteristics:

a) *Arctostaphylos uva-ursi* phase—Conspicuous abundance of both tall and low shrubs in the understory. Tall shrubs include *Amelanchier alnifolia* and *Salix scouleriana.* Low, evergreen shrubs include *Arctostaphylos uva-ursi* (20%-25% cover in two plots), *Pachistima myrsinites, Berberis repens* (4%-8% cover), and *Juniperus communis.* Low, deciduous shrubs are represented by *Rosa woodsii, Symphoricarpos oreophilus,* and *Rubus parviflorus.* Herbaceous cover was 15% and 44% in plots. Herbs present include *Oryzopsis asperifolia, Geranium* spp., *Lithospermum multiflorum, Achillea lanulosa, Pedicularis canadensis, Fragaria virginiana,* and *Poa pratensis.*

b) *Valeriana acutiloba* phase—A tall shrub layer may be represented by *Quercus gambelii, Acer glabrum,* or *Amelanchier alnifolia,* but it is typically rather sparse. Low shrubs include *Rosa* spp., *Lonicera arizonica, Juniperus communis,* and *Jamesia americana.* However, no shrub species exhibited sufficient constancy or dominance to be regarded as diagnostic. The herb cover is well expressed, with *Valeriana acutiloba, Bromus ciliatus, Fragaria vesca, Poa fendleriana, Aquilegia* spp., and *Cystopteris fragilis* characteristically present (fig. 7).

c) *Linnaea borealis* phase—The low evergreen shrub layer is very conspicuous, with *Linnaea borealis* 30%-60% cover. *Pachistima myrsinites, Juniperus communis,* and *Vaccinium myrtillus* may also be common.

d) *Juniperus communis* phase—Characterized by a very sparce understory cover, with only *Juniperus communis* reaching 1%-2% cover.

Geography.—The *Arctostaphylos uva-ursi,* the *Linnaea borealis,* and *Juniperus communis* phases occur in the Sangre de Cristo Mountains, with the latter extending into the San Juans. The *Valeriana acutiloba* phase occurs in the Sacramento, Mogollon, and White Mountains, Arizona.

Topography.—The *Valeriana acutiloba* and the *Linnaea borealis* phases occupy lower slopes of northerly aspect at 7,800-8,100 feet (2,380-2,470 m) and 8,700-8,900 feet (2,650-2,700 m) elevation respectively. The *Arctostaphylos uva-ursi* phase occurs on benches or lower slopes of east and south aspect at about 9,100 feet (2,760 m). The *Juniperus communis* phase is found on drier, upper slopes and ridges at 9,100 and 9,500 feet (2,770 and 2,900 m).

Soils.—Plots of the *Arctostaphylos uva-ursi* phase occur on the Jaroso-Encebado-Mascarenas Complex, and the Granite and Rhyolite Rockland mapping units. The *Valeriana acutiloba* phase plots along Gilita Creek were identified as the Rocker-Rockland Complex, and those in the Beaver Creek drainage as the Sprucedale very stony loam. Plots of the *Linnaea borealis* phase are mapped as the Jaroso-Encebado-Mascarenas Complex. The plot of the *Juniperus communis* phase along the Red River is mapped as Mallette-Granite and Rhyolite Stony Land.

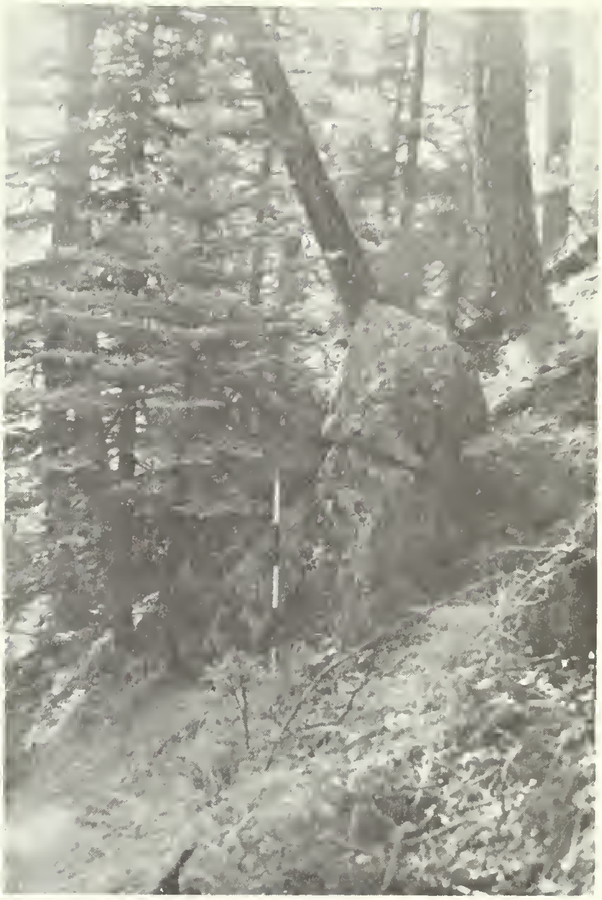


Figure 7.—*Picea pungens-Pseudotsuga menziesii* HT, Mogollon Mountains. A rich herb flora on these steep, lower slopes (elevation 2,430 m) along Gilita Creek includes *Poa fendleriana, Bromus ciliatus, Valeriana acutiloba,* and *Geranium richardsonii.*

Ecotones and related habitats.—The adjoining streamsides of all four phases are the *Picea pungens/Poa pratensis* HT. The upper ecotones of the *Arctostaphylos uva-ursi* phase include the *Abies lasiocarpa/Erigeron superbus* HT on north-facing slopes and the *Abies concolor-Pseudotsuga menziesii/Quercus gambelii* HT on south-facing slopes. This phase does not appear to have related habitats in other geographic regions. The *Valeriana acutiloba* phase in the White and Sacramento Mountains often adjoins grassy, streamside meadows. This phase seems to be related to the *Abies concolor-Pseudotsuga menziesii/Acer glabrum* HT, but occupies somewhat warmer sites (or possibly within cold air drainage convection) at lower elevations. The *Linnaea borealis* phase has an upper ecotone on north-facing slopes with the *Abies lasiocarpa/Vaccinium scoparium-Linnaea borealis* HT. The *Juniperus communis* phase plot along Deer Trail Creek is situated on a minor ridge paralleling the creek and is fringed by *Populus tremuloides* at the edge of the grassy meadows along the creek. Stands adjoining the plot of this phase on the

Red River appear to be mostly of the *Abies concolor-Pseudotsuga menziesii* HT, *Berberis repens* phase.

Discussion.—This HT and its various phases are generally at the drier environmental extreme for *Picea pungens*. Soils are usually colluvial rather than alluvial. Site indexes for both *Picea pungens* and *Pseudotsuga menziesii* are poor or very poor. For example, in the *Arctostaphylos uvi-ursi* phase, specimens of *Picea pungens* at 64, 84, and 96 years of age at breast height were respectively only 50, 59, and 74 feet (15, 18, and 22.5 m) tall. Similar poor growth was measured for *Picea pungens* in the *Juniperus communis* phase. Slightly better growth for both *Picea pungens* and *Pseudotsuga menziesii* may take place in the *Valeriana acutiloba* phase (site index at 100 years around 70 to 80).

Since this is a forest HT of lower canyon slopes, it has a high scenic quality, with high visibility along roads and streams. It provides good habitat for wildlife, but sparse understories in some stands permit less use by livestock than the adjoining *Picea pungens/Poa pratensis* HT of streamsides.

Selection cutting and fires are the most common disturbances. Seral species are *Populus tremuloides, Quercus gambelii,* and *Pinus strobiformis*. *Abies concolor* may be co-climax or late seral with *Picea pungens* and *Pseudotsuga menziesii* in our *Arctostaphylos uvi-ursi* phase.

Abies concolor Series

14. *Abies concolor-Pseudotsuga menziesii/Acer glabrum* HT

Diagnostic vegetation.—Either or both *Abies concolor* and *Pseudotsuga menziesii* dominate the forest regeneration of this habitat. *Pinus ponderosa* is accidental or minor, since neither regeneration nor mature trees are important in climax stands. The tall shrub layer is characteristic and consists of *Acer glabrum, Acer grandidentatum,* and *Amelanchier alnifolia*. *Quercus gambelii* and *Salix scouleriana* may be important in narrow canyons or streamsides, but *Acer* is always present.

We distinguish two phases based on the low shrub layer. The *Berberis repens* phase features this shrub as well as *Pachistima myrsinites*. The *Holodiscus dumosus* phase lacks *Berberis*. Other low shrubs characteristic of both phases may include *Symphoricarpus oreophilus, Jamesia americana,* and *Rosa woodsii*. There is often an excellent cover of herbs, with *Bromus ciliatus, Artemisia franserioides, Clematis pseudoalpina, Haplopappus parryi,* and *Lathyrus arizonicus* common.

Geography.—The *Berberis repens* phase occurs mostly in the Mountains of northern New Mexico, with an outlier in the White Mountains of Arizona. The *Holodiscus dumosus* phase occurs in the Sacramento, Mogollon, Chiricahua, and Pinaleno Mountains.

Topography.—The *Berberis repens* phase in northern New Mexico is found on east, south, or west-facing canyon sideslopes at elevations from 8,900-9,600 feet (2,700-2,900 m). It extends down streamsides to 7,700 feet (2,300 m). In the San Juan Mountains, it occurs on gentle north-facing mesa tops at 9,200-9,400 feet (2,800-2,900 m). It occurs on knolls in the White Mountains. The *Holodiscus dumosus* phase in southern New Mexico and adjacent Arizona is found on moderate to steep canyon sideslopes of east, and northwest exposures generally between 7,900 and 9,500 feet (2,400-2,900 m) in elevation. It also extends along streamsides down to about 6,800 feet (2,100 m). When found on south-facing slopes, this phase occurs on deep, well drained soils at higher elevations between 9,400 and 10,000 feet (2,900-3,000 m).

Soils.—Our plots of the *Berberis repens* phase occur on the following soil mapping units: Maes and Jarosa Cobbly Loams, Jarosa-Encebado-Mascarenas Complex, Granite and Rhyolite Stony Land, Jarosa-Encebado-Shale and Sandstone Stony Land, and Mallette-Granite and Rhyolite Stony Land Complexes. Our plots of the *Holodiscus dumosus* phase are on undescribed soils.

Ecotones and related habitats.—Cooler, wetter sites have spruce-fir forest HT's according to geographic area; warmer, drier sites commonly feature the *Abies concolor-Pseudotsuga menziesii/Quercus gambelii* HT or the *Abies concolor-Pseudotsuga menziesii* HT with a sparse understory. The two phases of this HT are clearly related, but neither appear to be similar to other habitats in this geographic region.

Discussion.—This is a major HT of cool, moist canyons and uplands of much of New Mexico and bordering mountains in Arizona. It is among the coolest, wettest of mixed conifer forest habitats and usually subtends spruce-fir forest. Either *Picea engelmannii* or *Abies lasiocarpa* may be found as regeneration or occasional mature trees in some stands, but they are minor and almost always are under severe competition from dense regeneration and canopy dominance of *Abies concolor* and *Pseudotsuga menziesii*.

Examination of plot data reveals the following:

Indicated climax	Number of plots by phase *Berberis*	*Holodiscus*
Abies concolor	6	6
Pseudotsuga menziesii	7	0
Abies + Pseudotsuga	13	9

Most plots have both species as co-climax. However, even in those plots where either species alone was indicated climax, the other species was present in lesser amounts as young or advanced regeneration. Thus, we regard *Abies concolor* and *Pseudotsuga menziesii* as climax species of equal importance in this HT.

Site quality for *Pseudotsuga* is poor in the *Berberis repens* phase. Heights at age 100 (bh) averaged about 75 feet (23 m). However, growth may be somewhat better in the *Holodiscus dumosus* phase. Heights of 55-year-old trees were 60-70 feet (18-21 m). In general, these trees are about 10 feet (3 m) taller than trees of comparable age in the other phase.

Populus tremuloides is the most important seral tree after fires, but *Pseudotsuga menziesii* can also be seral after fire on certain sites or after certain fires where *Populus* is not stimulated. Fires in these wet mixed conifer habitats are probably mostly light, erratic, and infrequent. *Pinus ponderosa,* possibly an indicator of more intensive fires in this HT, is only infrequently encountered. Localized "hot spots" may account for the patchiness or irregular structure—a cluster of aspen stems, mixed aspen and conifers, an infrequent ponderosa pine, open canopy of large old Douglas fir, or sapling thickets of mixed Douglas fir and aspen—all on the same slope (Jones 1974). Other disturbance factors encountered which contribute to the irregular forest structure include windthrow of large specimens of Douglas fir, and selective logging of mature trees.

Successional relationships within the *Holodiscus dumosus* phase have been studied by Hanks (1966) in the Sacramento Mountains. The principal cause initiating sucession was fire. Burns occured in 1963, 1950, 1945, 1939, and around 1886. Vegetation is primarily dominated by herbaceous species for a few years after heavy burns. *Quercus gambelii* and *Robinia neomexicana* follow this herb stage the second or third year after fire and persist—often attaining tree size—until coniferous dominance gradually ensues. Other important shrubs of this sere are *Acer glabrum, Holodiscus dumosus,* and *Ptelea angustifolia.* The final coniferous stage of succession on the north and east exposures is marked by establishment of *Pinus strobiformis, Abies concolor,* or *Pseudotsuga menziesii.* Hanks found *Pinus ponderosa* to be an infrequent species of the coniferous stage. *Pinus strobiformis* occurred as young or advanced regeneration in 80% of our plots of this HT phase, with regeneration densities ranging from 4 to 36 stems per ha. *Populus tremuloides* is also seral in some sites, either with, or to the exclusion of, *Quercus gambelii.* Aspen may be less important as a seral species in this phase than it is within the *Berberis repens* phase of northern New Mexico.

There is considerable environmental variation within this HT. Wetter streamside vegetation contains rich species assemblages. For example, plot 169 along Gallina Creek on the Espanola Ranger District has 62 understory species, many of which are apparently restricted to the wettest sites within the *Berberis repens* phase; among these species are *Melica porteri, Glyceria striata, Ranunculus* spp,. *Aquilegia chrysantha.* and *Trautvetteria grandis.* Mesic species included within the *Holodiscus dumosus* phase of this HT are *Potentilla thurberi, Rudbeckia laciniata, Aquilegia chrysantha,* and *Cardamine cordifolia.* Drier mid- and upper-slope sites have fewer understory species and usually a rather sparse herbaceous cover. However, the well developed shrub layer is diagnostic of this HT across this environmental range from wetter to drier sites.

This HT has an outlier occurring on a basaltic knoll in the White Mountain of Arizona. Its tall and low shrub strata are conspicuous, and tree regeneration of both *Abies concolor* and *Pseudotsuga menziesii* is dense. A scattering of *Picea pungens* and *Pinus strobiformis* of various sizes from young regeneration to mature individuals are found. Both *Picea Pungens* and *Populus tremuloides* skirt this knoll at the border of grassy meadows.

15. *Abies concolor-Pseudotsuga menziesii/ Quercus gambelii* HT

Diagnostic vegetation.—Either or both *Abies concolor* and *Pseudotsuga menziesii* dominate forest regeneration, usually with moderate to heavy densities. Either or both *Pinus strobiformis* and *P. ponderosa* are common seral trees. The understory tree or shrub vegetation is dominated by *Quercus gambelii,* with *Robinia neomexicana* often subdominant; species of *Acer* are absent.

We identify three phases of this habitat type. The typical *Quercus gambelii* phase has such characteristic graminoid species as *Bromus ciliatus, Poa fendleriana, Carex rossii,* and occassionally rhizomatous species of *Carex.* The *Muhlenbergia virescens* phase may have up to 60% cover by this bunchgrass. Other grasses may include *Stipa pringlei, Sitanion hystrix,* and minor amounts of *Festuca arizonica, Poa fendleriana, P. interior,* and *Koeleria cristata.* Forbs occasionally important include *Pteridium aquilinum, Thermopsis pinetorum,* and *Vicia pulchella.* The *Festuca arizonica* phase is diagnostic when dominance or codominance by this grass is apparent. *Muhlenbergia montana* and *Poa fendleriana* may also be common. Typical forbs include *Geranium caespitosum, Erigeron platyphyllus,* and *Artemisia ludoviciana.*

Geography.—Widespread in New Mexico and Arizona: Bill Williams Mountain, Sierra Ancha Mountains (Pase and Johnson 1968), Mogollon Plateau, White Mountains, Chiricahua Mountains (mostly in canyon bottoms), Mogollon Mountains, Sacramento Mountains (Hanks and Dick-Peddie 1974), Capitan Mountains, San Juan Mountains, Sangre de Cristo Mountains, and probably in most minor mountain ranges of New Mexico where elevations of major peaks exceed about 9,000 feet (2,740 m).

Topography.—All plots are between 7,700 and 9,500 feet (2,340-2,900 m) mostly on moderate to steep canyon sideslopes and generally on west, south, and east exposures (see the *Abies concolor-Pseudotsuga menziesii/Acer glabrum* HT for a habitat description of opposite canyon slopes). On the Mogollon Plateau the plots range from 7,400-7,900 feet (2,250-2,400 m) on gentle to steep sideslopes of north-flowing drainages. In minor mountain areas, this HT is often found in wet canyon drainages above about 7,400 feet (2,250 m) elevation.

Soils.—The soils of this HT are highly variable with respect to parent material, stoniness, and depth. Plots are commonly on soils of mollisolic and entisolic classifications developed from coarse talus colluviums of rough broken land, stony land complexes, and rock outcrop complexes.

Ecotones and related habitats.—Because of the widespread geographic distribution of this HT, ecotones occur with a great variety of habitats. Generally wetter or cooler sites have the *Acer concolor-Pseudotsuga menziesii/Acer glabrum* HT or various "forb-rich" understory HT's; while drier or warmer sites may exhibit stands of the *Abies concolor-Pseudotsuga menziesii* (sparse understory) HT or stands of the *Abies concolor/Festuca arizonica* and related HT's with grass dominated understories. A major ecotone is with grass dominated open meadows.

This HT extends into Colorado along the Sangre de Cristo and Front Range to about Colorado Springs and along the San Juan Mountains into southwestern Colorado. The oakbrush types described by Brown (1958) in west-central Colorado are drier habitats well outside the mixed conifer forest zone.

Discussion.—This is one of the most important mixed conifer HT's in the Southwest by virtue of its widespread occurrence and utilization. Most of the areas visited are commercial forest lands, and most are within livestock grazing allotments. In addition, the oaks and related understory plants provide many habitat requirements of food and shelter for deer and other wildlife.

The 54 plots within the typical phase of this HT reflect the widespread distribution of this type. In terms of environmental gradients within the mixed conifer zone, this phase probably occupies moderate regimes of both temperature and moisture. The *Muhlenbergia virescens* and *Festuca arizonica* phases of this HT were found in the mountains of southern Arizona and New Mexico and thus probably represent the drier fringe of mixed conifer forests. Forest stands of these phases intergrade to the *Quercus gambelii* phases of the *Pinus ponderosa/Muhlenbergia virescens* and the *Pinus ponderosa/Festuca arizonica* HT's of Hanks et al. (1977). Although there is no definite explanation for the relative dominance between grasses and oaks in these phases, but edaphic variability, especially in soil rooting volume and stoniness, may be partly the cause.

Considerable variation in both tree and understory characteristics is found throughout this HT. Our study of the tree structure in the typical phase indicates that most plots have both *Abies concolor* and *Pseudotsuga menziesii* sharing climax status as codominants:

Indicated climax	No. of plots
Abies concolor	16
Pseudotsuga menziesii	7
Abies + Pseudotsuga	26

Quercus gambelii may occur as understory trees—specimens up to 50 feet (15 m) and 14-15 inches (35-40 cm) d.b.h. are common on the Mogollon Plateau—or as low shrubby patches. The cover of herbaceous vegetation varies from sparse to moderate (about 40% of the plots had herb cover under 10%; about 30% of the plots had herb cover between 10%-20%; and the remaining 30% of the plots had herb cover exceeding 20%). Graminoid species are the most constant (*Poa fendleriana* up to 8% cover; *Bromus ciliatus* up to 5%; and *Carex rossii* to 15%). Forbs present in over half the plots included *Lathyrus arizonica, Pseudocymopteris montanus,* and *Thalictrum fendleri.*

Fires occur rather frequently within this HT (Hanks and Dick-Peddie 1974). After hot fires, a stage of forb succession may last a year or so before new oak sprouts assume dominance (Hanks 1966). The oak stage of the sere is most persistent—the oak dominating until conifers again come in and overtop the oaks. Important seral conifers are *Pinus ponderosa* and *P. strobiformis.* However, both *Pseudotsuga menziesii* and *Abies concolor* can also establish themselves within the oak thickets. Recurring fires kill seedling conifers, and even light surface burns may cause high mortality among *Abies* and *Pseudotsuga.* Open, park-like savannas with scattered groves of oak result (Cooper 1961, Hanks and Dick-Peddie 1974, Weaver 1967).

On most sites, natural succession into the final coniferous stages may proceed very slowly, but the oakbrush stage of this sere is never climax in this HT as indicated in some of the Timber Management Plans (Hanks 1966). On some sites, natural regeneration of conifers may proceed rapidly. Factors influencing regeneration rates include: the proximity of good seed sources, favorable microclimates for seedling survival, the nature of the fire initiating succession, the degree of oak competition, and seedling mortality from mammals (Jones 1974).

The most important commercial tree in this HT is *Pinus ponderosa,* a seral species. Site quality for *Pinus ponderosa* ranges from poor (site index about 65) to good (site index about 90), with most plots exhibiting moderate growth potential. Site quality for *Pseudotsuga menziesii* is poor to moderate, with the fastest growing specimens mostly between 75-100 feet (23-30 m) at age 100 (bh). The potential for livestock grazing in the typical phase is generally poor, since herbage production is often low, and the canyon terrain is often steep and poorly watered for livestock needs. However, the wildlife value is good, since many shrubs and herbs of this phase are favorable browse and forage.

16. *Abies concolor-Pseudotsuga menziesii* HT (Sparse understory)

Diagnostic vegetation.—Either or both *Abies concolor* and *Pseudotsuga menziesii* in all size classes and moderate or heavy stocking of young and advanced regeneration. Crown dominance by *Abies, Pseudotsuga, Pinus strobiformis,* and *P. ponderosa* in closed canopy. The understory has very sparse shrub and herbaceous cover, mostly less than 1%, but occassionally as high as 15%.

Plots of this habitat type were sorted into two geographic phases. The *Berberis repens* phase has understory with low evergreen shrubs such as *Berberis repens* (trace to 7% cover), *Juniperus communis* (trace to 15% cover), or *Pachistima myrsinites* (up to 2% cover). These shrubs are absent from nearly all stands of the *Robinia neomexicana* phase, where instead, deciduous shrubs (*Robinia neomexicana, Symphoricarpos oreophilus, Salix scouleriana,* and *Quercus gambelii*) are usually of at least sporadic occurrence.

Geography.—Widespread; the *Berberis repens* phase was sampled on the North Kaibab Plateau, White Mountains, San Juan, and Sangre de Cristo Mountains; the *Robinia neomexicana* phase was sampled in the Sacramento, Pinaleno, Chiricahua, Mogollon, and White Mountains.

Topography.—This habitat type occupies cool, dry sites. In northern New Mexico, stands of the *Berberis repens* phase occurred on generally steep slopes of various aspects between 9,200-10,500 feet (2,800-3,200 m) elevation. In southern parts of the State and southern Arizona, stands of the *Robinia neomexicana* phase were found on moderate to steep, north- to east-facing slopes mostly between 8,050-9,200 feet (2,450-2,800 m) elevation. However, stands also occurred on south- or west-facing slopes (and sometimes on high ridgetops) at higher elevations (8,700-9,300 feet, or 2,650-2,830 m).

In central and northern Arizona, forests of the *Berberis repens* phase were sampled on undulant, gentle to moderately sloping uplands between 8,600-9,000 feet (2,620-2,740 m).

Soils.—Sponseller Loam (White Mountains), Corner Stony Loam and Whitetail Stony Sandy Loam (Mogollon Mountains), mostly stony soils of rough broken land and stony land mapping complexes in northern New Mexico, including Granite and Rhyolite Stony Land, Mallette-Granite-Rhyolite Stony Land, and Jaroso-Encebado-Mascarenas Complex.

Ecotones and related habitats.—Ecotones include *Abies concolor-Pseudotsuga menziesii/Quercus gambelii* HT, *Picea pungens/Carex foenea* HT (North Kaibab Plateau), and *Pseudotsuga menziesii/Quercus hypoleucoides* HT (Chiricahua Mountains). At the cooler, wetter border of this habitat type are forests of spruce-fir habitat types, depending upon the geographic area. We are unaware of related habitats in other western states.

Discussion.—The definition of this habitat type was difficult. There were very few consistent understory characteristics to conceptualize the habitat. Many herbs and shrubs of the mixed conifer region occur but these exhibit low constance and seldom have more than a trace of cover. In a few plots, *Quercus gambelii* or *Robinia neomexicana* suggested affinity to herb-sparse variations of the *Abies concolor-Pseudotsuga menziesii/Quercus gambelii* HT. We were concerned that some stands where sparse understories were found might be shade phases of other HT's under closed conifer canopies or local areas of intensive or prolonged wildlife browsing. Plots in the Chiricahua Mountains helped resolve these difficulties. The four plots all occurred on cool slopes of the highest peaks on sites that could not be assigned to any other habitat type that was clearly recognized in those mountains. The stands were all undisturbed by man, with largest trees between 95-140 years old at breast height. This distinctive forest habitat in the Chiricahua Mountains was initially defined as the *Abies concolor-Pseudotsuga menziesii-Pinus strobiformis* sparse shrub and herb habitat. Similar forests in the Pinaleno Mountains were identified later, providing a sufficient nucleus of plot types of this HT to identify similar plots from other geographic locations. Distinctive features of stands in this HT in late seral succession are closed canopies of mixed conifers and generally sparse understories (fig. 8).

Figure 8.—***Abies concolor-Pseudotsuga menziesii* HT at 2,740 m elevation on the North Kaibab Plateau. The sparse understory is typical of this habitat type.**

The environment of this HT is cool and relatively dry. In the Chiricahua Mountains, a pronounced drought occurs from May to early July, but the high elevation and northerly exposures may ease drought effects. Both seasonal soil water deficits and shading may combine to limit herb growth (small openings in the Chiricahua Mountains are dominated by *Bromus ciliatus, Helenium hoopsii,* and other herbs), while deer populations may limit shrub development.

Site quality is good in the Chiricahua Mountains. Measured specimens of *Pseudotsuga* were about 115 feet (35 m) in height at 100 years of age (bh). A 95-year-old specimen of *Abies concolor* near Rustlers Park was 119 feet tall (36 m). Unfortunately this high site quality is seldom found on commercial forest lands of other locations. In the White Mountains, Pinaleno, and

Sacramento Ranges, site quality for *Pseudotsuga menziesii* in our stands was generally moderate (site index about 80 at base age of 100 years). Observations on *Pinus ponderosa* were too few for estimating growth potential.

Neither *Populus tremuloides* nor *Quercus gambelii* are important seral trees after fire. We suggest that severe fires might bring about herb dominated clearings where conifers rapidly reestablish. Both *Pinus ponderosa* and *P. strobiformis* are important seral trees, and the latter persists well into the closed canopy stage. But *Abies concolor* and *Pseudotsuga menziesii* may also be seral, depending on seed sources and environmental conditions following disturbance. Fire behavior in these habitats may be erratic and unpredictable, with highly variable burn conditions from year to year.

In the Mogollon Mountains *Chimaphila umbellata* and *Pyrola picta* are constant, low evergreen herbs of this HT. The minor occurrence of *Picea engelmannii* or *Abies lasiocarpa* in most of our plots suggests environmental similarity to the cooler spruce-fir forests. Other rather distinctive features include the infrequent occurrence of such mesic forbs as *Viola canadensis, Senecio cardamine, Smilacina racemosa,* and *Clemotis pseudoalpina.* In addition, trees or suckers of *Populus tremuloides* occurred in five plots; this is not usually a seral species of the HT in southern New Mexico and Arizona. For these reasons we suggest that the Mogollon Mountains present a somewhat distinctive microclimate on mid-elevation north-facing slopes compared to adjoining, smaller mountain areas (Chiricahua, Pinaleno Mountains, Black Range) where stands of this HT are also found.

Plots in the North Kaibab Plateau were all within commercial forest land. Timber volume is mainly *Abies concolor* with lesser amounts of *Pseudotsuga* and *Pinus ponderosa.* Heights at 100 years of age (bh) for dominant *Abies* specimens are mostly 75-85 feet (23-26 m) with occasional trees to 95 feet (29 m). Periodic defoliation by budworms and infections of *Arceuthobium campylopodum* var. *abietinum* reduce growth rate in this HT. Measurements on six specimens of *Pinus ponderosa* between 102-157 years of age (bh) were from 77-92 feet (23-28 m).

Dominant vegetation of clearcut openings near plot 361 consisted of *Chenopodium album* and *Epilobium angustifolium.* Other common or abundant species were *Berberis repens, Ribes cereum, Rubus strigosus,* species of *Carex, Poa fendleriana,* and *Penstemon barbatus.* Such clearings provide major food resources for deer.

In the Sangre de Cristo Mountains, this habitat is found on the boundary of mixed conifer forests on dry south and west aspects with cobbly, coarse-textured soils. Unlike other habitat types with sparse herbaceous understories, here *Abies concolor* may be absent or of minor climax status.

Although many stands in the Sangre de Cristo Mountains are within commercial forest lands, the site quality for both *Pseudotsuga menziesii* and *Pinus ponderosa* is poor. Site index at base age of 100 years is about 60 for *Pseudotsuga menziesii.* Mostly visual estimates for pine suggest a similar slow growth rate and site index of 50-60.

Tree species of a fire sere include *Populus tremuloides* and *Pinus ponderosa.* Species of sporadic or minor importance include *Pinus aristata, P. strobiformis,* and *Quercus gambelii.*

The warm slopes of this HT appear to be of considerable value to wildlife. The steep slopes are often laced with game trails, and many of the shrub species are heavily browsed.

Although herbaceous vegetation is poorly developed under conifers, the nearby openings may exhibit good cover of grasses such as *Koeleria cristata, Muhlenbergia montana,* and *Poa fendleriana.* Possible explanations are discussed in the section on *Pseudotsuga menziesii-Pinus strobiformis/Muhlenbergia virescens* HT below and in Moir (1966).

17. *Abies concolor/Acer grandidentatum* HT

Diagnostic vegetation.—*Abies concolor* dominates regeneration; *Pseudotsuga menziesii* is minor. *Acer grandidentatum* is a strong dominant (70-90% cover) of the understory.

Geography.—Plots are on the Mogollon Plateau (Chevelon Ranger District). The habitat occurs locally in drainages along the Mogollon Rim and in the Pinaleno Mountains, and Santa Catalina Mountains (Whittaker and Niering 1965).

Topography.—Gentle northerly drainages of the Mogollon Plateau at 7,500-7,900 feet (2,300-2,400 m), and well watered intermittent drainages of steeper canyons to about 7,000 feet (2,100 m).

Soils.—Undescribed.

Ecotones and related habitats.—Plots all adjoin stands of the *Abies concolor-Pseudotsuga menziesii/Quercus gambelii* HT. The habitat is related to streamside variants of the *Abies concolor-Pseudotsuga menziesii/Acer glabrum* HT, *Holodiscus dumosus* phase. It is also similar in floristic composition to the *Abies concolor/Carex foenea* HT along gentle drainages at higher elevations, above 9,000 feet (2,700 m), in the Pinaleno Mountains, although this habitat lacks *Acer grandidentatum.*

Discussion.—This is a comparatively minor HT in Arizona, which is found mostly as a topographic climax along gentle drainages at comparatively low elevations. Dominance of the understory by *Acer grandidentatum* is the most characteristic feature of the HT, but the understory is also well developed with such herb species as *Carex foenea* (7%-30% cover), *Thalictrum fendleri* (trace to 40%), *Aquilegia chrysantha,* and others. The location of stands along gentle concave drainages or canyon bottoms is a consistent feature of the HT.

Seral conifers such as *Pseudotsuga menziesii* (common) or *Pinus ponderosa* (infrequent) have mostly been logged in this habitat. Other seral trees are *Populus tremuloides* and *Quercus gambelii* (the former reaching 120 feet (36 m) in sheltered canyon bottoms such as upper See Canyon on the Tonto Rim). Logging probably accelerates growth and development of *Acer grandidentatum* as a result of increased light in the understory. Some specimens of *Acer* in our plots were about 40 feet (12 m) tall. Strong dominance by *Acer* in logged plots does not seem to retard conifer establishment; young regeneration by *Abies concolor* ranged from 26-360 stems/ha and *Pseudotsuga menziesii* from 2-40 stems/ha.

In the Santa Catalina Mountains, Whittaker and Niering (1965) record the presence of *Acer grandidentatum* in ravines and draws at about 8,000 feet (2,500 m) elevation. They describe within their Montane Fir Forest Zone the dominance of *Pseudotsuga* and *Abies concolor* with *Acer grandidentatum* in ravines and on lower slopes between 7,000-8,000 feet (2,200-2,500 m). These forests most likely can be assigned to the *Abies concolor/Acer grandidentatum* HT.

18. *Abies concolor/Festuca arizonica* HT

Diagnostic vegetation.—Usually moderate to heavy stocking of young *Abies concolor* (densities of young regeneration vary from 22-330 stems/ha; young plus advanced regeneration vary from 44-400 stems/ha); light to moderate stocking of young *Pseudotsuga*. *Pinus ponderosa* is an important seral species, and may exhibit scattered regeneration in mature stands.

Shrubs are minor and unimportant. A well developed herbaceous vegetation is particularly conspicuous in openings. Dominants include combinations of the following bunchgrasses: *Festuca arizonica, Muhlenbergia montana,* and *M. virescens.* Other grasses usually present include *Poa fendleriana, Koeleria cristata, Sitanion hystrix,* and *Stipa pringlei.* Forbs commonly associated with the grasses include *Lithospermum multiflorum, Antennaria* spp., *Lathyrus arizonicus, Thalictrum fendleri, Achillea lanulosa,* and *Erigeron* spp.

Geography.—San Francisco Peaks, Mogollon Plateau, White Mountains, and San Juan Mountains.

Topography.—Ridges and gentle slopes or moderate to steep east, south, or west-facing canyon slopes. Elevations from 7,000-9,400 feet (2,130-2,860 m).

Soils.—Generally unmapped and undescribed. Parent materials include basalt and sandstones. Soils on plot 85 were mapped as Sponseller Silt Loam. A roadcut near plot 301 exhibited a shallow, cobbly A1 over sandstone bedrock.

Ecotones and related habitats.—The *Abies concolor/Festuca arizonica* HT intergrades into *Picea pungens/Carex foenea* HT and *Abies concolor-Pseudotsuga menziesii, Berberis repens* phase. Along hotter, drier gradients this HT merges into the *Pinus ponderosa/Festuca arizonica* HT and related habitat types of the ponderosa pine region (Hanks et al. 1977).

This HT is related to *Abies concolor-Pseudotsuga menziesii/Elymus triticoides* HT, *Abies concolor-Pseudotsuga menziesii/Poa fendleriana* HT, and *Abies concolor-Pseudotsuga menziesii/Quercus gambelii* HT, *Muhlenbergia virescens* phase. These HT's all exhibit strong regeneration by *Abies concolor* and grass dominated herbaceous understories. They probably occur within seasonally dry climates near the warmest temperature range of mixed conifer forest.

Discussion.—*Festuca arizonica* ranged from 3%-40% cover, species of *Muhlenbergia* were found from trace amounts to 20% cover. Grasses and associated herbs are best expressed in openings and often have very sparse cover in dense pole stands or under closed conifer canopies. The value of this HT for seasonal livestock grazing is very good, and several plots are within grazing allotments.

The patchy distribution of conifer regeneration commonly seen in this HT can be attributed, at least in part, to the erratic course of wildfires. Fire was a common thinning agent. Dormant shoots of the herbaceous layer could carry a surface fire into thickets of regeneration. If coniferous debris is heavy within these thickets, the fire might crown and consume the entire thicket; otherwise only the smaller trees might be killed, depending upon fire intensity (Weaver 1967, Cooper 1961a, 1961b). Seedlings and poles of *Abies concolor* are particularly sensitive to fire. However, fires are mostly beneficial to herbs, especially during herb dormancy. The fire-created openings produce more favorable conditions of light, nutrient supply (especially nitrogen), and other requirements for enhanced herbaceous growth (Moir 1966).

Pinus ponderosa and *Pseudotsuga menziesii* are important commercial species of this habitat. Gentle terrain and multistoried, patchy canopy distribution encourages selective cutting at many sites. The primary silvicultural problem may be restocking with ponderosa pine, especially in some of the larger herbaceous openings. This problem has been addressed in numerous papers by G. A. Pearson (Axelton 1967). Pearson was concerned mostly with drier pine sites, and it must be kept in mind that this HT is still within the mixed conifer forest zone and at the mesic end of natural ponderosa pine regeneration. Our plots exhibit light to moderate stocking of pine regeneration, but this is usually swamped by competition from *Abies* and *Pseudotsuga*. Cutting and thinning techniques can be used to encourage the young pines.

Site quality appears moderate for *Pinus ponderosa* and poor for *Pseudotsuga menziesii.* The pines are about 70-80 feet (21-24 m) at 100 years of age (bh). Our height and age measurements for six Douglas fir specimens are variable, but fall within the growth range of *Pseudotsuga* for the *Abies concolor-Pseudotsuga menziesii/Acer glabrum* HT.

Although *Pinus ponderosa* is the most important seral tree, the plots occasionally exhibit a scattering of stems and suckers of *Populus tremuloides* or *Quercus gambelii*. These are considered minor seral species of this habitat type.

Pseudotsuga menziesii Series

19. *Pseudotsuga menziesii-Pinus strobiformis/Muhlenbergia virescens* HT

Diagnostic vegetation.—*Pinus ponderosa* in all sizes, with moderate stockings of young and advanced regeneration. *Pinus strobiformis* is usually of moderate regeneration density. *Pseudotsuga menziesii* is often in dense sapling (0-4 inches d.b.h.) thickets. *Abies concolor* is infrequent or absent. Shrubs are minor. The well developed herbaceous layer is dominated by *Muhlenbergia virescens* (fig. 9).

Geography.—Chiricahua, Mogollon, Pinaleno, and Santa Catalina Mountains (Whittaker and Niering 1965).

Topography.—Ridges and dry mid- to upper-slopes between 7,600-9,200 feet (2,300-2,800 m) elevation. The slopes vary from gentle to steep and are of southerly, west, or less common east-facing aspects.

Ecotones and related habitats.—This HT has many similar features to the *Pinus ponderosa/Muhlenbergia virescens* HT described in the White Mountains by Hanks et al. (1977). The principal distinction concerns the high regeneration potential of *Pseudotsuga menziesii* in plots of the *Pseudotsuga menziesii-Pinus strobiformis/Muhlenbergia virescens* HT. The wettest plots in the *Pinus ponderosa/Muhlenbergia virescens* HT also contain *Abies concolor* in very minor amount, and clearly there is gradation between the two habitat types.

The *Pseudotsuga menziesii-Pinus strobiformis/Muhlenbergia virescens* HT is ecologically similar to other HTs where caespitose grasses are dominant or codominant with shrubs in the understory such as HTs 15 and 18 (table 2). Ecological processes such as fire, seasonal drought, and influences of grazing animals may play similar roles in these conifer-bunchgrass ecosystems, although their intensity and frequency may vary from habitat to habitat (Pearson 1950, Moir 1966, Weaver 1967, Cooper 1960).

Ecotones can occur between *Pseudotsuga menziesii-Pinus strobiformis/Muhlenbergia virescens* and *Pseudotsuga menziesii/Quercus hypoleucoides* HT's on wetter slopes. Hot, drier slopes sometimes exhibit ecotone to Pine-oak woodland (Whittaker and Niering 1965). Adjacent north-facing slopes and lower slopes or canyon bottoms may be within the *Abies concolor-Pseudotsuga menziesii* (sparse understory) or *Abies concolor-Pseudotsuga menziesii/Quercus gambelii* HT's.

Figure 9.—*Pseudotsuga menziesii-Pinus strobiformis/Muhlenbergia virescens* HT, Mogollon Mountains. The meter stick is near a specimen of *Pinus ponderosa* with fire scarred base. The dominant grass is *Muhlenbergia virescens.*

Discussion.—This is the hottest and driest of mixed conifer forests in the above mountain ranges. *Abies concolor* with low regeneration potential occurred in only 45% of the plots. But thickets of other mixed conifers (mostly *Pseudotsuga)* may have total stem densities as high as 5,700/ha (14,000/acre). Such regeneration is usually in patchy mosaics.

There is a pronounced inverse relationship between coniferous densities and cover of herbaceous vegetation. Mechanisms of herb suppression under conifer thickets probably include shading, soil nitrogen depletion, growth suppressing effects of terpenes and other coniferous biochemicals of the forest floor, altered soil water supply at sites of increasing tree dominance, and interactive effects (Moir 1966, Whittaker and Feeny 1971).

Fire appears to be a critical factor for determining the spatial and cover relationship between trees and herbs. The frequency of surface fires before about 50 years ago is evidenced by fire scars at the bases of most larger *Pinus ponderosa* and *P. strobiformis* in all plots (fig. 9). Charcoal is a common material of surface organic horizons. Decades of fire suppression are resulting in heavy fuel load accumulation and extensive suppression of understory grasses.

The effect on water yield of converting open, grass-dominated, savanna-like ecosystems to closed coniferous forests is possibly very substantial (Swank and Douglas 1974), but little data are available for Southwestern mountain watersheds.

Although the grazing potential of this HT is good where conifer thickets are not extensive, the high ridges and upper slopes may lack reliable water sources for domestic livestock, and access may be difficult in remote areas.

SPRUCE-FIR FORESTS: OTHER HABITAT TYPES

There are a variety of other habitat types of spruce-fir forests in Arizona and New Mexico. These are all of restricted geographic distribution, although each may be important within its particular location.

The *Picea engelmannii/Geum rossii* HT and the *Abies lasiocarpa/Lathyrus arizonicus* HT both occur in the San Francisco Peaks. The former is near timberline and is characterized by absence or accidental status of *Abies lasiocarpa* and by presence in the understory of numerous species of high elevation or tundra affinity, including *Geum rossii, Festuca brachyphylla, Polemonium delicatum,* and dwarfed ecotypes of *Aquilegia chrysantha* and *Mertensia franciscana.* The latter subtends the spruce-fir zone at its lowest elevation. Plots were on westerly slopes at 9,700-9,800 feet (2,900-3,000 m). *Picea engelmannii* was only occasional; the dominant tree overstory consisted of admixtures of *Abies lasiocarpa* and *Populus tremuloides.* Understory is very herbaceous. Abundant species included *Lathyrus arizonicus, Smilacena stellata, Geranium richardsonii, Pteridium aquilinum,* and *Bromus ciliatus.*

The *Picea engelmannii/Elymus triticoides* HT is restricted to the Capitan Mountains at uppermost elevations. *Pseudotsuga menziesii* is codominant; *Abies lasiocarpa* varies from absent to codominant. A shrubby understory varying from 2% to 23% cover consists of *Acer glabrum, Holodiscus dumosus, Jamesia americana,* and *Ribes* spp. Soils are very cobbly, and understory vegetation appears to be related to the buildup of soils, commencing from raw talus. On best developed soils *Elymus triticoides* may have up to about 20% cover.

The *Picea engelmannii/Carex foenea* HT is found in the Pinaleno Mountains on upper slopes and ridges around 10,200 feet (3,100 m) elevation. Soils are cobbly and skeletal, with best expression of *Carex foenea* (up to 70% cover) on finer textured microsites. Clearings after logging are dominated by *Carex* and grasses; aspen is absent. Regeneration by spruce in these meadows may be difficult because of dry site conditions and possible seedling mortality through solarization (Ronco 1970).

The *Abies lasiocarpa/Vaccinium myrtillus* HT is found at Bear Canyon, Mogollon Plateau. Spruce is absent. This disjunct outlier of *Abies lasiocarpa* at 7,750 feet (2,400 m) elevation is most related to *Abies lasiocarpa/Rubus parviflorus* HT of the Mogollon Mountains. Both contain rich herb and shrub understories. Refugium species at Bear Canyon include *Vaccinium myrtillus, Disporum trachycarpum, Calamagrostis canadensis, Polemonium flavum, Lonicera involucrata,* and *Stellaria jamesiana.*

Disjunct outliers of *Picea engelmannii* are also found in the Chiricahua Mountains and in Hubbell and Sacramento Canyons of the Sacramento Mountains. These were assigned to the *Picea engelmannii/Acer glabrum* HT. *Pseudotsuga menziesii* is the most important codominant tree. *Acer glabrum* is usually present in the understory. Herb cover from 5% to 17% in plots included, as most constant species, *Bromus ciliatus, Viola canadensis, Smilacina stellata,* and *Ligusticum porteri.* The HT is of interest primarily because of the presence of Engelmann spruce at low elevations (8,900-9,200 feet, or 2,700-2,800 m) at its southern limits in North America (lat. 31°52'N. in the Chiricahua Mountains).

MIXED CONIFER FORESTS: OTHER HABITAT TYPES

A number of habitat types of mixed conifer forests are either of limited geographic range in Arizona and New Mexico or more widespread, but of insufficient sample frequency to construct reasonably complete habitat type tables.

The *Abies concolor-Pseudotsuga menziesii/Erigeron superbus* HT was sampled in the San Juan Mountains and Mogollon Plateau. Both *Abies concolor* and *Pseudotsuga menziesii* dominate the tree regeneration, and the understory is richly herbaceous with such species as *Erigeron superbus, Lathyrus arizonicus, Fragaria virginiana, Thermopsis pinetorum,* and *Carex foenea.* The habitat appears to be closely related to the *Abies concolor-Pseudotsuga menziesii/Acer glabrum* HT, differing primarily by the absence of *Acer glabrum.*

The *Abies concolor/Carex foenea* HT is restricted to the Pinaleno Mountains in our sample, but may possibly occur elsewhere in Arizona. *Abies concolor* dominates forest regeneration, and *Carex foenea* has 80% cover in a single plot on a gentle south-facing minor concave drainage at 9,100 feet (2,760 m) elevation.

The *Abies concolor/Robinia neomexicana* HT in the White Mountains in the vicinity of Juan Garcia Mountain and upper Pulcifer Creek appears to be an edaphic type on deep volcanic ash soils. The diagnostic habitat characteristic is dominance (30%-60% cover) by *Robinia neomexicana* in the understory. Herbaceous cover is also good. Much of the forest is logged, although site quality for species of *Pseudotsuga* and *Pinus ponderosa* is poor.

The *Abies concolor-Pseudotsuga menziesii/Lathyrus arizonica* HT occurs in the San Francisco Peaks. Either or both *Abies* and *Pseudotsuga* dominate forest regeneration. *Berberis repens* has cover up to about 4%, and *Lathyrus arizonicus* with cover up to 20% dominates the herb layer.

Abies concolor-Pseudotsuga menziesii/Elymus triticoides HT is a special HT in the Capitan Mountains where it fringes the *Picea engelmannii/Elymus triticoides* HT. Soils are rubble pavements and lithic, skeletal profiles with thin mollic epipedon over cobbles. This HT is within the group of mixed conifer habitats characterized by grass-dominated understories (such as habitat types 12, 15, and 18).

The *Abies concolor-Pseudotsuga menziesii/Poa fendleriana* HT was sampled at 8,600-8,900 feet (2,600-2,700 m) in the Bear Creek drainages of the White Mountains. Soils are probably of the Sprucedale Series. The habitat type is characterized by moderate regeneration of both *Abies* and *Pseudotsuga,* and the herbaceous understory dominated by *Poa fendleriana* (15-20% cover). A long list of forb species are important constituents of the herb layer, including *Fragaria vesca, Senecio wootoni, Achillea lanulosa, Geranium richardsonii,* and species of *Erigeron.*

The *Pseudotsuga menziesii/Festuca arizonica* HT may be more common and widespread than our limited sample suggests. Plots occurred in northern New Mexico and the San Francisco Peaks. Stands are comparatively open with light regeneration of *Pseudotsuga menziesii. Abies concolor* is rare; *Pinus strobiformis* may be common. Characteristically, the understory is grassy, with dominance by *Festuca arizonica.* Other herbs include *Muhlenbergia montana, Erigeron subtrinervis, Koeleria cristata,* and *Fragaria vesca.* Plots were all on moderate to steep, southerly facing slopes between 9,600-10,200 feet (2,900-3,100 m). Soils were skeletal-cobbly at all sites, and shallow to underlying bedrock.

The *Pseudotsuga menziesii/Physocarpus monogynus* HT is closely related to *Picea pungens-Pseudotsuga menziesii* HT. It was sampled only once on very poor site with thin, cobbly solum at Rio Chiquito in the Sangre de Cristo Mountains at 8,900 feet (2,680 m). The conspicuous, low shrub layer was dominated by *Physocarpus monogynus* and *Symphoricarpos oreophilus. Pseudotsuga menziesii* is the dominant tree but has poor growth. *Abies concolor* and *Picea pungens* are rare or accidental.

The *Pseudotsuga menziesii/Quercus hypoleucoides* HT is found in Basin and Range Mountains of southern Arizona (Whittaker and Niering 1965) and southwestern New Mexico. *Abies concolor* has minor regeneration potential at the upper elevational edge of this HT, namely around 7,400-7,700 feet (2,250-2,340 m) elevation on northerly or east-facing slopes or draws. The principal climax species, however, is *Pseudotsuga menziesii.* The habitat type is best characterized by abundance of such Madrean species as *Quercus hypoleucoides, Q. rugosa,* and *Yucca schottii.* In the Chiricahua Mountains, the robust grass, *Muhlenbergia longiligula,* is the ground dominant, achieving cover around 25% or more. Other grasses include *Panicum bulbosum, Bromus ciliatus,* and *Agropyron arizonicum.*

The *Pinus strobiformis/Festuca arizonica* HT is rather open forest of windy sites and lithic-skeletal soils. The all-aged pine and grassy understory are diagnostic. *Pseudotsuga menziesii* occurs as scattered regeneration and a few old trees. Principal grasses are *Festuca arizonica* and *Muhlenbergia montana.* The type is closely related to the *Pseudotsuga menziesii-Pinus strobiformis* HT and may be more common in Arizona and New Mexico than our single sample at San Francisco Peaks suggests.

SUMMARY AND CONCLUSIONS

This study presented a habitat type classification of spruce-fir and mixed conifer forests in Arizona and New Mexico, based on field measurements in 415 forest plots.

The classification yielded 8 habitat types in the spruce-fir region and 11 habitat types in the mixed conifer region. In addition, 6 other spruce-fir and 10 other mixed conifer forest habitat types in Arizona and New Mexico were tentatively defined. Most of these 16 other habitat types are of restricted geographical occurrence in Arizona or New Mexico, or are special forest types related to unusual soils, isolated geographic outliers, or restricted topographic occurrences. However, it is possible that some of these may be more extensive or important, and are merely undersampled.

High elevation forests in Arizona and New Mexico are discontinuous by virtue of the varied physiographic regions and discontinuous mountain ranges. In addition, the major routes of migration and evolution of forest floras and communities have been from the north along the Rocky Mountain and Cascade-Sierra Nevada Cordilleras. For these reasons, the high elevation coniferous forests at their southern North American limits in Arizona and New Mexico usually exhibit varying degrees of floristic and ecologic distinctiveness in each of the mountain ranges.

Each habitat type encompasses a relatively narrow range of environmental conditions. We also believe that the biological potential and management opportunities are more uniform and better defined within each habitat type than between habitat types.

Principal seral trees are *Populus tremuloides, Pinus strobiformis, P. ponderosa,* and *Quercus gambelii. Pinus contorta,* a major seral species of mixed conifer and spruce-fir forests of the central and northern Rocky Mountains (Moir 1969), does not occur in Arizona or New Mexico. All other trees of our study can be variously seral or climax depending upon habitat type (appendix table A1). In the drier HT's, where fire frequencies allow species such as *Pinus ponderosa* or *P. strobiformis,* which are normally seral, they can be regarded as fire climax, and *Pseudotsuga menziesii* and *Abies concolor,* otherwise climax, may be minor or absent.

To help identify these habitat types in the field, keys have been prepared (see appendix). The keys are applicable to mature forest stands only, and cannot be used in seral types such as aspen. Two further limitations on the applicability of these keys should be noted:

The keys work best for modal plots of our habitat types. Environmental variants or integrades to other habitat types may not key out;

The keys do not purport to exhaust the habitat types of a region.

We expect refinements and modifications of both our habitat type classification and the descriptive keys as additional data are acquired. This study has been based mostly upon extensive reconnaissance survey throughout high elevation forests of Arizona and New Mexico.

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APPENDIX

Plant List—Spruce-fir and Mixed Conifer Forests, Arizona and New Mexico[1]

I. Trees

Abies concolor (Gord. & Glend.) Hoopes
A. lasiocarpa (Hook.) Nutt.
A. lasiocarpa var. *arizonica* (Merriam) Lemmon
Picea engelmannii Parryi
P. pungens Engelm.
Pinus aristata Engelm.
P. engelmannii Carr
P. ponderosa Laws.
P. ponderosa var. *arizonica* (Engelm.) Shaw
P. strobiformis Engelm.
Populus angustifolia James
P. tremuloides Michx.
Pseudotsuga menziesii (Mirbel) Franco
Quercus gambelii Nutt.
Q. hypoleucoides A. Camus
Q. rugosa Nee
Robinia neomexicana Gray

II. Understory Trees or Shrubs

Acer glabrum Torr.
A. grandidentatum Nutt.
A. negundo L.
Alnus oblongifolia Torr.
A. tenuifolia Nutt
Amelanchier alnifolia Nugg. (4,115,210)
Arctostaphylos uva-ursi (L.) Spreng
Berberis repens Lindl.
Brickellia grandiflora (Hook.) Nutt. (407)
Ceanothus fendleri Gray
Chimaphila umbellata (L.) Nutt. (323)
Chrysothamnus parryi var. *nevadensis* (Gray) Kittell (365)
Cornus stolonifera Michx. (183)
Gaultheria humifusa (Gray) Rydb. (217)
Holodiscus dumosus (Nutt.) Heller (267)
Jamesia americana T. & G. (147)
Juniperus communis L.
J. deppeana Steud.
J. scopulorum Sarg.

[1] *Collection number in parentheses; hyphenated numbers are specimens from the Sacramento Mountains, New Mexico, deposited at University of Colorado, and University of Wyoming herbaria; all other numbers are deposited at the USDA Forest Service Herbarium, Fort Collins, Colo., with duplicates for some numbers at New Mexico State University herbarium, Las Cruces, N. Mex.*

Linnea borealis L. (116)
Lonicera arizonica Rehder (35, 298)
L. involucrata (Rich.) Banks (208)
L. utahensis Wats. (32,166)
Pachistima myrsinites (Pursh) Raf. (16)
Philadelphus microphyllus Gray
Physocarpus monogynus (Torr.) Coult. (124)
Populus tremuloides Michx.
Potentilla fruticosa L.
Prunus emarginata (Doug.) Walp. (19,332)
P. virginiana L.
Quercus arizonica Sarg.
Q. gambelii Nutt.
Q. hypoleucoides A. Camus
Q. rugosa Nee
Rhamnus betulaefolia Greene (268)
Robinia neomexicana Gray
Rosa arizonica Rydb (252)
R. fendleri Crepin
R. woodsii Lindl. (126)
Ribes cereum Dougl. (186)
R. coloradense Cov.
R. inerme Rydb. (240)
R. montigenum McClatchie (92, 128)
R. pinetorum Greene (30,266)
R. wolfii Rothrock (125,263)
Rubus neomexicanus Gray
R. parviflorus Nutt. (253)
R. strigosus Michx. (264)
Sambucus glauca Nutt
S. racemosa L.
Salix spp.
S. scouleriana Barratt (113,169)
Saxifraga bronchialis L.
Shepherdia canadensis (L.) Nutt.
Sorbus dumosa Greene
Symphoricarpos oreophilus Gray (136)
Vaccinium caespitosum Michx.
V. myrtillus L. (165)
V. scoparium Leib. (88)

III. Graminoids

Agropyron arizonicum (Gray) Petrak (395)
A. trachycaulum (Link) Malte (95,329)
Agrostis alba L. (299)
A. scabra Willd. (239,353)
Andropogon scoparius Michx.
Blepharoneuron tricholepsis (Torr.) Nash (66-14,66-15)
Bromus anomalus Rupr. (357,414,160)
B. ciliatus L (98,158,228,322,368,383,398,399)
B. frondosus (Shear) Wood. & Stand. (241)
Calamagrostis canadensis (Michx.) Beauv.
C. inexpansa Gray (167)

Carex spp. (260,417,418)
C. bella Bailey (231,300)
C. brevipes W. Boott (26)
C. capillaris L. (108)
C. foenea Willd. (25,37,143,66-8)
C. geophila Mack. (338)
C. hoodii Boott (402)
C. microptera Mack. (192)
C. occidentalis Bailey (6,292,352)
C. rossii Boott (251,258,262,269)
Danthonia intermedia Vasey (236,304)
Deschampsia caespitosa (L.) Beauv.
Elymus glaucus Buckl. (179)
E. triticoides Buckl. (265)
Festuca arizonica Vasey (67-13)
F. brachyphylla Schultes (325)
F. ovina L. (351)
F. sororia Piper (175,334,399)
F. thurberi Vasey (67-6)
Glyceria striata (Lam.) Hitchc. (271)
Juncus drummondii E. May (218)
Koeleria cristata (L.) Pers. (90)
Luzula parviflora (Ehrh.) Desv. (122,129,187,405)
L. spicata (L.) DC (216)
Melica porteri Scribn. (235)
Muhlenbergia longiligula Hitchc. (376,412)
M. montana (Nutt.) Hitchc. (349,394)
M. virescens (HBK) Kunth. (18,282,284)
Oryzopsis asperifolia Michx.
O. micrantha (Trin. & Rupr.) Thurb. (238)
Panicum bulbosum H.B.K. (413)
Phleum pratense L.
Poa fendleriana (Steud.) Vasey (14)
P. interior Rydb. (110)
P. occidentalis Vasey (257)
P. pratensis L. (146)
P. reflexa Vasey & Schrib. (193,200,231)
Schizachne purpurascens (Torr.) Swall. (117,303)
Scirpus microcarpa Pers. (272)
Sitanion hystrix (Nutt.) J.G. Sm (161)
Stipa columbiana Macoun
S. pringlei Scribn.
Stipa viridula Trin. (342)
Trisetum montanum Vasey (159,227,247,321,66-44)
Trisetum spicatum (L.) Richt. (328)

IV. Perennial Forbs

Achillea lanulosa Nutt.
Aconitum columbianum Nutt. (188)
Actaea arguta Nutt.
Agastache pallidiflora (Heller) Rydb. (66-47)
Agoseris glauca (Pursh) D. Dietr. (362)
Allium cernuum Roth. (67-2)
A. geyeri Wats. (67-1)
A. gouddingii Ownbey (275)
Anaphalis margaritacea (L.) Gray (66-37)
Angelica grayii C. & R. (202)
Antennaria aprica Greene (1)
Apocynum androsaemifolium L.
Aquilegia caerulea James
A. chrysantha Gray (326)
A. elegantula Greene (121,256)
A. triternata Pays. (3,150)
Arabis spp. (66-11)
Arenaria confusa Rydb. (308,310,361)
A. fendleri Gray (67-14)
A. macrophylla Hook. (222)
Arnica cordifolia Hook. (205)
A. latifolia Bong. (204)
Artemisia dracunculoides Pursh
A. franserioides Greene (224,66-43)
A. frigida Willd.
A. ludoviciana Nutt. spp. *mexicana* (Willd.) Keck (66-27)
A. scopulorum Gray
Aster adenolepsis Blake (359)
Astragalus humistratus Gray (341,358)
A. subcinereus Gray (350)
Brickellia grandiflora (Hook.) Nutt. (250,391)
Cacalia decomposita Gray (378)
Calochortus spp.
Caltha leptosepala DC
Calypso bulbosa (L.) Oakes (29)
Campanula rotundifolia L.
Cardamine cordifolia Gray (120,190)
Castilleja confusa Greene (270,289,363)
C. miniata Hook. (81,123)
C. patriotica Fern. (379)
C. wootonii Standl. (66-13,66-53,67-9)
Cheilanthes fendleri Hook. (415)
Chrysopsis villosa var. *foliosa* (Nutt.) D.C. Eat. (360)
Circium arizonicum (Gray) Petrak (366,389)
C. pallidum Woot. & Standl. (181,66-21,67-4)
Clematis ligusticifolia Nutt.
C. pseudoalpina (Kuntze) A. Nels. (15, 145)
Commelina dianthifolia Delile (386)
Corallorhiza maculata Raf. (105)
C. striata Lindl.
C. trifida Chat.
Corydalis aurea Willd.
Cynoglossum offininale L.
Cypripedium calceolus L.
Cystopteris fragilis (L.) Bernh. (229)
Dodecatheon ellisiae Standl.
Draba aurea Vahl. (313)
D. helleriana Greene (111,173,195,196,219,221,233,66-2)
Disporum trachycarpum (Wats.) B. & H. (33)
Epilobium adenocaulon Hausskn. (273)
E. angustifolium L.
Erigeron spp. (401)
Erigeron coulteri Porter (201)
E. flagellaris Gray (97)
E. formosissimus Greene (343,364,397,286,184)
E. lobatus A. Nels. (372)
E. melanocephalus Nels. (215)

E. neomexicanus Gray (248,372,335)
E. peregrinus (Pursh) Greene
E. platyphyllus Greene (261,293,317,337,66-46)
E. rusbyi Gray (385,411)
E. speciosus (Lindl.) DC var. *macranthus* (Nutt.) Cronq. (318,66-31)
E. speciosus (Lindl.) DC var. *speciosus* (176)
E. subtrinervis Rydb. (96,213)
E. superbus Rydb. (101,163,220,226,286,314,67-8)
Eriogonum racemosum Nutt. (331,348)
E. jamesii Benth (85)
Erysimum asperum (Nutt.) DC (89)
Eupatorium herbaceum (Gray) Greene (416)
Fragaria vesca var. *bracteata* (Heller) Davis (23)
Fragaria virginiana var. *glauca* Wats. (= F. ovalis (Lehm.) Rydb.) (22)
Frasera speciosa Doubl.
Galium asperrimum Gray (382)
G. boreale L. (180)
G. triflorum Michx. (149,225,307)
Gaultheria humifusa (Gray) Rydb. (217)
Gentiana amarilla L. (211,66-48)
G. microcalyx Lemmon (419)
Geranium caespitosum James (99,278)
G. richardsonii Fisch. & Trautv. (107,134,157,311,373)
Geum rossii (R.Sr.) Ser. (330)
Gilia aggregata (Pursh) Sprengel
G. macombii Torr. (367)
Goodyera oblongifolia Raf. (296)
G. repens (L.) R.Br.
Habenaria hyperborea (L.) R.Br. (245)
H. saccata Greene (83)
H. viridis var. *bracteata* (Muhl.) Gray (82)
Haplopappus parryi Gray *(Oreochrysum parryi* Rydb.) (148,223,66-52)
Hedeoma hyssopifolium Gray (291,400)
Helenium hoopesii Gray (66-6)
Helianthella parryi Gray (214)
H. quinquenervis (Hook.) Gray (66-9)
Heracleum lanatum Michx.
Heuchera spp.
Hieracium fendleri Schutz-Bip. (164,173,316,409)
H. gracile Hook. (194)
Houstonia wrightii Gray (281)
Hydrophyllum fendleri (Gray) Heller (135)
Hymenopappus radiatus Rose
H. mexicanus Gray (306)
Hymenoxys subintegra Cockl. (344)
Iris missouriensis Nutt.
Lathyrus spp. (133)
Lathyrus arizonicus Britt. (9,20,21)
L. graminifolius (Wats.) White (380)
Ligusticum porteri C. & R. (191,207)
Linanthrastrum nuttallii (Gray) Ewan (297)
Linnaea borealis L. (116)
Listera cordata (L.) R.Br. (84)
Lotus rigidus (Benth.) Greene (346)
L. wrightii (Gray) Greene (283)
Lupinus argenteus Nutt. (340)
L. sierrae-blancae Woot. & Standl. (66-7)
Lithospermum multiflorum Torr. (132,155,324)
Malaxix corymbosa (Wats.) Kuntze
M. soulei L.O.Williams (246)
Macromeria viridiflora DC
Mertensia franciscana Heller (131,140,141,171,259,327)
Moneses uniflora (L.) Gray (104)
Monarda menthaefolia Graham (279)
Oenothera hookeri T. & G. (319)
Oreoxis alpina (Gray) C. & R.
Osmorhiza depauperata Phil. (127,144,67-15)
Oxalis metacalfei (Small) Kunth (312)
Oxybaphus comatus (Small) Weatherby (375,392,66-50)
Oxypolis fendleri (Gray) Heller (232)
Pedicularis angustissima Greene (309)
P. canadensis L. (142)
P. centranthera Gray (294,302)
P. grayii A. Nels. (285)
P. parryi Gray (162)
P. racemosa Dougl. (168)
Penstemon barbatus (Cav.) Roth. (277)
P. virgatus Gray (305)
P. virgatus ssp. *arizonicus* (Gray) Keck (153)
P. whippleanus Gray (318)
Perideridia gairdneri (H. & A. Math.) (301)
Phacelia heterophylla Pursh
Phaseolus parvulus Greene (371)
Physaria australis (Payson) Rollins
Podistera eastwoodii (C. & R.) Math. & Const. (234)
Polemonium pulcherrimum var. *delicatum* (Rydb.) Cronq. (203) (= *P. delicatum* Rydb.)
P. foliosissimum Gray (182)
P. flavum Greene
Polygonum bistortoides Pursh
Potentilla concinna Richards (10)
P. diversifolia Lehm. (206)
P. hippiana Lehm. (287)
P. pennsylvanica L. (66-24)
P. gracilis var. *pulcherrima* (94,66-26,255) (= *P. pulcherrima* Lehm.)
P. thurberi Gray (393)
P. subviscosa Greene (404)
Prunella vulgaris L.
Primula ellisiae Pollard & Cockll.
P. parryi Gray
Pteridium aquilinum (L.) Kuhn.
Pseudocymopteris montanus (Gray) C. & R. (138,67-10)
Pterospora andromedea Nutt.
Pyrola asarifolia Michx. (212)
P. picta Smith (310)
P. secunda L. (= *Ramishia secunda* (L.) Garke) (102,67-17)
P. uniflora L. (= *Moneses uniflora* (L.) Gray) (104)
P. virens Schweigg (5,103,114)
Ranunculus hydrocharoides Gray (274)
R. subsagittatus (Gray) Greene (31)
Rudbeckia hirta L.
R. laciniata L. (174)

Salvia arizonica Gray (406)
S. davidsonii Greenm.
Sedum spp.
S. amplectens Gray (197)
Senecio atratus Greene
S. bigelovii Gray (230,66-33)
S. cardamine Greene (11,244)
S. cymbalarioides Nutt. (100,109,112,185)
S. eremophilus Richards (408,66-20)
S. fendleri Gray (93)
S. Macdougalii Heller
S. neomexicanus Gray (24,152,170)
S. sanguisorboides Rydb. (189,66-1)
S. triangularis Hook.
S. wootoni Greene (27)
Sibbaldia procumbens L.
Sidalcea neomexicana Gray (276,288)
Silene laciniata Cav. (66-41)
S. scouleri Hook (345,396)
Smilacina racemosa (L.) Desf. (7)
S. stellata (L.) Desf. (12)
Solidago altissima L. (336)
S. spathulata var. *neomexicana* (Gray) Cronq. (209,243)
S. wrightii Gray (384)
Stellaria jamesiana Torr. (130)
Stevia serrata Cav. (369,388,410)
Streptopus amplexifolium (L.) DC
Taraxacum spp. (cf. T. officinale Weber) (34)
Thalictrum fendleri Engelm. (66-45)
Thelypodium integrifolium (Nutt.) Endl. (290,335)
Thermopsis pinetorum Greene
Thlaspi fendleri Gray (28)
Townsendia formosa Greene (156)
Tragopogon dubius Scop.
Trautvetteria grandis Nutt.
Trifolium spp.
T. dasyphyllum T. & G. (198)
Urtica spp.
Valeriana acutiloba Rydb.
V. edulis Nutt.
Verbena macdougalii Heller (66-21)
Veronica wormskjoldii R. & S. (199)
Vicia americana Muhl. var. *americana* (137)
V. pulchella H.B.K. (249,370)
Viola adunca J.E. Sm. (118,119)
V. canadensis L. (17)
V. nephrophylla Greene (13,106)
Zygadenus elegans Pursh (295,333)
Z. virescens (HBK) Macbr. (315)

V. Annuals

Androsace septentrionalis L. (36)
Bidens lemmonii Gray (377)
Cerastium arvense L. (254)
Chenopodium incisum Poir (s.n.)
Conyza schiedeana (Less.) Cronq. (403)
Halenia recurva (J.E. Sm.) Allen (242)
Muhlenbergia wolfii (Vasey) Rydb. (66-35)
Verbesina longifolia Gray (390)

Key to Forest Habitat Types by National Forest Area and Geographic Location

Apache and Sitgreaves Forests (White Mountains, Mogollon Plateau)

1. PIEN or ABLA climax (regeneration clearly not accidental) 2
1. PIEN and ABLA regeneration absent or accidental 6
2. *Vaccinium myrtillus* common 3
2. *Vaccinium myrtillus* absent or rare 4
3. PIEN absent; Chevelon Ranger District . . . . . ABLA/VAMY HT
3. PIEN present; Mount Baldy . . . . . ABLA/VASC HT
4. ABLA regeneration light to moderate . . . . . PIPU-PIEN/SECA HT, ABLA Phase
4. ABLA regeneration absent or rare 5
5. Patches of SECA present . . . . . PIPU/PIEN/SECA HT, ABCO Phase
5. Patches of SECA absent 6
6. PIPU present and clearly not accidental 7
6. PIPU absent or accidental 11
7. PSME the leading codominant tree; regeneration by PIEN and PIPO usually sparse or absent 8
7. PIEN or PIPO leading codominants; PSME regeneration minor 10
8. CAFO common (3%-10%) . . . . . PIPO/CAFO HT, PSME Phase
8. CAFO cover less than 1% or absent 9
9. JUCO or *Lonicera arizonica* common . . . . . PIPO-PSME HT, VAAC Phase
9. POFE common . . . . . ABCO-PSME/POFE HT
10. PIEN regeneration absent or light . . . . . PIPU/CAFO HT, PIPO Phase
10. PIEN regeneration common; ERSU usually common . . . . . PIPU-PIEN/ERSU HT
11. Tall shrubs (or low deciduous trees) present 12
11. Tall shrubs absent or very infrequent 18
12. Species of *Acer* present 13
12. *Acer* absent 14
13. *Acer grandidentatum* dominant . . . . . ABCO/ACGR HT
13. *A. grandidentatum* absent or minor . . . . . ABCO-PSME/ACGL HT, BERE Phase
14. Forest of deep ash soils; RONE dominant . . . . . ABCO/RONE HT
14. RONE sparse, minor or absent; soils otherwise 15
15. QUGA dominant; MUVI absent or infrequent . . . . . ABCO-PSME/QUGA HT
15. QUGA cover less than about 5%, or if more then MUVI dominant in herbaceous layer 16
16. ERSU common . . . . . ABCO-PSME/ERSU HT
16. ERSU absent or uncommon; POFE or MUVI common 17
17. MUVI common . . . . . ABCO-PSME/QUGA HT, MUVI Phase
17. POFE cover over 10% . . . . . ABCO-PSME/POFE HT
18. Understory cover sparse; bunch-grasses uncommon . . . . . ABCO-PSME HT
18. Grass cover well developed (MUVI, MUMO, FEAR) 19
19. MUVI dominant . . . . . PSME-PIST/MUVI HT
19. FEAR or MUMO dominant . . . . . ABCO-FEAR HT

Coronado National Forest (Chirichua, Pinaleno, Santa Catalina Mountains)

1. PIEN or ABLA climax (regeneration clearly not accidental) 2
1. Regeneration of PIEN and ABLA absent or accidental 5
2. VAMY or CAFO common 3
2. Both VAMY and CAFO uncommon, rare or absent 4
3. VAMY common . . . . . ABLA/VASC HT
3. CAFO common . . . . . PIEN/CAFO HT
4. ACGL absent . . . . . PIEN/Moss HT
4. ACGL present . . . . . PIEN/ACGL HT
5. Species of *Acer* absent 6
5. *Acer* absent 7
6. *Acer grandidentatum* present or dominant . . . . . ABCO/ACGR HT
6. *A. grandidentatum* absent or rare . . . . . ABCO-PSME/ACGL HT, HODU Phase
7. QUGA present, usually common 8
7. QUGA absent or minor 9
8. MUVI absent or minor . . . . . ABCO-PSME/QUGA HT
8. MUVI common . . . . . ABCO-PSME/QUGA HT, MUVI Phase
9. Evergreen oaks common . . . . . PSME/QUHY HT
9. Evergreen oaks absent or infrequent 10
10. Herbs very sparse; CAFO and MUVI clearly not dominant . . . . . ABCO-PSME HT
10. CAFO or MUVI dominate herb layer (except where sometimes suppressed under conifer thickets) 11
11. CAFO dominant; MUVI absent or uncommon 12
11. MUVI dominant . . . . . PSME-PIST/MUVI HT

12. ABCO regeneration common . . . . ABCO/CAFO HT
12. ABCO regeneration absent or minor . . . . PSME/CAFO HT

Lincoln National Forest (Sacramento and Capitan Mountains)

1. PIEN or ABLA climax (regeneration clearly not accidental) 2
1. PIEN and ABLA regeneration absent or accidental 4

2. *Senecio sanguisorboides* and either or both *Ribes wolfii* and *R. montigenum* dominants of the understory . . . . ABLA/SESA HT
2. The above species minor or absent 3

3. Low elevation forests, Sacramento Mts.; no ABLA . . . . PIEN/ACGL HT
3. High elevation forests, Capitan Mts. . . . . PIEN/ELTR HT

4. PIPU present 5
4. PIPU absent 6

5. Forests of alluvial soils of valleys . . . . PIPU/POPR HT
5. Forests of canyon sideslopes . . . . PIPU-PSME HT, VAAC Phase

6. QUGA or species of *Acer* common 7
6. *Acer* absent; QUGA with less than 5% cover, but if greater then both PSME and ABCO with only minor regeneration 10

7. *Acer* species present; PIPO uncommon . . . . ABCO-PSME/ACGL HT, HODU Phase
7. *Acer* absent; PIPO a common seral tree 8

8. Combinations of MUMO, FEAR, MUVI, or *Stipa pringlei* important understory grasses (but sometimes suppressed under conifer thickets) 9
8. Above combination of grasses minor; POFE, BRCI, or caespitose sedges (*Carex* spp.) may be common . . . . ABCO-PSME/QUGA HT, QUGA Phase

9. ABCO or PSME regeneration usually of light or moderate density . . . . ABCO-PSME/QUGA HT, FEAR Phase
9. ABCO and PSME regeneration absent or rare 11

10. ELTR common; Capitan Mountains . . . . ABCO-PSME/ELTR HT
10. ELTR absent or rare 11

11. Very little shrub or herb cover under mature stands . . . . ABCO-PSME HT
11. Understory grasses with at least 2% cover . . . . ABCO-PSME/QUGA HT, FEAR Phase

Carson and Santa Fe National Forests (San Juan, Sangre de Cristo Mountains, San Pedro, Jamez Mountains)

1. PIEN or ABLA climax (regeneration clearly not accidental) 2
1. Regeneration by PIEN and ABLA absent or accidental 9
2. PSME not even seral, or only minor (see also 5,8) 3
2. PSME seral, common in understory 4
3. Forests near timberline; *Polemonium delicatum* or *Senecio amplectens* common . . . . PIEN/VASC/PODE HT
3. Forests at timberline or below, often on dry ridges or upper slopes; understory vascular flora rather sparse . . . . PIEN/Moss HT
4. *Vaccinium* dominant 5
4. *Vaccinium* minor or absent 6
5. LIBO dominant or codminant . . . . ABLA/VASC/LIBO HT
5. LIBO minor or absent . . . . . ABLA/VASC HT

6. LIBO dominant or codminant; PIPU common . . . . PIPU-PSME HT, LIBO Phase
6. LIBO absent 7

7. Moderate or heavy cover by understory forbs 8

7. Sparse cover of understory forbs . . . . ABLA/JUCO HT

8. ERSU dominant or at least common . . . . ABLA/ERSU HT
8. SESA, *Cardamine cordifolia* or *Oxypolis fendleri* common; forests of creeks or drainages . . . . ABLA/SESA HT

9. PIPU climax or co-climax 10
9. PIPU absent or minor 13

10. Forests of streamsides, alluvial terraces, or benches 11
10. Forests of canyon sideslopes 12
11. *Poa pratensis* common; ABCO and PSME minor . . . . PIPU/POPR HT
11. ABCO or PSME apparently co-climax; POPR infrequent . . . . PIPU-PSME HT, ARUV Phase
12. LIBO common; forests of mesic lower or midslopes . . . . . PIPU-PSME HT, LIBO Phase
12. LIBO absent; forests of dry mid or upper slopes . . . . PIPU-PSME HT, JUCO Phase
13. Mesic forbs (ERSU, HAPA, VICA, ARFR, LAAR) common; tall shrubs (ACGL, SASC, QUGA) present or absent 14
13. Mesic forbs infrequent; tall shrubs usually absent, but low shrubs (BERE, PHMO, SYOR, *Ribes cereum*) may be common 16
14. Both ACGL and QUGA absent or rare; CAFO common . . . . ABCO-PSME/ERSU HT

14. Either ACGL or QUGA present, or if absent then CAFO also absent or minor (cover less than 10%) 15
15. ACGL present . . . . ABCO-PSME/ACGL HT, BERE Phase
15. ACGL absent . . . . . ABCO-PSME/QUGA HT
16. FEAR and MUMO absent or rare 17
16. FEAR or MUMO common 18
17. PHMO common . . . . PSME/PHMO HT
17. PHMO minor at best; BERE, SYOR, or JUCO present . . . . . . ABCO-PSME HT, BERE Phase
18. Regeneration of ABCO moderate or heavy . . . . ABCO/FEAR HT
18. Regeneration of ABCO absent or sparse . . . . PSME/FEAR HT

Coconino and Kaibab National Forests (Kaibab Plateau, San Francisco Peaks, Bill Williams Mountain)

1. PIEN and ABLA climax (regeneration clearly not accidental) 2
1. Regeneration by PIEN and ABLA absent or accidental 6
2. Forests near timberline, *Geum rossii* or other tundra species present . . . . PIEN/GERO HT
2. Forests either well below timberline or *Geum rossii* absent 3
3. Herbaceous cover usually over 10% 4
3. Herbaceous cover usually sparse, less than 10% 5
4. ERSU common; PIEN common to occasional . . . . ABLA/ERSU HT
4. ERSU absent or rare; LAAR common; PIEN uncommon . . . . ABLA/LAAR HT
5. Forests below 10,000 ft elevation; JUCO or BERE present, but understory herbaceous cover usually sparse . . . . ABLA/JUCO HT
5. Forests over 10,000 ft elevation; BERE absent . . . . PIEN/Moss HT
6. PIPU climax or co-climax 7
6. PIPU minor or absent 8
7. PIPO regeneration common, or if uncommon then MUMO or FEAR common; ERSU usually absent . . . . PIPU/CAFO HT, PIPO Phase
7. PIPO regeneration minor; MUMO and FEAR uncommon; ERSU usually present . . . . PIPU/CAFO HT, PSME Phase
8. FEAR or MUMO common 9
8. FEAR and MUMO absent or uncommon 10
9. Regeneration of ABCO common . . . . ABCO/FEAR HT
9. Regeneration of ABCO absent or minor . . . . PSME/FEAR HT
10. QUGA common . . . . ABCO-PSME/QUGA HT
10. QUGA absent 11
11. CAFO less than 5% cover, if more then JUCO present 12
11. CAFO cover over 5% and JUCO usually absent . . . . ABCO/CAFO HT
12. LAAR absent or under 1% cover . . . . ABCO-PSME HT, BERE Phase
12. LAAR cover exceeds 10% . . . . ABCO-PSME/LAAR HT

Gila National Forest (Mogollon Mountains)

1. PIEN or ABLA climax (see also 8) 2
1. PIEN and ABLA regeneration absent or accidental 6
2. *Vaccinium myrtillus* dominant or codominant in understory 3
2. *Vaccinium myrtillus* minor or absent 4
3. Mature PSME absent or infrequent; RUPA absent or cover less than about 5% . . . . ABLA/VASC HT
3. Mature PSME common; RUPA cover 7% or more . . . . ABLA/RUPA HT, VAMY Phase
4. PIEN common to absent, low elevation forests with ACGL and numerous herbs in the understory . . . . ABLA/RUPA HT, ACGL Phase
4. PIEN common; mostly high elevation forests 5
5. *Pedicularis angustissima* dominant . . . . ABLA/VASC HT
5. *P. angustissima* uncommon; ERSU and GERI common . . . . ABLA/ERSU HT
6. PIPU climax or co-climax 7
6. PIPU absent or accidental 8
7. Forests of streamside alluvium . . . . PIPU/POPR HT
7. Forests of colluvial sideslopes . . . . PSME-PIPU HT, VAAC Phase
8. Sparse understory cover; RONE *Chimaphila umbellata* usually with about 1% cover . . . . ABCO-PSME HT, RONE Phase
8. Understory herb or shrub strata well-developed 9
9. ACGL present . . . . ABCO-PSME/ACGL HT, HODU Phase
9. ACGL absent 10
10. QUGA or QUHY present 11
10. Oaks absent or rare 14
11. ABCO with at least light regeneration 12
11. ABCO regeneration absent or rare 13
12. MUVI, FEAR, MUMO or some combination dominates the herb layer 15

12. The above grasses uncommon or absent . . . . . .
. . . . ABCO-PSME/QUGA HT

13. QUHY present . . . . PSME/QUHY HT
13. QUHY absent 15

14. CAFO dominant . . . . PSME/CAFO HT
14. MUVI dominant . . . . PSME-PIST/MUVI HT

15. FEAR or MUMO common . . . .
. . . . . ABCO-PSME/QUGA HT, FEAR Phas
15. FEAR and MUMO rare or absent 1
16. MUVI common . . . .
. . . . . ABCO-PSME/QUGA HT, MUVI Phas
16. MUVI uncommon . . . .
. . . . . ABCO-PSME/QUGA HT, QUGA Phas

Table A-1.—Dynamic status of the trees within spruce-fir and mixed conifer forest habitat types, Arizona and New Mexico. Dynamic status has been summarized and interpreted from the plot tables as C = major climax, c = minor climax, S = major seral, s = minor seral, cs = minor climax or seral (data not clear). Accidental or rare occurrences in random size classes are omitted

	Species									
	PIEN	ABLA	PSME	ABCO	PIPU	PIST	PIPO	POTR	PIAR	QUGA
Spruce-Fir Forest Habitat Types										
1. PIEN/VASC/PODE HT [1]	C	c						s	s	
2. PIEN/Moss HT	C	C						s	s	
3. ABLA/VASC HT	C	C	s					S	s	
4. ABLA/VASC/LIBO HT	C	C	S	s	s			S		
5. ABLA/RUPA HT, VAMY Phase	C	C	S	s				S		
, AGCL Phase	c	C	S	S				S		
6. ABLA/ERSU HT	C	C	S	s	s	s		S		
7. ABLA/JUCO HT	C	C	S	S				S		
8. ABLA/SESA HT	C	C	s					S		
Mixed Conifer Forest Habitat Types										
9. PIPU-PIEN/SECA HT, -ABLA Phase	C	C	S	s	c	s	s	S		
, -ABCO Phase	C	c	C	C	C	s	s	S		
10. PIPU-PIEN/ERSU HT	C	c	C	cs	C	s	s	S		
11. PIPU/POPR HT			s	s	C		s	S		
12. PIPU/CAFO HT, PSME Phase			C	c	C	s	s	S		
, PIPO Phase			c		C		SC[2]	S		
13. PIPU-PSME HT, ARUV Phase			C	C	C	s	s	S		
, VAAC Phsae			C	cs	C	s				s
, LIBO Phase	c		C	s	C			S		
, JUCO Phase			C	c	C	s	s	s		
14. ABCO-PSME/ACGL HT, BERE Phase			C	C		s		S		s
, HODU Phase			C	C		s		s		S
15. ABCO-PSME/QUGA HT, Typical Phase			C	C		S	S	s		S
, MUVI Phase			C	C		S	S	s		S
, FEAR Phase			C	C		c	c			S
16. ABCO-PSME HT, BERE Phase			C	C		s	S	s	s	s
, RONE Phase	c		C	C		S	S	s		
17. ABCO/ACGR HT			c	C		s	s	S		s
18. ABCO/FEAR HT			C	C		s	S	s		s
19. PSME-PIST/MUVI HT			C	c		SC	SC[2]			

[1]See table 2 for full species names of these HT abbreviations.
[2]Seral or fire climax depending on fire frequency.

Table A-2.—Spruce-fir forest habitat types. Summary of 66 species (listed by life form) importance values (square root of mean density or cover times frequency)

	Habitat Type[1]							
Trees	1	2	3	4	5	6	7	8
Picea engelmannii								
Young regeneration[2]	62	68	79	51	36	54	40	44
Advanced regeneration	51	61	56	37	28	33	35	28
Mature	40	32	29	11	10	22	22	20
Abies lasiocarpa								
Young regeneration	61	79	104	95	66	83	65	94
Advanced regeneration	26	41	47	29	40	35	38	35
Mature	19	18	18	0	15	12	16	32
Populus tremuloides								
Regeneration	0	0	0	5	4	5	1	0
Mature	0	1	3	25	35	15	28	1
Abies concolor								
Young regeneration	0	0	0	36	29	6	13	0
Advanced regeneration	0	0	1	14	10	4	6	0
Mature	0	0	0	1	2	2	1	0
Pseudotsuga menziesii								
Young regeneration	0	1	2	56	30	22	11	0
Advanced regeneration	0	0	4	29	16	14	15	0
Mature	0	2	7	31	24	18	7	4
Picea pungens								
Young regeneration	0	0	0	3	0	4	0	0
Advanced regeneration	0	0	0	6	0	3	0	0
Mature	0	0	0	2	0	3	0	0
Pinus strobiformis								
Young regeneration	0	0	0	7	2	3	0	0
Advanced regeneration	0	0	1	0	2	2	0	0
Mature	0	0	0	0	0	2	0	0
Pinus ponderosa								
Young regeneration	0	0	0	0	0	0	0	0
Advanced regeneration	0	0	0	0	2	1	1	0
Mature	0	0	0	0	0	1	0	0
Quercus gambelii								
Regeneration	0	0	0	0	0	0	0	0
Mature	0	0	0	0	0	0	0	0
Robinia neomexicana								
Regeneration	0	0	0	0	0	0	0	0
Mature	0	0	0	0	0	0	0	0
Pinus aristata								
Mature	0	0	0	0	0	0	0	0
Quercus hypoleucoides								
Mature	0	0	0	0	0	0	0	0
Tall shrubs								
Acer glabrum	0	0	0	6	23	2	1	4
Acer grandidentatum	0	0	0	0	0	0	0	0
Amelanchier alnifolia	0	0	0	3	0	0	0	0
Prunus virginiana	0	0	0	0	0	0	0	0
Quercus gambelii	0	0	0	0	0	0	0	0
Robinia neomexicana	0	0	0	0	6	0	0	0
Salix scouleriana	0	0	0	10	13	2	0	0
Low deciduous shrubs								
Holodiscus dumosus	0	0	0	0	4	0	0	0
Jamesia americana	0	0	0	0	0	2	0	0
Lonicera arizonica	0	0	0	0	0	0	0	0
L. involucrata	0	0	2	3	0	2	0	9
L. utahensis	0	0	3	0	8	2	0	0
Physocarpus monogynus	0	0	0	0	6	0	0	0
Ribes montigenum	4	0	2	0	0	4	0	18
Rosa spp.	0	0	1	12	0	4	2	0
Rubus parviflorus	0	0	2	12	43	6	0	7
Symphoricarpos oreophilus	0	0	1	3	2	3	1	0
Low evergreen shrubs								
Berberis repens	0	0	1	7	0	2	5	0
Juniperus communis	0	2	3	3	0	5	20	0
Linnaea borealis	0	0	2	55	0	1	0	0
Pachistima myrsinites	0	2	6	29	0	8	0	0
Pyrola secunda	2	2	4	6	4	5	2	1
Vaccinium spp.	73	17	75	65	35	7	0	0

Table A-2.—Continued

Trees	Habitat Type[1] 1	2	3	4	5	6	7	8
Forbs								
Achillea lanulosa	1	0	0	0	0	6	0	1
Antennaria aprica	0	0	0	0	0	0	0	0
Aquilegia elegantula	0	0	1	5	0	2	0	1
Artemisia franserioides	0	0	2	14	7	10	1	4
Clematis pseudoalpina	0	0	1	4	0	1	0	0
Epilobium angustifolium	0	1	2	2	6	3	1	7
Erigeron spp.	0	0	0	0	0	0	0	0
E. superbus	1	5	8	15	18	43	1	19
Fragaria vesca var. *bracteata*	0	0	0	0	11	2	0	0
F. virginiana var. *glauca*	4	4	6	11	4	17	1	2
Galium boreale	0	0	0	1	0	1	0	0
Geranium richardsonii	0	0	3	3	28	16	0	3
Goodyera oblongifolia	0	0	1	2	1	1	1	0
Haplopappus parryi	3	2	13	18	13	16	0	19
Helenium hoopesii	0	0	0	0	0	3	0	0
Lathyrus arizonicus	1	5	3	19	2	18	0	0
Ligusticum porteri	2	0	1	1	6	2	0	7
Mertensia franciscana	4	0	1	2	0	6	0	2
Osmorhiza depauperata	3	1	2	0	2	6	0	14
Pedicularis spp.	8	0	6	0	0	0	0	0
Polemonium pulcherrimum var. *delicatum*	23	0	0	0	0	0	0	2
Pseudocymopteris montanus	1	1	3	0	3	6	1	12
Pteridium aquilinum	0	0	0	0	4	3	0	0
Senecio neomexicanus	0	0	0	3	0	0	0	0
S. cardamine	0	0	0	0	9	0	0	0
S. sanguisorboides	5	0	0	0	0	1	0	32
S. wootoni	0	0	0	0	0	5	0	0
Smilacina racemosa	0	0	0	0	1	1	0	0
S. stellata	0	0	0	0	2	9	0	0
Solidago spp.	0	0	0	0	0	0	0	0
Thalictrum fendleri	0	0	0	0	1	2	0	0
Thermopsis pinetorum	0	0	0	3	4	0	0	0
Valeriana acutiloba	0	0	0	0	3	0	0	0
Vicia americana	0	0	0	2	0	4	0	0
Viola canadensis	0	0	1	7	2	11	0	7
Graminoids								
Bromus ciliatus	1	1	5	9	10	17	4	12
Carex foenea	0	0	0	0	0	6	2	3
Carex rossii	1	3	1	2	0	4	2	0
Elymus glaucus	0	0	0	0	0	1	0	0
Festuca arizonica	0	0	0	0	0	1	0	0
Koeleria cristata	0	0	0	0	0	0	0	0
Luzula parviflora	9	0	1	0	0	0	0	13
Muhlenbergia montana	0	0	0	0	0	0	0	0
M. virescens	0	0	0	0	0	0	0	0
Poa fendleriana	0	0	0	0	0	0	0	0
P. pratensis	0	0	0	0	0	2	0	0
Sitanion hystrix	0	0	0	0	0	0	0	0
Trisetum montanum	0	0	1	3	1	3	0	12

[1]*Habitat types are numbered as follows:*

1. *Picea engelmannii/Vaccinium scoparium/Polemonium delicatum* HT
2. *Picea engelmannii*/Moss HT
3. *Abies lariocarpa/Vaccinium scoparium* HT
4. *Abies lasiocarpa/Vaccinium scoparium/Linnaea borealis* HT
5. *Abies lasiocarpa/Rubus parviflorus* HT
6. *Abies lasiocarpa/Erigeron superbus* HT
7. *Abies lasiocarpa/Juniperous communis* HT
8. *Abies lasiocarpa/Senecio sanguisorboides* HT

[2]*Young regeneration = trees less than 2" d.b.h. Advanced regeneration = trees 2-10" d.b.h. Mature = trees larger than 10" d.b.h.*

Table A-3.—Mixed conifer forest habitat types. Summary of 66 species (listed by life form) importance values (square root of mean density or cover times frequency)

	Habitat type[1]										
Trees	9	10	11	12	13	14	15	16	17	18	19
Picea engelmannii											
Young regeneration	36	32	5	6	12	2	0	5	0	0	0
Advanced regeneration	25	25	9	2	5	1	0	4	0	0	0
Mature	16	10	0	0	1	0	0	0	0	0	0
Abies lasiocarpa											
Young regeneration	30	11	6	6	4	1	0	4	0	0	0
Advanced regeneration	9	2	5	2	1	1	0	2	0	0	0
Mature	7	2	0	1	0	0	0	1	0	0	0
Populus tremuloides											
Regeneration	0	7	11	13	5	6	1	3	6	6	0
Mature	9	17	22	27	8	13	5	9	20	15	0
Abies concolor											
Young regeneration	38	8	15	20	29	62	59	55	94	82	5
Advanced regeneration	13	2	12	1	19	33	29	33	32	49	3
Mature	5	0	0	1	3	17	11	15	19	14	1
Pseudotsuga menziesii											
Young regeneration	39	54	24	23	54	42	43	49	30	43	82
Advanced regeneration	20	30	14	12	42	28	28	34	7	27	30
Mature	20	19	9	7	29	24	14	24	13	7	10
Picea pungens											
Young regeneration	14	38	52	59	39	4	2	2	0	0	0
Advanced regeneration	12	36	52	29	31	2	1	0	0	2	0
Mature	6	8	31	17	12	1	0	1	0	0	0
Pinus strobiformis											
Young regeneration	14	11	0	8	11	13	18	15	15	4	36
Advanced regeneration	13	6	0	3	3	7	12	11	6	5	16
Mature	3	2	0	0	3	3	7	5	2	1	7
Pinus ponderosa											
Young regeneration	1	0	0	21	0	1	10	8	2	23	44
Advanced regeneration	2	0	0	11	1	1	16	7	0	21	36
Mature	3	9	0	15	3	1	13	10	0	16	27
Quercus gambelii											
Regeneration	0	0	0	0	6	2	9	0	0	0	0
Mature	0	0	0	0	2	5	24	0	5	2	0
Robinia neomexicana											
Regeneration	0	0	0	0	0	0	0	0	0	0	0
Mature	0	0	0	0	0	0	0	0	5	0	0
Pinus aristata											
Mature	0	0	0	0	0	0	0	1	0	0	0
Quercus hypoleucoides											
Mature	0	0	0	0	0	0	0	0	0	0	0
Tall shrubs											
Acer glabrum	0	0	18	0	3	25	0	1	0	0	0
Acer grandidentatum	0	0	0	0	0	2	0	0	89	0	0
Amelanchier alnifolia	0	0	9	0	5	6	0	0	0	0	0
Prunus virginiana	0	0	22	0	0	3	2	0	0	0	0
Quercus gambelii	0	0	0	0	5	13	50	1	13	7	0
Robinia neomexicana	1	0	0	1	0	2	10	3	22	0	0
Salix scouleriana	0	1	24	1	0	5	0	1	2	0	0
Low deciduous shrubs											
Holodiscus dumosus	0	0	0	0	1	13	2	1	0	0	2
Jamesia americana	0	0	0	0	3	10	2	1	0	0	0
Lonicera arizonica	2	0	0	0	4	0	6	2	11	0	0
L. involucrata	0	0	15	0	2	0	0	0	0	0	0
L. utahensis	1	0	0	0	0	0	0	0	0	0	0
Physocarpus monogynus	0	0	0	0	0	7	1	1	0	0	0
Ribes montigenum	0	0	0	0	0	0	0	0	0	0	0
Rosa spp.	0	0	33	1	14	7	4	1	0	2	0
Rubus parviflorus	3	0	15	0	5	4	0	0	0	0	0
Symphoricarpos oreophilus	1	0	22	0	4	12	8	5	0	0	0
Low evergreen shrubs											
Berberis repens	0	0	0	0	6	10	4	5	17	1	0
Juniperus communis	0	7	1	9	17	1	1	4	0	0	0
Linnaea borealis	0	0	0	0	13	1	0	0	0	0	0
Pachistima myrsinites	5	0	13	1	13	12	3	1	0	0	0
Pyrola secunda	3	0	1	0	3	1	0	1	0	0	0
Vaccinium spp.	0	0	0	0	10	3	0	1	0	0	0

Table A-3.—Continued

Trees	Habitat type[1] 9	10	11	12	13	14	15	16	17	18	19
Forbs											
Achillea lanulosa	2	7	17	8	9	2	6	0	0	8	4
Antennaria aprica	0	0	0	9	1	0	3	1	0	8	3
Aquilegia elegantula	3	0	3	0	5	3	0	0	0	0	0
Artemisia franserioides	0	3	1	0	8	13	1	1	0	0	0
Clematis pseudoalpina	1	0	1	0	5	7	1	1	0	0	0
Epilobium angustifolium	0	0	0	0	0	0	0	0	1	0	0
Erigeron spp.	0	3	7	7	0	0	3	0	0	11	0
E. superbus	5	33	32	4	16	15	0	1	0	0	0
Fragaria vesca var. *bracteata*	10	5	12	0	13	7	4	2	8	1	1
F. virginiana var. *glauca*	7	23	16	13	11	6	3	2	11	6	0
Galium boreale	0	0	9	0	5	1	1	0	4	0	5
Geranium richardsonii	7	8	17	4	9	4	2	1	10	1	3
Goodyera oblongifolia	1	0	0	0	0	0	0	2	0	0	0
Haplopappus parryi	0	5	1	3	2	10	2	1	0	1	0
Helenium hoopesii	9	1	0	0	0	0	1	0	0	0	0
Lathyrus arizonicus	11	29	10	11	10	13	9	2	10	12	0
Ligusticum porteri	0	0	0	0	0	0	1	1	2	0	0
Mertensia franciscana	1	0	13	0	0	1	0	0	0	0	0
Osmorhiza depauperata	1	0	5	0	0	2	1	0	7	0	0
Pedicularis spp.	0	0	0	0	0	0	1	0	0	0	0
Polemonium pulcherrimum var. *delicatum*	0	0	0	0	0	0	0	0	0	0	0
Pseudocymopteris montanus	1	9	6	3	1	1	4	1	1	8	9
Pteridium aquilinum	12	4	0	0	1	0	4	3	30	0	16
Senecio neomexicanus	0	0	0	4	0	1	2	0	1	4	0
S. cardamine	35	0	0	0	0	0	0	0	0	0	0
S. sanguisorboides	0	0	0	0	0	0	0	0	0	0	0
S. wootoni	11	11	0	7	2	2	2	0	0	8	0
Smilacina racemosa	1	0	0	0	3	2	1	0	5	0	0
S. stellata	1	0	7	2	1	4	1	0	0	0	0
Solidago spp.	4	1	0	0	2	0	3	0	0	0	3
Thalictrum fendleri	7	9	15	2	4	8	6	1	24	5	0
Thermopsis pinetorum	13	0	0	0	0	3	5	1	14	2	4
Valeriana acutiloba	0	0	0	0	8	1	1	0	0	2	0
Vicia americana	1	8	5	3	1	1	1	0	0	6	2
Viola canadensis	10	7	0	1	4	6	5	0	43	0	0
Graminoids											
Bromus ciliatus	12	12	14	6	15	20	9	4	14	3	10
Carex foenea	11	28	13	32	14	2	4	3	46	1	0
Carex rossii	7	5	6	6	9	6	11	6	5	5	0
Elymus glaucus	0	0	0	0	0	0	1	0	0	0	0
Festuca arizonica	0	21	0	15	0	0	3	1	0	35	0
Koeleria cristata	1	6	0	4	4	1	3	4	0	4	6
Luzula parviflora	0	0	0	0	0	0	0	0	0	0	0
Muhlenbergia montana	0	3	0	14	0	0	1	0	0	14	0
M. virescens	1	6	0	3	0	0	9	1	0	7	41
Poa fendleriana	4	0	0	6	15	1	10	3	2	10	0
P. pratensis	0	11	51	0	0	1	0	0	0	0	0
Sitanion hystrix	0	1	0	4	0	0	3	2	0	5	1
Trisetum montanum	3	0	2	0	3	4	0	0	0	0	0

[1]*Habitat types are numbered as follows:*

9. *Picea pungens-Picea engelmannii/Senecio cardamine* HT
10. *Picea pungens-Picea engelmannii/Erigeron superbus* HT
11. *Picea pungens/Poa pratensis* HT
12. *Picea pungens/Carex foenea* HT
13. *Picea pungens-Pseudotsuga menziesii* HT
14. *Abies concolor-Pseudotsuga menziesii/Acer glabrum* HT
15. *Abies concolor-Pseudotsuga menziesii/Quercus gambelii* HT
16. *Abies concolor-Pseudotsuga menziesii* HT
17. *Abies concolor/Acer grandidentatum* HT
18. *Abies concolor/Festuca arizonica* HT
19. *Pseudotsuga menziesii-Pinus strobiformis/Muhlenbergia virescens* HT

Table A-4.—Other (minor) spruce-fir forest habitat types. Summary of 66 species (listed by life form) importance values (square root of mean density or cover times frequency)

Trees	Habitat Type[1] 20	21	22	23	24	25
Picea engelmannii						
Young regeneration	85	28	59	68	0	36
Advanced regeneration	75	10	40	42	0	38
Mature	39	9	24	35	0	31
Abies lasiocarpa						
Young regeneration	22	101	8	5	82	0
Advanced regeneration	0	48	17	0	41	0
Mature	0	22	8	0	22	0
Populus tremuloides						
Regeneration	0	0	5	0	0	0
Mature	0	46	9	0	14	18
Abies concolor						
Young regeneration	0	0	0	0	44	15
Advanced regeneration	0	0	0	0	0	8
Mature	0	0	0	0	14	5
Pseudotsuga menziesii						
Young regeneration	0	0	11	0	0	15
Advanced regeneration	0	0	3	0	17	14
Mature	0	0	30	0	14	14
Picea pungens						
Young regeneration	0	0	0	0	0	0
Advanced regeneration	0	0	0	0	0	0
Mature	0	0	0	0	0	0
Pinus strobiformis						
Young regeneration	0	7	6	0	22	5
Advanced regeneration	0	0	5	0	22	0
Mature	0	0	3	0	14	0
Pinus ponderosa						
Young regeneration	0	0	0	0	0	0
Advanced regeneration	0	0	0	0	0	0
Mature	0	0	0	0	0	0
Quercus gambelii						
Regeneration	0	0	0	0	0	0
Mature	0	0	0	0	0	0
Robinia neomexicana						
Regeneration	0	0	0	0	0	0
Mature	0	0	0	0	0	0
Pinus aristata						
Mature	0	0	0	0	0	0
Quercus hypoleucoides						
Mature	0	0	0	0	0	0
Tall shrubs						
Acer glabrum	0	0	9	0	3	15
Acer grandidentatum	0	0	0	0	0	0
Amelanchier alnifolia	0	0	0	0	14	0
Prunus virginiana	0	0	0	0	0	0
Quercus gambelii	0	0	0	0	1	0
Robinia neomexicana	0	0	0	0	0	0
Salix scouleriana	0	0	0	0	0	0
Low deciduous shrubs						
Holodiscus dumosus	0	0	19	0	0	5
Jamesia americana	0	0	14	0	0	3
Lonicera arizonica	0	0	0	0	14	0
L. involucrata	0	0	0	0	1	0
L. utahensis	0	0	0	0	0	0
Physocarpus monogynus	0	0	0	0	0	0
Ribes montigenum	26	0	0	0	0	0
Rosa spp.	0	0	0	0	0	0
Rubus parviflorus	0	0	0	0	0	7
Symphoricarpos oreophilus	0	0	0	0	0	0

Table A-4.—Continued

Trees	Habitat Type[1] 20	21	22	23	24	25
Low evergreen shrubs						
Berberis repens	0	0	0	0	14	0
Juniperus communis	0	0	0	0	0	0
Linnaea borealis	0	0	0	0	0	0
Pachistima myrsinites	0	0	0	0	22	7
Pyrola secunda	1	0	0	0	1	1
Vaccinium myrtillus	0	0	0	0	39	0
Forbs						
Achillea lanulosa	0	0	0	0	0	0
Antennaria aprica	0	0	0	0	1	0
Aquilegia elegantula	0	0	1	0	0	1
Artemisia franserioides	0	0	0	0	0	9
Clematis pseudoalpina	0	0	0	0	0	0
Epilobium angustifolium	1	0	0	0	0	1
Erigeron spp.	0	0	0	0	0	1
E. superbus	0	0	4	0	1	0
Fragaria vesca var. *bracteata*	0	0	5	0	1	1
F. virginiana var. *glauca*	1	0	0	0	3	2
Galium boreale	0	0	0	0	0	1
Geranium richardsonii	0	9	0	1	10	1
Goodyera oblongifolia	0	0	0	0	14	0
Haplopappus parryi	17	0	0	1	0	12
Helenium hoopseii	0	2	0	0	0	0
Lathyrus arizonicus	0	47	0	1	0	7
Ligusticum porteri	0	0	0	0	14	2
Mertensia franciscana	1	5	0	1	0	0
Osmorhiza depauperata	0	0	0	0	3	1
Pedicularis sp.	0	0	0	0	0	0
Polemonium polcherrimum var. *delicatum*	3	0	0	0	0	0
Pseudocymopteris montanus	3	0	0	0	3	1
Pteridium aquilinum	0	7	0	0	3	0
Senecio neomexicanus	0	0	0	0	0	0
S. cardamine	0	0	0	0	0	0
S. sanguisorboides	0	0	0	0	0	7
S. wootoni	0	0	0	2	0	0
Smilacina racemosa	0	0	0	0	32	1
S. stellata	0	21	1	0	0	1
Solidago spp.	0	0	0	0	0	0
Thalictrum fendleri	0	0	0	0	22	0
Thermopsis pinetorum	0	0	0	0	10	0
Valeriana acutiloba	0	0	0	0	0	0
Vicia americana	0	12	0	1	0	0
Viola canadensis	0	0	0	0	20	3
Graminoids						
Bromus ciliatus	0	27	0	3	10	13
Carex foenea	0	7	0	60	39	0
Carex rossii	0	7	1	0	1	0
Elymus triticoides	0	0	29	0	0	0
Festuca arizonica	0	0	0	0	0	0
Koeleria cristata	0	0	0	0	0	0
Luzula parviflora	1	0	0	0	0	0
Muhlenbergia montana	0	0	0	0	0	0
M. virescens	0	0	0	0	0	0
Poa fendleriana	0	0	0	2	1	0
P. pratensis	0	0	0	10	0	0
Sitanion hystrix	0	0	0	0	0	0
Trisetum montanum	1	0	6	0	10	2

[1]*Habitat types are numbered as follows:*
20. *Picea engelmannii/Geum rossii* HT
21. *Abies lasiocarpa/Lathyrus arizonica* HT
22. *Picea engelmannii/Elymus triticoides* HT
23. *Picea engelmannii/Carex foenea* HT
24. *Abies lasiocarpa/Vaccinium myrtillus* HT
25. *Picea engelmannii/Acer glabrum* HT

Table A-5.—Other (minor) mixed conifer habitat types. Summary of 66 species (listed by life form) importance values (square root of mean density or cover times frequency)

	Habitat type[1]									
Trees	26	27	28	29	30	31	32	33	34	35
Picea engelmannii										
Young regeneration	6	3	5	0	0	5	0	0	0	0
Advanced regeneration	6	0	5	9	0	0	0	0	0	0
Mature	0	3	5	0	0	0	0	0	0	0
Abies lasiocarpa										
Young regeneration	0	0	0	0	0	0	0	0	0	0
Advanced regeneration	3	0	0	0	0	0	0	0	0	0
Mature	0	0	0	0	0	0	0	0	0	0
Populus tremuloides										
Regeneration	12	0	9	0	0	0	0	0	0	24
Mature	11	26	25	23	11	0	0	0	0	0
Abies concolor										
Young regeneration	70	70	75	75	46	67	18	17	0	0
Advanced regeneration	32	16	59	23	22	20	15	0	14	0
Mature	21	16	13	12	13	19	6	0	0	0
Pseudotsuga menziesii										
Young regeneration	40	40	16	37	49	50	34	0	13	17
Advanced regeneration	28	24	19	40	21	27	37	44	22	0
Mature	27	10	9	12	15	24	25	33	20	17
Picea pungens										
Young regeneration	0	0	0	0	0	12	0	0	0	0
Advanced regeneration	3	0	0	0	0	5	0	14	0	0
Mature	3	0	0	0	0	0	0	0	0	0
Pinus strobiformis										
Young regeneration	6	21	10	21	21	20	0	0	9	22
Advanced regeneration	5	26	5	0	24	0	0	0	0	17
Mature	0	12	0	0	4	9	0	0	0	28
Pinus ponderosa										
Young regeneration	6	21	10	5	4	0	0	0	9	0
Advanced regeneration	0	9	0	15	0	0	0	0	10	0
Mature	0	16	5	24	0	5	0	0	0	0
Quercus gambelii										
Regeneration	0	0	0	0	0	0	0	0	0	0
Mature	6	0	0	0	4	0	0	0	29	0
Robinia neomexicana										
Regeneration	0	0	5	0	0	0	0	0	0	0
Mature	0	0	16	0	0	0	0	0	0	0
Pinus aristata										
Mature	0	0	0	0	0	0	11	0	0	0
Quercus hypoleucoides										
Mature	0	0	0	0	0	0	0	0	44	0
Tall shrubs										
Acer glabrum	0	9	0	0	0	0	0	0	0	0
Acer grandidentatum	0	0	0	0	0	0	0	0	0	0
Amelanchier alnifolia	5	0	0	0	0	0	0	3	0	0
Prunus emarginata	0	0	0	0	0	0	0	0	0	10
Quercus gambelii	7	0	0	0	9	9	0	1	0	0
Robinia neomexicana	0	0	71	0	0	12	0	0	0	0
Salix scouleriana	3	0	0	0	0	0	0	0	0	0
Low deciduous shrubs										
Holodiscus dumosus	0	0	0	0	9	0	11	0	0	14
Jamesia americana	0	0	0	0	22	0	0	0	0	0
Lonicera arizonica	6	0	11	0	0	0	0	0	0	3
L. involucrata	0	0	0	0	0	0	0	0	0	0
L. utahensis	0	0	0	0	0	0	0	0	0	0
Physocarpus monogynus	0	0	0	0	0	0	0	63	0	0
Ribes montigenum	0	0	0	0	0	0	0	0	0	0
Rosa spp.	5	0	0	0	0	2	7	3	0	10
Rubus parviflorus	5	0	0	0	0	10	0	0	0	0
Symphoricarpos oreophilus	0	0	0	1	0	0	11	32	0	0
Low evergreen shrubs										
Berberis repens	3	0	0	17	0	0	0	0	0	22
Juniperus communis	0	0	0	0	0	0	8	0	0	0
Linnaea borealis	0	0	0	0	0	0	0	0	0	0
Pachistima myrsinites	7	0	0	0	0	5	0	0	0	0
Pyrola secunda	5	0	0	0	0	2	0	0	0	0
Vaccinium spp.	7	0	0	0	0	0	0	0	0	0

Table A-5.—Continued

Trees	Habitat type[1] 26	27	28	29	30	31	32	33	34	35
Forbs										
chillea lanulosa	7	5	0	0	0	10	1	0	0	0
ntennaria aprica	7	0	0	2	0	0	1	0	0	0
quilegia elegantula	0	0	0	0	0	0	0	0	0	0
rtenisia franserioides	5	0	0	0	0	1	2	10	0	0
lematis pseudoalpina	0	0	0	0	0	0	2	3	0	0
pilobium angustifolium	0	0	0	0	0	0	0	0	0	0
rigeron spp.	0	3	0	0	0	2	16	17	0	0
. superbus	48	3	2	2	3	0	5	0	0	0
ragaria vesca var. *bracteata*	11	1	16	0	0	19	11	3	0	0
virginiana var. *glauca*	23	8	7	0	0	7	1	0	0	0
alium boreale	5	0	0	0	0	0	0	3	0	0
eranium richardsonii	3	13	1	0	0	2	0	0	0	0
oodyera oblongifolia	0	0	0	1	0	0	0	0	0	0
aplopappus parryi	3	0	2	0	0	7	0	0	0	0
elenium hoopesii	0	3	0	0	0	2	0	0	0	0
athyrus arizonicus	53	1	0	42	1	19	0	0	0	0
gusticum porteri	9	0	0	0	0	0	0	0	0	0
ertensia franciscana	0	0	0	0	0	0	0	0	0	0
smorhiza depauperata	8	0	0	0	0	0	0	0	0	0
edicularis spp.	0	0	0	0	0	0	0	0	0	0
olemonium pulcherrimum var. *delicatum*	0	0	0	0	0	0	0	0	0	0
seudocympoteris montanus	5	5	0	0	0	2	0	0	2	0
teridium aquilinum	0	12	11	0	0	5	0	0	0	0
enecio neomexicanus	0	0	0	0	0	2	9	0	2	0
cardamine	0	0	0	0	0	0	0	0	0	0
sanguisorboides	0	0	0	0	0	0	0	0	0	0
wootoni	0	11	0	0	0	14	0	0	0	0
milacina racemosa	0	0	5	0	0	0	0	0	0	0
. stellata	5	0	0	7	0	0	0	0	0	0
olidago spp.	0	0	0	0	7	0	0	0	12	3
halictrum fendleri	10	2	32	0	0	7	0	10	5	0
hermopsis pinetorum	27	0	2	0	0	0	6	0	0	0
aleriana acutiloba	0	0	0	2	0	0	0	0	0	0
icia americana	1	5	0	0	0	0	1	3	0	0
iola canadensis	16	0	2	0	0	2	0	0	0	0
Graminoids										
romus ciliatus	13	31	39	10	22	19	0	0	0	14
arex foenea	38	71	35	0	10	7	0	0	0	0
arex rossii	2	6	7	2	9	14	8	3	0	3
lymus triticoides	0	0	0	0	54	0	0	0	0	0
estuca arizonica	0	3	0	0	3	0	40	0	0	17
oeleria cristata	0	1	0	2	8	5	9	14	2	0
uzula parviflora	0	0	0	0	0	0	0	0	0	0
uhlenbergia montana	0	1	0	0	19	0	7	0	0	22
. virescens	0	0	0	0	0	2	0	0	0	0
oa fendleriana	3	2	2	9	1	41	2	1	2	3
. pratensis	0	14	9	0	1	0	0	0	0	0
itanion hystrix	0	1	0	0	1	0	3	0	0	0
risetum montanum	8	0	0	0	0	0	0	0	0	0

[1]*Habitat types are numbered as follows:*

26. *Abies concolor-Pseudotsuga menziesii/Erigeron superbus* HT
27. *Abies concolor/Carex foenea* HT
28. *Abies concolor/Robinia neomexicana* HT
29. *Abies concolor-Pseudotsuga menziesii/Lathyrus arizonicus* HT
30. *Abies concolor-Pseudotsuga menziesii/Elymus triticoides* HT
31. *Abies concolor-Pseudotsuga menziesii/Poa fendleriana* HT
32. *Pseudotsuga menziesii/Festuca arizonica* HT
33. *Pseudotsuga menziesii/Physocarpus monogynus* HT
34. *Pseudotsuga menziesii/Quercus hypoleucoides* HT
35. *Pinus strobiformis/Festuca arizonica* HT

Moir, William H., and John A. Ludwig. 1979. A classification of spruce-fir and mixed conifer habitat types of Arizona and New Mexico. USDA For. Serv. Res. Pap. RM-207, 47 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Nineteen major forest habitat types (HT's) are described on the basis of extensive reconnaissance data throughout the major mountain ranges and plateaus of Arizona and New Mexico. Eight of these HT's are within spruce-fir forests where either *Picea engelmannii* or *Abies lasiocarpa* are the climax dominants; the remainder are within mixed conifer forests where *Abies concolor, Picea pungens,* and *Pseudotsuga manziesii* are climax dominants or codominants. Sixteen other HT's are briefly described based on limited data, usually from one geographic location.

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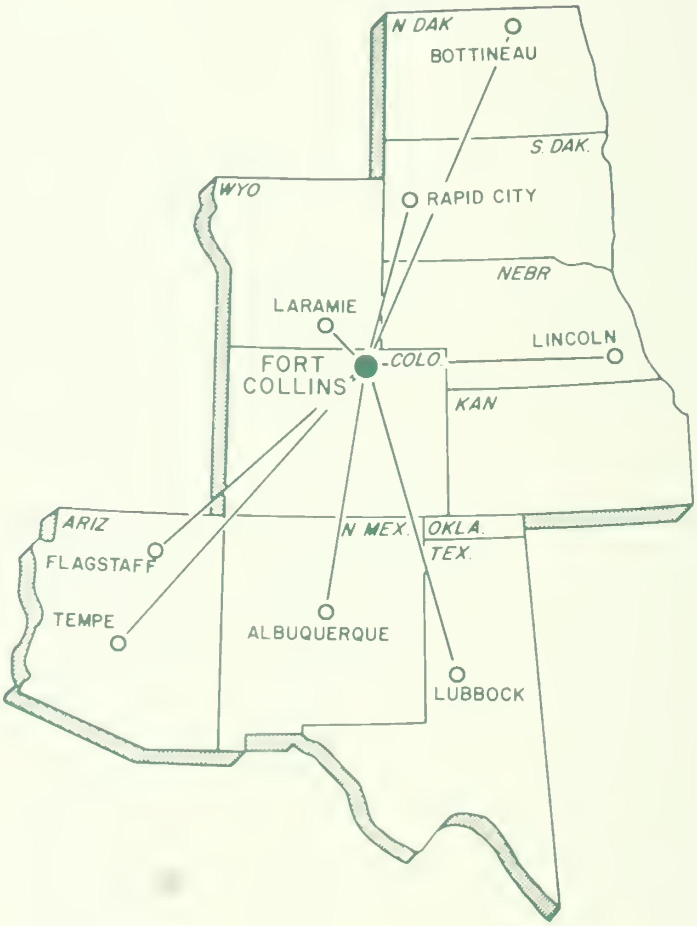
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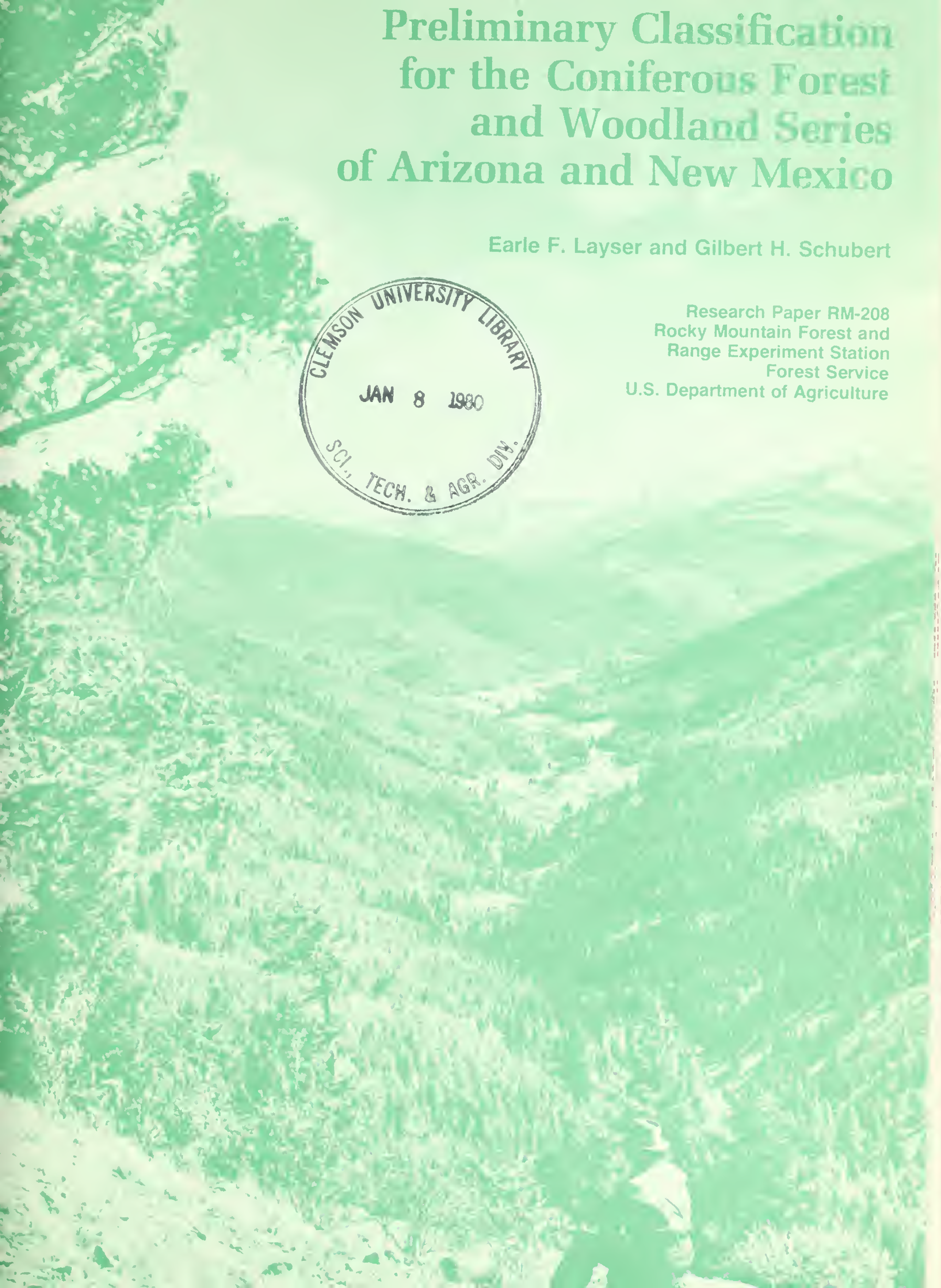
ALBUQUERQUE
LUBBOCK

Preliminary Classification for the Coniferous Forest and Woodland Series of Arizona and New Mexico

Earle F. Layser and Gilbert H. Schubert

Research Paper RM-208
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture



Abstract

The series level of a hierarchical classification for coniferous forest vegetation for the Southwest is described. A review of plant ecological literature and vegetation mapping is followed by discussion of synecological perspective and review of terminology for vegetation classification. A research framework for development of the vegetation classification system is outlined.

Research Paper RM-208

July 1979

Preliminary Classification for the Coniferous Forest and Woodland Series of Arizona and New Mexico

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[2]Schubert, now retired, was located at the Station's Research Work Unit located at Flagstaff, in cooperation with Northern Arizona University. Station's central headquarters is maintained at Fort Collins, in cooperation with Colorado State University.

Contents

Preliminary Classification for the Coniferous Forest and Woodland Series of Arizona and New Mexico

Earle F. Layser and Gilbert H. Schubert

INTRODUCTION

The vegetation of southwestern United States, because of this geographic area's climatic patterns and extreme ranges in topographic relief, is complex and diverse. For purposes of land management and planning, a systematic classification and a uniform understanding and application of vegetation classification concepts are needed in the Southwest. The vegetation classification system must be applicable to project and prescription level planning, as well as to long range planning involving land classification systems[3] and resource assessment under the Forest and Rangeland Resources Planning Act of 1974.

The ways vegetation classification can serve land management and research have been reviewed elsewhere (Daubenmire 1976, Layser 1974, Pfister 1976, Volland 1975). Classification can aid in communication about forest and rangelands, and can assist in greater understanding of ecological factors as they relate to management and site. The mappable hierarchial categories permit different levels of generalization, adding to the usefulness of the system for land management. Information on both existing and potential vegetation[4] is necessary where management attempts to raise the productivity of a region to optimum and sustain it there, and where consideration of the dynamic as well as static features of vegetation is essential (fig. 1) (Kuchler 1967).

[3]*Gallaher, W. B. Modified ECOCLASS report to Regional Foresters, Rocky Mountain and Southwestern Regions, USDA Forest Service, and Director, Rocky Mountain Forest and Range Experiment Station; 4040 Habitat Type Classification, January 31, 1977. Report contains recommendations dealing with staffing and research needs to implement Modified ECOCLASS.*

[4]*The term potential vegetation, as applied here, can refer to any, or collectively all, the classification levels (i.e., formation, series, association). The term relates to climax (Tansley 1935) potential as it exists today, not the possible vegetation responses resulting from management treatments.*

LITERATURE REVIEW

The Southwest is a particularly good area to study plant ecology because of the insular nature of the mountain ranges and the abrupt differences in physiography and climate. Some of the earliest work (Merriam 1890, 1898) on bioclimatic classification in the United States was conducted in the Southwest. Other early students of plant ecology for the area included Hanson (1924), Korstian (1917), Pearson (1920), Shreve (1915), and Watson (1912).

While this partial review is directed primarily at the coniferous forest and woodland[5] vegetation in the Southwest, it should be pointed out that considerable literature for the grassland, and scrubland vegetation also exists.

Shreve (1942) named and defined nine principal types of vegetation for Arizona based on altitude. Howell (1941), Kesek (1966), Merkle (1952), and Whiting (1942) studied and described facets of pinyon and juniper ecology in various parts of the Southwest. Lindsley (1951) described the forest vegetation at the Grants lava bed in New Mexico.

Nichol (1937, 1952) described and mapped natural vegetation of Arizona. In 1954, the Society of American Foresters published the Forest Cover Types of North America. Merkle (1954) analyzed the spruce-fir community on the Kaibab Plateau, Arizona. The vegetation of the Huachuca Mountains, Arizona, was described and mapped by Wallmo (1955). Castetter (1956) reported on the vegetation of the Manzano, Jemez, and Sandia Mountains, New Mexico. Changes in ponderosa pine forests in Arizona since white settlement have been characterized by Cooper (1960). Merkle

[5]*Woodland is used in this paper as a category because of its general acceptance and application for describing certain vegetation in the Southwest. The definition (Brown and Lowe 1974) is incorporated into the key leads; Ford-Robertson (1971) also define woodlands in the sense it is used here. This is not to be confused with eastern United States, where "woodland" is sometimes used in forestry terminology tc refer to any lands adapted to production of woodcrops.*

(1962) described some of the forest communities of the Grand Canyon area, Arizona. Little (1950, 1971, 1975, 1976) described the trees of the Southwest, their distributions, and associated forest species. In the 1950 publication, he also presented a map of the principal vegetation of Arizona and New Mexico.

In 1964, Kuchler prepared a map and accompanying manual of the potential natural vegetation of the conterminous United States. Lowe (1961, 1964) reviewed the literature and presented discussion of the life zones and biotic communities for Arizona. Gehlbach (1967) described the vegetation of the Guadalupe escarpment in New Mexico. The vegetation of the Organ Mountains, New Mexico, was treated by Dick-Peddie and Moir (1970); and Hanks and Dick-Peddie (1974) described forest succession in the White Mountains, New Mexico. Freeman and Dick-Peddie (1970) studied woody riparian vegetation in the Black and Sacramento Mountain Ranges of New Mexico.

The vegetation of the mountainous portions of Utah has been described in part by Dixon (1935), Ellison (1954), Pfister (1972), and Ream (1963). Brown (1973) described and mapped the vegetation of Arizona. Alexander (1974a, 1974b), Hanley et al: (1975), Jones (1974), and Schubert (1974) portrayed successional relationships of tree species in the southern Rockies.

Brown and Lowe (1974) have proposed a computer-compatible system for organizing and classifying natural and potential vegetation information. Their approach has merit for land management and planning purposes.

Turner (1974) prepared a general map and discussion for the vegetation of the Tucson area of Arizona. Whittaker and Niering (1975) described in detail the vegetation of the Santa Catalina

Figure 1.—Forest vegetation forms a mosaic pattern in mountainous terrain reflecting differences in habitat and in successional stages. Carson National Forest, New Mexico.

Mountains, Arizona. Brown et al. (1977) published a map of biotic communities of the Southwest.

The USDA Forest Service contracted for vegetation classification studies with Moir and Ludwig (1977) on the spruce-fir and mixed conifer in New Mexico and Arizona; and with Hanks et al. (1977) for the ponderosa pine habitat types on the Colorado Plateau.

Much of the literature lacks quantitative data for rigorous comparison, and describes vegetation only in a general way which is useful for rough comparisons. In other cases, data in the literature are presented for gradient analyses, but not in the form of community analyses or sampling.

THE CLASSIFICATION FRAMEWORK, SYNECOLOGICAL PERSPECTIVE, AND TERMINOLOGY

Problems generally encountered in developing and utilizing a vegetative classification system are: (1) different ecologists may use the same terms differently; and (2) different authors may recognize different types for similar situations. This can cause confusion in relating different ecological works to a common system, especially for those unfamiliar with the terminology, concepts, or problem. This section provides clarification, and encourages uniform application of terms and concepts.

Recent, extensive adoption of the methods and applications for vegetation classification proposed here, have demonstrated the merit of this approach in land management and research (Daubenmire 1976, Pfister 1976). Continuity is desirable in classification of coniferous forest vegetation for the southern Rocky Mountains with what has been done in the central (Cooper 1975, Hoffman and Alexander 1976, Pfister 1972, Reed 1976, Wirsing and Alexander 1975), and northern Rocky Mountains (Daubenmire and Daubenmire 1968, Pfister et al. 1977, Steele et al. 1975), as well as elsewhere (Hall 1973, Sawyer and Thornburgh 1971, Westveld 1951) by the Forest Service.

The Classification Framework

The vegetation classification system proposed in this work represents what may be considered a physiognomic-ecological approach. The major units (formation, subformation) are physiognomic. Poore (1962) pointed out that for the major levels, ". . . physiognomy . . . reflects rather faithfully the sum total of the ecological factors of the habitat." The more fundamental units (series, association, phase) are based on dominance and floristics. Whittaker (1962) referred to this approach as an "informal hierarchy" (fig. 2).

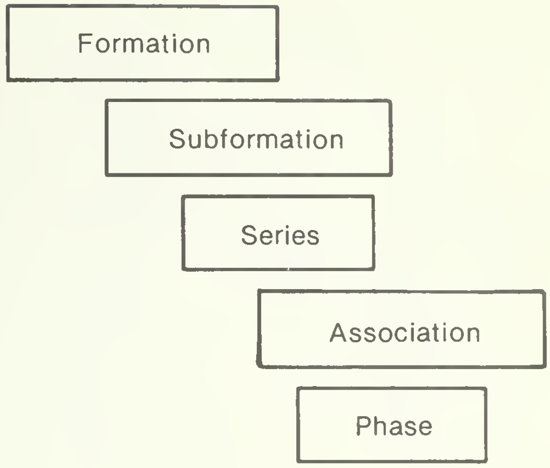


Figure 2.—The classification hierarchy—a taxonomic framework.

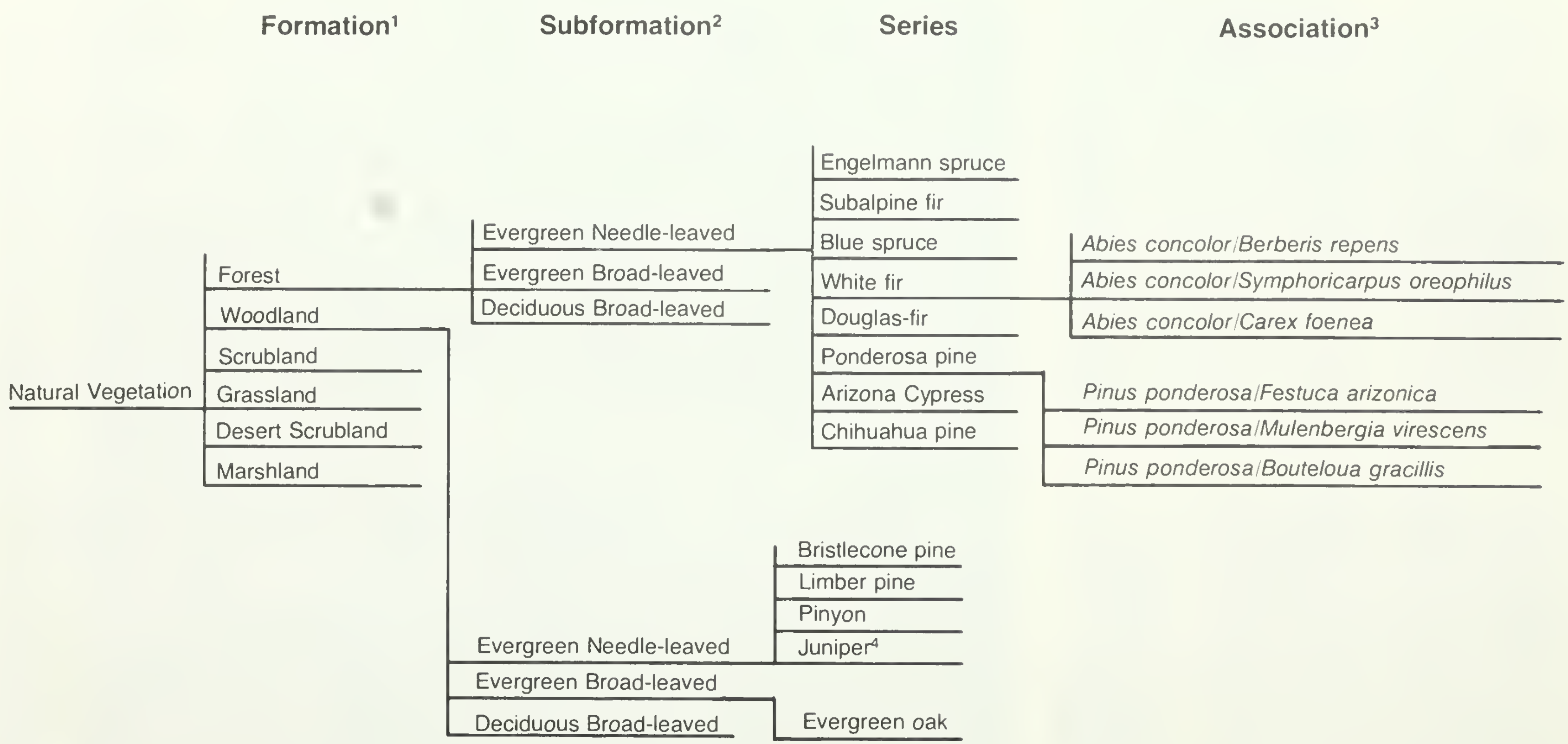
Synecological Perspective and Terminology

"Formations" are distinguished on the basis of a potentially uniform physiognomy at climax which represents a response from integration of the environmental factors. Formations are the broadest interpretive units of continental synecology. They include not only the climatic climax vegetation, which is the key to recognition, but all the various seral development stages as well. The term formation is Clementsian in origin, and was initially used without definition of rank (Pound and Clements 1898). Nothing here, however, is intended to imply adoption of the monoclimax ideas of Clements (1936).

The taxonomic levels (subformation, series, association) are categories that may be grouped into successively higher units. Thus, formations are groups of subformations and series with similar physiognomies.

"Subformations" refer to a distinctive physiognomy within a formation (Daubenmire 1968). For purposes of this paper, forest and woodland subformations are shown in figure 3. The "biotic communities" mapped by Brown and Lowe (1977) approximate the formations and subformations described here.

"Series" encompass all the associations having the same potential dominant species at climax. Series are named after the climax dominant(s). The series name implies a particular potential vegetation and a predictable sere, although frequency of species in the succession may vary, depending on the kind and intensity of perturbation. For conifer-



[1]*From Brown and Lowe (1974), but for the most part widely adopted in the literature, as described by Daubenmire (1968, p. 350-352).*
[2]*From Daubenmire (1968, p. 251).*
[3]*Associations shown are examples only.*
[4]*All juniper stands are treated here under the woodland formation. If a savanna formation (Dyksterhuis 1957) were to be recognized, some juniper situations, included here in woodland, must be shifted to savanna.*

Figure 3.—Example of the classification structure for forest and woodland in the southwestern United States. Each formation can be expanded within the different hierarchical levels to complete the classification for the natural vegetation of the Southwest.

ous forest vegetation, the series are named after the climax tree species (Pfister et al. 1977, and Steele et al. 1975). Potential climax tree species are recognized on the basis of tolerance (ability to withstand shading) and their ability to reproduce despite a layer of duff and litter covering mineral soil (Graham 1941).

"Association" is a combination of overstory and understory climax dominants having similar or overlapping ecological requirements. A problem of inconsistency in use of this term was already apparent, when the International Botanical Congress of 1910 sought to standardize the definition of the term "plant association" to mean ". . . a plant community of certain floristic composition, of uniform habitat conditions, and of uniform physiognomy. Floristic composition includes not only the list of species, but also a (phyto) sociological evaluation based on abundance, dominance . . . constancy, fidelity . . ."

Collectively, those physical environments capable of supporting a particular climax plant association are called "habitat types" (Daubenmire and Daubenmire 1968). Theoretically, a habitat type displays uniformity of dominant vegetation in all layers at climax. For a more detailed discussion of the definition of habitat type and other synecological terms see Daubenmire (1976) and Pfister (1976).

"Phase" is a taxonomic term to designate subdivisions within an association and its habitat type. "Community type" (Hall 1973, Pfister et al. 1977) is a term applied to a recognizable and recurring stable plant community of uncertain successional status. In classification it is at the same hierarchical level as an association (figs. 2 and 3).

The use of the term "climax" in this paper follows the polyclimax concepts of Tansley (1935). The reference to climax vegetation in the development of the classification, and in nomenclature, in no way implies that climax vegetation is or must be a management objective. Neither does a climax stand need be present to identify a habitat type. The purpose in relating to climax in the development of the classification is to hold the time or successional factor constant (Pfister 1976), and to best ascertain the useful indicator plants (Daubenmire 1976).

Confusion has sometimes resulted between application of vegetative classification concepts and forest cover typing. Part of this may result from the fact that the term "forest type" was used by foresters in practically the same sense that association is now used by ecologists, long before the latter term originated (Clements 1920). However, a similar phrase, "forest cover type" (Society of American Foresters 1954), does not convey any implication as to whether the type is temporary or permanent. Therefore, even though the names used for a particular forest cover type and series maybe the same, there are fundamental differences between their meanings and applications (fig. 4).

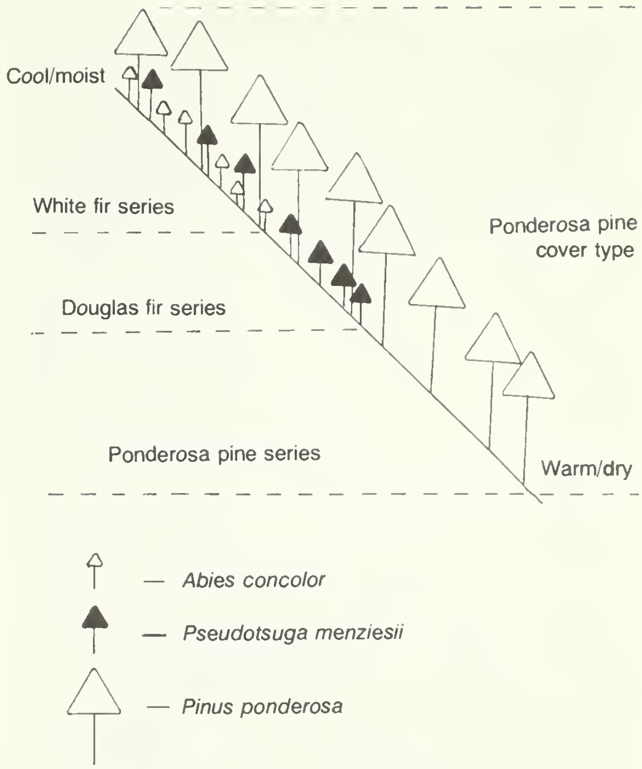


Figure 4.—Example of how a theoretical forest along an environmental gradient would be classified as to series and cover type. The site along the gradient that is occupied by ponderosa pine, which is too warm and dry for Douglas-fir and true firs, is the ponderosa pine series. Progressing toward cooler and moister situations, the Douglas-fir and white fir series are encountered, although all support a ponderosa pine cover type in the example.

Cover typing stresses uniformity of species composition to characterize existing stands (figs. 5, 6, 7, and 8). There is no consideration of successional status. For example, a mature stand of ponderosa pine with a dense understory of Douglas-fir and *Abies concolor* would be cover typed ponderosa pine. Classified as to series, it would be *A. concolor*. The cover type tells something about the current forest cover, but, since ponderosa pine can range from the upper limits of the pinyon zone into the subalpine, it tells little if anything about the site. The series, by stressing the potential climax tree species, does not necessarily tell what forest cover currently exists, but it does communicate something about secondary succession, potential cover, and the site or environment. Both the cover type and potential vegetation are necessary information for management.

In the example above, the series is identified as white fir (*Abies concolor*); it is, therefore, im-

Figure 5.—Aspen is a common seral species in the spruce and true fir series in the Southwest. Over time, the aspen will give way to a succession of more tolerant conifer species. Here, an understory of Douglas-fir and white fir is gradually replacing the aspen. Coconino National Forest, Arizona.

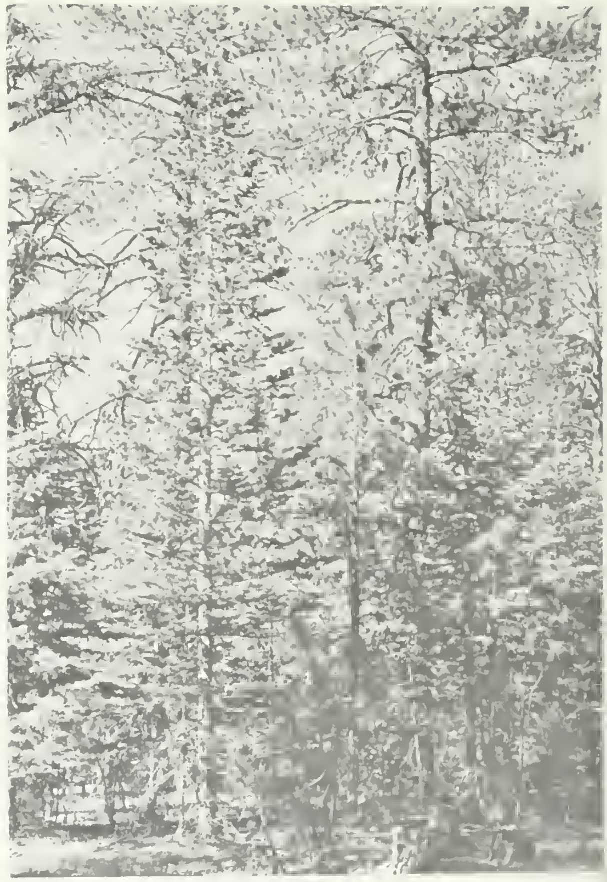


Figure 7.—Secondary succession where ponderosa pine is being replaced by a dense stand of white fir in Jemez Canyon, Santa Fe National Forest, New Mexico.

Figure 6. — Secondary succession in the white fir series. The site in the foreground is presently occupied by a dense stand of *Quercus gambelii*, under which a nearly pure stand of *Abies concolor* is developing. Sandia Mountains, New Mexico.

mediately known that the ponderosa pine stand is seral or temporary, and, assuming that no major disturbances such as fire intervene, the ponderosa pine will not maintain itself over time, but give way to a succession of more tolerant species. Also, the white fir series represents a cool-moist site relative to true ponderosa pine, and it can support a mixture of species, as compared to the latter, which is too warm and dry for Douglas-fir or true firs.

Confusion also has resulted from mixing geographic and vegetation taxonomic categories in certain recent attempts to develop hierarchical systems for land classification and mapping. A recent paper by Bailey et al. (1978), and discussion by Daubenmire (1968), and Kuchler (1973), helped to clarify this situation as follows:

Taxonomic Terms	**Geographic Terms**
Classification Levels in the Taxonomic Hierarchy	Mapping Levels of the Physical Environment
Formation	Region
Subformation	Province
Series	Zone
Association (community type)	Habitat Type
Phase	Phase

For example, zones are determined by the climax dominant species that are recognized as representing one segment of a sequence along a major environment gradient. In the Southwest, this is illustrated by the progression of tree species along an elevation gradient from ponderosa pine at moderate elevations to subalpine fir at higher elevations. Therefore, it becomes feasible to construct two parallel keys, one of potential vegetation and one of habitat, which coincide (Pfister 1976, Poore 1962).

The principles of "competitive exclusion" and "monospecific dominance" (Daubenmire and Daubenmire 1968)—wherein several trees may find the physical conditions of a site within their range of ecologic amplitudes, but only one of them will eventually dominate over time because of competitive superiority—sometimes are not apparent in the forests of the Southwest, especially in arid or subtropical situations. Two or more species may appear equally adapted and competitive within the same habitat. Therefore, forest or woodland series, in some cases, may involve co- or multi-dominance, but still be named after a single tree species (table 1). Naming series after a single climax dominant species or associations by binomials, does not imply monospecific dominance.

Habitat types and zones are generally named after the associations and series they respectively support. For example, the ponderosa pine series represents the ponderosa pine zone, and the *Pinus ponderosa/Festuca arizonica* association identifies the *P. ponderosa/F. arizonica* habitat type.

The potential vegetation concept can convey more information for management about the site than cover typing (Volland 1975). Because vegetation effectively reflects the integration of environmental factors, it may be used in a relative sense to assist in the identification of areas of "equivalent biotic potential" (Rowe 1960, Lowe 1964). This is important to mapping, because, whereas the cover type is temporary, a map of the potential natural vegetation is as permanent as the land itself (Daubenmire 1973, 1976).

Figure 8. — Densely forested places at relatively moderate elevations often support stands of mixed species composition. Generally, these stands are *Abies concolor* series. Carson National Forest, New Mexico.

Table 1. Estimated distribution and successional role of tree species in forest and woodland series of the Southwest

Proposed Series	**Major Tree Species**	*Pinus aristata*	*Picea engelmannii*	*Abies lasiocarpa*	*Picea pungens*	*Abies concolor*	*Pinus strobiformis*	*Pinus flexilis*	*Pseudotsuga menziesii*	*Pinus ponderosa scopulorum*	*Populus tremuloides*	*Pinus ponderosa arizonica*	*Cupressus arizonica*	*Pinus leiophylla*	*Pinus latifolia*	*Pinus edulis*	*Pinus monophylla*	*Pinus cembroides*	*Juniperus californica*	*Juniperus deppeana*	*Juniperus monosperma*	*Juniperus osteosperma*	*Juniperus scopulorum*	*Juniperus pinchotii*	*Quercus oblongifolia*	*Quercus arizonica*	*Quercus chrysolepis*	*Quercus emoryi*	*Quercus hypoleucoides*	*Quercus reticulata*	*Quercus gambelii*	*Arbutus arizonica*	*Quercus arisea*	*Robinia neo-mexicana*
Pinus aristata		C	a	a				(C)																										
Picea engelmannii		(s)	C	a							s																							
Abies lasiocarpa			C	C	(s)	a	s	s	(S)	(s)	S																							
Picea pungens				a	C	(s)	s		S	S	S																							
Abies concolor				a	(s)	C	(C)	(s)	(C)	S	S	(s)		(s)	(s)			(s)													(S)			(S)
Pinus flexilis								C	C	s		(s)																						
Pseudotsuga menziesii						s	(s)		C	(C)	s					(c)					(c)		(c)				(c)		(s)	(s)	(S)		(s)	(S)
Pinus ponderosa scopulorum							(c)			C	s	(C)	(c)			(S)				(c)	(S)	(S)	(c)			(s)			(s)	(s)	(S)	(c)		(S)
Cupressus arizonica													C													?		?	?	s				
Pinus leiophylla												(c)	c	C	c			(c)		c	(c)				c			c	c	c		c		
Pinyon																(C)	(C)	?		(C)	(C)	(C)		(c)			(c)							
Juniperus																			(C)	?	C	?	?	c										
Evergreen oak																		(C)		(C)	(C)				(C)	(C)		(C)	(C)				(C)	

+ *Legend: C=dominant; c=minor climax species; a=accidental; S= major seral species, usually long lived; s=minor seral species; ()=in some places, but not everywhere in the Southwest*

PRELIMINARY CLASSIFICATION OF CONIFEROUS FOREST AND WOODLAND SERIES

Methods

A preliminary classification for the coniferous forest and woodland series, within the vegetation classification framework described earlier, is proposed here for the Southwest. The proposed classification is based upon the literature, field observations, and data of Moir and Ludwig (1977), and Hanks et al. (1977), following procedures developed by Daubenmire and Daubenmire (1968), and Pfister and Arno.[6] This work is a first step in the development of a vegetation classification by a method of "successive approximations" (Poore 1962). As new knowledge is obtained, the classification can be extended and improved.

[6]*Pfister, Robert D., and Stephen F. Arno. (In press). Classifying forest habitat types based on potential climax vegetation. Manuscript submitted to Forest Science on December 5, 1978.*

Results

Eight coniferous forest and five woodland series are proposed. Table 1 lists the series, and shows the estimated distribution and successional status of trees species within the series classification. Figure 9 shows the distribution of the major tree species encountered with increasing elevation.

A dichotomous key for the classification is followed by general descriptions of the series. The key leads imply potential to support the climax dominants. Generally, "present and successfully reproducing" refers to the presence of 10 or more individuals of the species per acre that are obviously not just confined to microsites; accidentals are considered to be fewer than 10 trees per acre (Pfister et al. 1977, Steele et al. 1975). The use of fewer than 10 trees per acre as criteria for accidentals is somewhat arbitrary and may have less validity in semiarid, open forest or woodland types. This needs to be further evaluated in field studies. Criteria for accidentals may then be adjusted as appropriate.

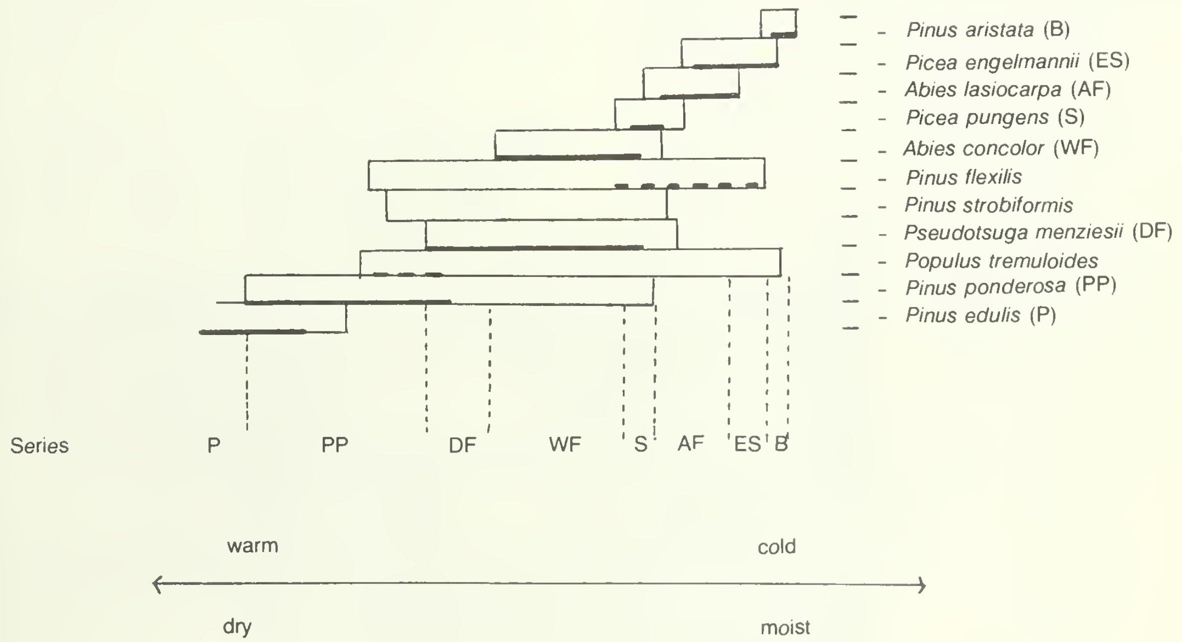


Figure 9.—An estimation of the distribution of tree species encountered with increasing elevation. The horizontal bars designate upper and lower limits of the species relative to the environmental gradient. The diagram treats only those series above the Pinyon Zone. The part of the tree species range in which it is estimated to occupy the role of a climax species is indicated by the heavy line. Habitats representing edaphic or topo-edaphic climaxes do not fit neatly into the scheme of depicting or generalized temperature-moisture gradient and are generally indicated by a heavy broken line.

Descriptive Key to the Coniferous Forest and Woodland Series

1. Dominant vegetative strata comprised principally of trees potentially over 50 feet in height characterized by closed and/or multi-layered canopies . . . FOREST FORMATION . . . 2
1. Dominant strata comprised of trees, but with a mean potential height under 50 feet, the canopy of which is usually open, or very open, and singular . . . WOODLAND FORMATION . . . 10
    2. Trees deciduous and broadleaved (often confined to canyon bottoms, drainageways, or floodplains), consisting of pure or mixed stands of *Alnus*, *Fraxinus*, *Juglans*, *Platanus*, and *Populus* . . . DECIDUOUS FOREST SUBFORMATION
    2. Trees evergreen and needle-leaved . . . CONIFEROUS FOREST SUBFORMATION . . . 3
3. *Abies lasiocarpa* and/or *Picea engelmannii* present and successfully reproducing, and clearly not just confined to microsites . . . 4
3. *Abies lasiocarpa* and/or *Picea engelmannii* absent or accidental . . . 5
    4. *Abies lasiocarpa* present and successfully reproducing; *Picea engelmannii* sometimes strongly codominant . . . *ABIES LASIOCARPA* SERIES.
    4. *Abies lasiocarpa* absent or accidental; *Picea engelmannii* present and successfully reproducing, often occurring in relatively pure stands . . . *PICEA ENGELMANNII* SERIES.
5. *Picea pungens* present and successfully reproducing; *Pseudotsuga* sometimes codominant; often confined to lower slopes, moist bottoms, and meadow margins . . . *PICEA PUNGENS* SERIES
5. *Picea pungens* absent or accidental . . . 6
    6. *Abies concolor* present and successfully reproducing, sometimes codominant with *Pseudotsuga menziesii* or *Pinus strobiformis*; *Pinus ponderosa* often present as a long-lived seral species . . . *ABIES CONCOLOR* SERIES
    6. *Abies concolor* absent or accidental . . . 7
7. *Pseudotsuga menziesii* present, sometimes codominant with *Pinus ponderosa*; *Abies*, *Picea*, or *Pinus flexilis* absent or accidental . . . *PSEUDOTSUGA MENZIESII* SERIES
7. *Pseudotsuga* absent or confined to microsites . . . 8
    8. *Pinus leiophylla* and/or *P. latifolia* present, generally codominant with *Cupressus arizonica*, *Juniperus* spp., *Pinus cembroides* and/or evergreen oaks; *Pinus ponderosa*, if present, represented by the var. *arizonica* . . . *PINUS LEIOPHYLLA* SERIES
    8. *Pinus leiophylla* and/or *P. latifolia* absent or accidental; dominant vegetation not as described above . . . 9
9. *Pinus ponderosa* present and successfully reproducing, often occurring in pure stands, but may also be codominant with pinyon, juniper, and/or evergreen oaks in some areas; *Pinus ponderosa* generally represented by var. *scopulorum*, but in some places in southern Arizona by var. *arizonica* . . . *PINUS PONDEROSA* SERIES
9. *Cupressus arizonica* the dominant tree species, forming nearly pure stands; generally local in occurrence and confined to north-facing slopes of canyon bottoms . . . *CUPRESSUS ARIZONICA* SERIES
    10. Woodlands dominated by broad-leaved deciduous species such as *Acer*, *Alnus*, *Morus*, *Prosopis*, *Prunus*, and *Salix*, often confined to waterways . . . DECIDUOUS WOODLAND SUBFORMATION
    10. Woodlands of other than deciduous broadleaved species . . . 11
11. Woodlands dominated by evergreen broad-leaved species (in our area primarily oaks such as *Q. emoryi*, *Q. hypoleucoides*, *Q. arizonica*) . . . EVERGREEN OAK SERIES
11. Woodlands dominated by evergreen needle-leaved species . . . CONIFEROUS WOODLANDS SUBFORMATION . . . 12
    12. *Pinus aristata* present, often in relatively pure (and ancient) stands at high elevations; sometimes codominant with *Pinus flexilis* and/or *Picea engelmannii* . . . *PINUS ARISTATA* SERIES
    12. *Pinus aristata* absent or accidental . . . 13
13. *Pinus flexilis* present, sometimes codominant with *Pseudotsuga menziesii*, mostly confined to lithosolic situations in the mountains at relatively high elevations . . . *PINUS FLEXILIS* SERIES
13. *Pinus flexilis* absent or accidental . . . 14
    14. Pinyon (*Pinus cembroides*, *P. edulis*, or *P. monophylla*) present and not just confined to microsites; often codominant with *Juniperus* spp. . . . PINYON SERIES

14. Pinyon absent or widely scattered in microsites; Juniper (*Juniperus deppeana*, *J. monosperma*, *J. osteosperma*) present forming open to very open (savanna), pure or mixed stands . . . *JUNIPERUS* SERIES

Discussion

Forest vegetation may begin about 5,000 feet and occur up to timberline, about 11,500 feet, in the Southwest. Patterns of forest vegetation are generally stratified altitudinally (Merriam 1898). Forest species are commonly depicted in a series of altitudinal belts (Spencer 1966). This phenomena has been the focus of considerable plant ecology research in the Southwest (Shreve 1922, Whittaker and Niering 1975).

Upon close inspection, however, altitudinal belts of forest vegetation exist only in a general sense (Watson 1912, Shreve 1922, Whittaker and Niering 1975). For example, Daubenmire (1943) described vegetation distribution patterns by stating that, "Zones in the sense of rigidly defined altitudinal belts clearly do not exist . . . but no careful student of plant sociology . . . would deny the existence of regularly repeated series of distinct vegetative types, each of which bears a constant altitudinal or topographic relationship to contiguous types."

Essentially, altitude is only one factor in determining occurrence of plant communities. Others, such as slope, aspect, cold air drainage, precipitation patterns, and soil characteristics, interact to create a mosaic of habitat types in mountainous terrain (fig. 1). Understanding the natural distribution of tree species and their role in forest succession in relation to these different types of habitats is fundamental to forest land management (Daubenmire 1976, Pfister 1972).

The following relates the literature and describes the general basis for recognition of the different series.

General Series Descriptions

***Pinus aristata* series.**—The *Pinus aristata* series occurs at high elevations. It appears to occupy cold, dry sites. It may occur in pure ancient stands or with *Pinus flexilis*. At its lower elevational limits, it grades into the *Picea engelmannii* or the *Abies lasiocarpa* series. In some cases, it may border the *Pinus flexilis* series. *Picea engelmannii*, which occupies cold, wet sites, may go above *Pinus aristata* in elevation at places. The *P. aristata* series is widely scattered and minor in occurrence. It is known from the highest mountains of the Sangre de Cristo Range and the San Francisco Peaks (Schubert and Rietveld 1970) (fig. 10), and from high peaks in Colorado, Utah, Nevada, and California (Little 1950). The series[7] is recognizable in work by Brown and Lowe (1974), Kuchler

[7]*Not all authors cited used the series category. Different authors may classify similar types at different taxonomic levels. The important point is that the type was recognized by others as a recurring entity warranting taxonomic treatment.*

Figure 10. — *Pinus aristata* series, San Francisco Peaks, Coconino National Forest, Arizona.

(1964), Lowe (1964), Pearson (1920, 1931), and the Society of American Foresters (1954).

***Picea engelmannii* series.**—Engelmann spruce is reported to go above *Abies lasiocarpa* in altitude in the Southwest. At places it occurs with virtual exclusion of any other trees (Pearson 1931, Pfister 1972). Those habitats where Engelmann spruce forms nearly pure stands, with *Abies lasiocarpa* being absent or accidental, are recognized as the *Picea engelmannii* series (fig. 11). The series grades into *Pinus aristata* series at high elevations, and *Pinus flexilis* on steep, south-facing slopes and exposed ridges. At lower elevations, it forms ecotones with the *Abies lasiocarpa* or *Abies concolor* series. The *Picea engelmannii* series is recognizable in work by Moir and Ludwig (1977), Pearson (1931), Pfister (1972), and Brown and Lowe (1974).

***Abies lasiocarpa* series.**—The *Abies lasiocarpa* series is typified by stands of *Picea engelmannii* with variable amounts of *Abies lasiocarpa* in association (figs. 12 and 13). The key factor for recognizing the series is that *Abies lasiocarpa* is present and successfully reproducing. Aspen is a notable seral species, and *Pinus contorta* is conspicuously absent from the series in the Southwest (Kuchler 1964). In the Southwest, there is little evidence that succession in spruce-fir stands tends toward dominance by *Abies lasiocarpa* (Jones 1974). Therefore, the *Abies lasiocarpa* series, as proposed, generally represents a situation of codominance between *Picea engelmannii* and *Abies lasiocarpa*. Stands dominated by *A. lasiocarpa* would also belong to this series. Spruce

Figure 12.—*Abies lasiocarpa* series, Kaibab National Forest, Arizona.

Figure 11.—*Picea engelmannii* series, Truchas Peaks area, Santa Fe National Forest, New Mexico.

bark beetle outbreak or removal of spruce tends to favor fir reproduction (Alexander 1973), but apparently not to the exclusion of spruce. Understanding of the successional relationships in this series may be complicated by the fact that, in the Southwest, two varieties of the fir occur—*A. lasiocarpa* var. *lasiocarpa* (subalpine fir) and *A. lasiocarpa* var. *arizonica* (corkbark fir). On the Kaibab Plateau and other places, subalpine fir replaces corkbark fir (Lowe 1964). Whether the varieties reflect environmental differences, or assume different roles in succession, is not known. Because of lack of any basis at this time to do otherwise, corkbark and subalpine fir have both been included in the proposed *Abies lasiocarpa* series. The series, as proposed, includes the Engelmann spruce-subalpine fir type referred to by many authors, but distinguishes between those habitats where subalpine or corkbark fir does not occur. At upper limits, the series forms ecotones with the *Pinus flexilis* or *Picea engelmannii* series, and, at its lower limits, it grades into the *Abies concolor* or *Picea pungens* series. The *Abies lasiocarpa* series is recognizable in work by Brown and Lowe (1974), Kuchler (1964), Lowe (1964), Merkle (1954), Moir and Ludwig (1977), Pearson (1920, 1931), Pfister (1972), Society of American Foresters (1954), and Whittaker and Niering (1975).

***Abies concolor* series.**—The *Abies concolor* series is characterized by the presence and successful reproduction of *A. concolor* (figs. 6, 8, and 14). Subalpine fir and Engelmann spruce are sometimes present as accidentals. *Pseudotsuga menziesii*, and at places *Pinus strobiformis*, appear codominant (fig. 15). *Pinus ponderosa* is a long-

Figure 14.—*Abies concolor* series, Santa Fe National Forest, New Mexico.

Figure 13. — *Abies lasiocarpa* series, Santa Fe National Forest, New Mexico. Engelmann spruce is codominant, and Douglas-fir is a long-lived seral species.

Figure 15.—*Abies concolor* series on Mount Graham, Arizona. Douglas-fir and white fir are codominants in this stand.

lived seral species. Habitats representing the *Abies concolor* series sometimes support fire-maintained stands of *Pinus ponderosa* and *Pseudotsuga menziesii*, but those situations can generally be recognized by occurrence of *Abies concolor* in the understory. Aspen is a notable seral species in this series. The *A. concolor* series and its ecotones with the *Abies lasiocarpa* series, have often been referred to as "mixed conifer forest."

Nearly pure stands of *Abies concolor* occur at places such as on the east slope of the Sandia Mountains, New Mexico, where Castetter (1956) remarked on the "extensive solid stands," or at places in the Black Range, New Mexico, and elsewhere. Photos of old growth stands of *A. concolor* and *Pseudotsuga* on the Santa Catalina Mountains, Arizona, are often figured in vegetation studies (Lowe 1964, Turner 1974).

The *A. concolor* series has the most complex ecotone relationship of any of the southwestern forest series. It may occur adjacent to nearly every other forest series, but most often it grades into the Douglas-fir or ponderosa pine series at lower elevations and the subalpine fir series at higher altitudes.

Successional relationships in this series, as in others, may be complicated by floristic differences in the various mountain ranges of the Southwest. Aspen, Gambel oak, and New Mexico locust are common seral species in some areas. In the mountains of southern Arizona, five-needled pines and evergreen oaks may replace species more commonly associated with *A. concolor*, as is the case in the Huachuca Mountains, Arizona, where *A. concolor* reportedly occupies the highest elevation zone (Wallmo 1955). In the Organ Mountains, New Mexico, it is reported as a topo-edaphic climax (Dick-Peddie and Moir 1970).

From reports in the literature, the *Abies concolor* series appears to be represented in nearly all the major mountain ranges in the Southwest (Castetter 1956; Dick-Peddie and Moir 1970; Merkle 1954, 1962; Moir and Ludwig 1977; Pfister 1972; Wallmo 1955; and Whittaker and Niering 1975).

***Picea pungens* series.**—The *Picea pungens* series represents a topo-edaphic climax bordering meadows, stream banks, and bottoms in the Southwest (fig. 16). It is typified by dominance of *Picea pungens* on those habitats that are too warm and dry for *Picea engelmannii* or *Abies lasiocarpa*. Douglas-fir and ponderosa pine may occur as long lived seral species.

The *Picea pungens* series may form ecotones with the *Abies concolor*, *Abies lasiocarpa*, *Pseudotsuga* series and deciduous riparian forest or woodland riparian types. Generally, where *Picea pungens* occurs in association with *Abies concolor* or *A. lasiocarpa*, it must be considered seral, since it is the least tolerant of the three species (Pfister 1972). Lowe (1964) reports, "blue spruce is a major dominant on the extensive summit area of the Kaibab Plateau, where it dominates the forest bordering mountain grasslands."

Moir and Ludwig have revised their 1977 manuscript to recognize low-elevation situations where *Abies lasiocarpa*, *Picea engelmannii*, and *Picea pungens* occur, as being the *P. pungens* series (Moir and Ludwig 1979). Their reasoning was that these stands occur at too low an elevation for *P. engelmannii* or *A. lasiocarpa* series. The authors' interpretation of this situation is that these are frost pocket sites in which the occurrence of subalpine and Engelmann spruce is depressed in elevation below where one would normally expect to find these species occurring as dominants. These sites will key to *P. engelmannii* or *A. lasiocarpa* series in the authors' key to series.

Daubenmire and Daubenmire (1968) reported similar low elevation occurrence of *A. lasiocarpa* in frost pockets in the steppe of Washington. This phenomena is not inconsistent with the classification proposed here. Other examples where environmental factors compensate with one another to produce a community, which can at first appear incongruent to the vegetative zone, are not uncommon. These are sometimes called, "topo-edaphic climaxes" or "habitats of compensation" (Daubenmire 1968). In any case, the point should be stressed that this paper and Moir and Ludwig's are preliminary, and additional research may be required to resolve questions of this kind that may be raised by either work.

The series may be complicated by taxonomic problems between *P. pungens* and *P. engelmannii*, similar to those described by Pfister et al. (1977) for *P. engelmannii* and *P. glauca* in Montana.

The *Picea pungens* series has been recognized as a category by Brown and Lowe (1974), Kuchler (1964), Moir and Ludwig (1977), Pfister (1972), and Society of American Foresters (1954).

***Pinus flexilis* series.**—The *Pinus flexilis* series represents a topo-edaphic climax generally associated with lithosolic situations at high elevations, or occasionally extending to lower elevations on southern windswept exposures (fig. 17). *Pinus flexilis* may appear in pure stands, or Douglas-fir may sometimes be a codominant. Ponderosa pine sometimes shows up as a long lived seral species. The *Pinus flexilis* series as described here is separate from where the species occurs in association with *Abies lasiocarpa*, *Picea engelmannii*, or *Pinus aristata*. Those situations, where *P. flexilis* is seral, are treated within the subalpine fir, Engelmann spruce, or bristlecone pine series.

The limber pine series is complicated by the taxonomy, and possible hybridization, between *Pinus strobiformis* and *P. flexilis*. The former has been treated as a variety (*P. flexilis* var. *reflexa*) by some authors (Little 1950). Considerable confusion exists between these two trees in the Southwest. Generally, the limber pine series is represented by subalpine or lithosolic woodland situations; whereas, southwestern white pine is generally found in forest situations.

The limber pine type has been reported for the Jemez and Monzano Mountains, New Mexico (Castetter 1956). Layser has observed it on the Sandia Mountain Crest in New Mexico. Gehlbach (1967) reported a Douglas-fir/limber pine asociation from the Guadalupe Mountains "in the bowl at the head of Pine Spring Canyon." Pearson (1920) stated, "limber pine is able to occupy windswept slopes and ridges where Douglas-fir will not grow." The series is recognized by Ellison (1954), Pfister (1972), Ream (1963), Society of American Foresters (1954), and Steele et al. (1975, 1977).

***Pseudotsuga menziesii* series.**—The *Pseudotsuga menziesii* series is characterized by pure stands of Douglas-fir, or stands that appear codominant between Douglas-fir and ponderosa pine. True firs are notably absent, or at most accidental. *Pinus strobiformis*, quaking aspen, pinyon, junipers, and various oaks may be seral, or occur as understory components. At its upper distributional limits, the *Pseudotsuga menziesii* series commonly forms ecotones with *Abies concolor*, *Picea pungens*, *Pinus flexilis*, *Abies*

Figure 16. — *Picea pungens* series, Jemez Mountains, Santa Fe National Forest, New Mexico.

lasiocarpa, or *Picea engelmannii* series. At its lower limits, it generally intergrades into ponderosa pine. The Douglas-fir series in the Southwest is recognizable in work by Brown and Lowe (1974), Castetter (1956), Kuchler (1964), Lindsley (1951), Moir and Ludwig (1977), and Pfister (1972).

***Pinus ponderosa* series.**—The *Pinus ponderosa* series is generally dominated by the Rocky Mountain variety (*P. ponderosa* var. *scopulorum*) of ponderosa pine (figs. 18, 19, and 20). Pinyon, junipers, and various oaks may occur in the understory. *Quercus gambelii* is often a long-lived seral species. The habitats comprising the ponderosa pine series are too warm and dry for Douglas-fir or true firs to occur.

The ponderosa pine series is complicated by the occurrence of *P. ponderosa* var. *arizonica* in southeastern Arizona. Where *P. ponderosa* var. *arizonica* is the dominant tree species, such as on the Catalina and Huachuca Mountains of Arizona (Wallmo 1955), evergreen oak, and *Arbutus arizonica* are often common in the understory. In general, the ponderosa pine series in the Southwest is more complex than has been described for the northern Rocky Mountains because of additional asociated tree species and the occurrence of two taxonomic varieties of ponderosa pine. Typically, *Pinus ponderosa* var. *scopulorum* occurs in pure stands on numerous plateaus and ranges of the Colorado Plateau and southern Rocky Mountains. The *Pinus ponderosa* series is described by Brown and Lowe (1974), Hanks et al. (1977), Lindsley (1954), Lowe (1964), Merkle (1962), Pearson (1920, 1931), and Society of American Foresters (1954).

***Cupressus arizonica* series.**—The *Cupressus arizonica* series represents a topo-edaphic climax occurring in the Southwest only in southeastern and central Arizona (figs. 21 and 22). It occurs as relic stands restricted to north-facing slopes and canyon bottoms. Evergreen oaks are common components of the series. Tentatively, the series includes both *C. a. glabra* and *C. a. arizonica*, but additional study may show the former, a more northern variety, to be only a minor climax or seral species within other series; whereas, the southern variety (*C. a. arizonica*) represents relic climax situations. The series has been described by Brown and Lowe (1974) and Lowe (1964).

***Pinus leiophylla* series.**—The series is represented by a heterogenous mixture of conifers and evergreen oaks (fig. 23). It is characterized by five-needle pines (*P. leiophylla*, *P. latifolia*, and *P. ponderosa* var. *arizonica*) and evergreen oaks (*Q. arizonica*, *Q. emoryi*, *Q. hypoleucoides*, and *Q. reticulata*). *Pinus cembroides* and *Arbutus*

Figure 17.—*Pinus flexilis* series, Mt. Dutton, Utah.

Figure 18.—*Pinus ponderosa* series, Coconino National Forest, Arizona.

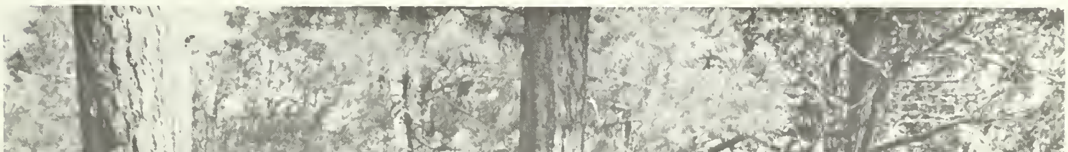


Figure 19.—*Pinus ponderosa* series, Tonto National Forest, Arizona. The ponderosa pine series in the Southwest is often complicated by occurrence of subordinate tree species.

arizonica are also present. Sufficient pines occur in this series to give it a different appearing aspect than woodland (Wallmo 1955). This series occurs only in southeastern Arizona and southwestern New Mexico in the Southwest, but it may be more extensive in Mexico. It has also been recognized by Brown and Lowe (1974).

Pinyon series—Pinyon series is characterized by the absence of conifers other than pinyon and junipers (figs. 24 and 25). The series includes those stands dominated by *Pinus edulis*, *P. monophylla*, or *P. cembroides*, or where those species are codominate with *Juniperus* spp. *Pinus monophylla* is reported to occur in pure stands at places (Harlow and Harrar 1950), and *P. cembroides* is confined to southeastern Arizona in the Southwest.

In the Guadalupe mountains, *Juniperus deppena* is reported to be the tree most frequently associated with *P. edulis* (Gehlbach 1967). Whereas, in northern New Mexico and northeastern Arizona, *J. monosperma* and *J. scopulorum* commonly occur (Howell 1941). *J. osteosperma* is often common in *P. monophylla* woodlands. It may also occur with *P. edulis* (Kesek 1966).

The different pinyon species and their respective associations represent different types of habitats, but because of the similarity in life form and climatic controls, they are grouped into one series for purposes of this paper. Future studies should provide bases to distinguish between environments supporting pinyon stands dominated by *P. edulis* or *P. monophylla* at the association level.

Brown and Lowe (1974) recognized a category for pinyon in which they included all *Pinus edulis*

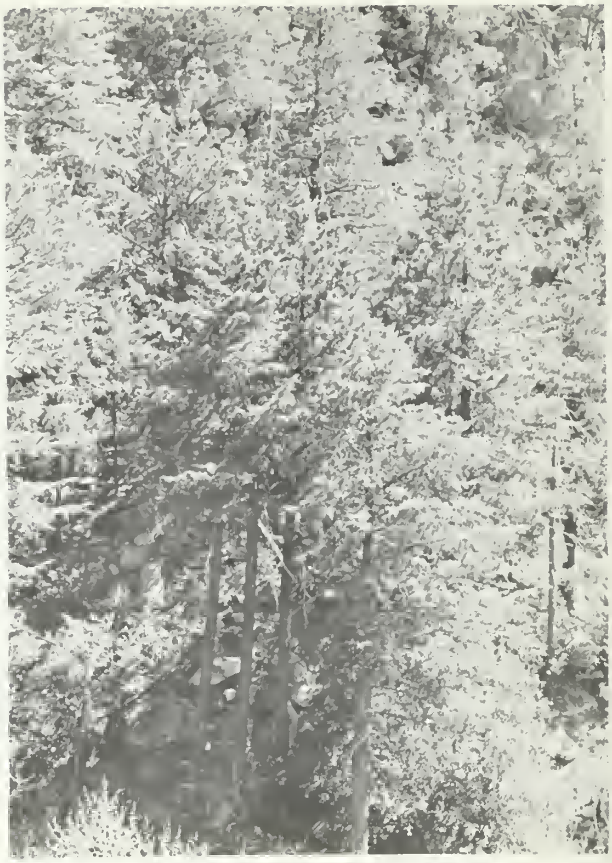


Figure 21.—*Cupressus arizonica* series on north slope of Bear Canyon, Catalina Mountains, Coronado National Forest.

Figure 20. — *Pinus ponderosa* series, Apache-Sitgreaves, Arizona, approaching the warm-dry end of the environmental gradient on which ponderosa pine is a climax dominant.

associations. For more discussion on the treatment of the pinyon-juniper complex see the *Juniperus* series discussion.

***Juniperus* series.**—The *Juniperus* series, as proposed, is characterized by open stands of juniper (figs. 26 and 27). No other conifer is represented, or at most, pinyon or evergreen oak is widely scattered and confined to microsites. Woodlands dominated wholly or partially by junipers are widespread. Daubenmire (1943) recognized this type as a zone extending from Mexico to Canada. Traditionally, the coniferous woodlands have been lumped into an ubiquitious category called "pinyon-juniper" or "juniper-pinyon." The approach suggested here is that a logical break, consistent with the treatment of other series, is where pinyons successfully occupy the juniper woodlands, as compared to those communities where only junipers occur.

Literature and observations support this approach. Watson (1912) noted pinyon and juniper ". . . shade into each other very gradually, even imperceptibly, but no more so than ponderosa pine and Douglas-fir which are separated by the same authors," and, "*Pinus edulis* never extends as far down the mountain side as *Juniperous monosperma*, the difference being an average of 500 '." Merkle (1952) reported juniper to be the principal tree from 6,500 to 6,800 feet elevation in the Grand Canyon area, Arizona. Pearson (1920) also pointed out pinyon makes appearance at higher elevations than juniper.

In west central Arizona, *J. californica* is reported to occur only on alluvial fans below canyons, while in the same area, *J. osteosperma* and

Figure 23.—*Pinus leiophylla* series on Coronado National Forest, Arizona.

Figure 22. — *Cupressus arizonica* series, Coconino National Forest, near Sedona, Ariz.

Figure 24.—Pinyon series on the Zuni Indian Reservation, Arizona.

Figure 25.– Pinyon series, Santa Fe National Forest, New Mexico.

Figure 26.—*Juniperus* series near Albuquerque, N. Mex.

Figure 27.—*Juniperus* series with *Juniperous osteosperma* and *Holacantha emoryi.* The juniper species and associations comprising this series may vary, but generally it is recognizable from Mexico to Canada.

Pinus monophylla are codominants in the canyonlands (Kesek 1966). *J. monosperma* is reported to dominate on rain-washed slopes in the Guadalupe escarpment, and to have the broadest ecological amplitude of any tree species in the Guadalupes (Gehlback 1967). *J. deppena* is reported to occupy wetter sites above *J. monosperma*, usually in association with *Pinus edulis*. *J. pinchotii*, a rare conifer for the Southwest (Little 1975), is not considered to be ecologically important because of its limited occurrence (Gehlbach 1967). Pearson (1920) reported that *J. deppena* has a higher moisture and lower temperature requirement than *J. osteosperma* and *J. monosperma*. On the basis of the literature, it appears relatively safe to say that, in New Mexico, much juniper-savanna is dominated by *J. monosperma*.

While *Juniperus* woodland (and savanna) is a readily recognizable physiognomy, it occurs over a wide range of environments.Six species of juniper occur in the Southwest. A center for distribution of juniper species in the Southwest is the Flagstaff area, where ranges of four species are sympatric (Whiting 1942). Some of the species' (e.g., *J. osteosperma* and *J. deppena*) ecological amplitudes are such that they do not appear to form monospecific stands in the Southwest, but are always in association with other conifers, evergreen oak, or other small trees. The literature indicates an ecological individuality exists between the various juniper species, but additional studies are required to better determine the ecological and habitat relationships between them.

Juniper woodland is recognized by Brown and Lowe (1974), Kuchler (1964), Merkle (1952), Pearsón (1920), Society of American Foresters (1954), and Watson (1912).

Evergreen oak series.—The evergreen oak series is characterized by open woodlands dominated wholly or partially by evergreen oaks (*Quercus arizonica*, *Q. emoryi*, *Q. hypoleucoides*, and *Q. oblongifolia*), sometimes in association with *Juniperous deppena* and/or *J. monosperma*, and at places *Pinus cembroides* (fig. 28). The series is not to be confused with seral stands of oaks (*Quercus hypoleucoides*, and *Q. reticulata*) that may sometimes occur on conifer sites (Wallmo 1955) or evergreen oak scrubland.

Occurrence of evergreen oak species is stratified altitudinally (Lowe 1961). Wallmo (1955) reported that the lowest elevational type of oak woodlands in the Huachuca Mountains, Arizona, are dominated by *Q. oblongifolia* (at 5,000 feet and seldom above 5,200 feet). It is soon joined by *Q. emoryi* and *Q. arizonica*. At 5,200 feet *Q. hypoleucoides* appears. *J. deppena* is reported to be the most common species of juniper throughout the oak woodlands in the Huachuca Mountains. In parts of New

Figure 28.—Evergreen oak woodland series in southeastern Arizona.

Mexico, Q. *grisea* may be an important component of evergreen oak woodlands (Dick-Peddie and Moir 1970, Gehlbach 1967). Evergreen oak woodlands are described in part by Dick-Peddie and Moir (1970), Gehlbach (1967), Lowe (1964), Shreve (1942), Society of American Foresters (1954), Wallmo (1955), and Whittaker and Niering (1975).

Deciduous broad-leaved forest.—Deciduous forest in the Southwest may be divided into several types. The first is forest dominated by one or more of the following species: *Fraxinus velutina*, *Juglans major*, *Platanus wrightii*, *Populus fremontii*, and *Salix bonpladiana* (Lowe 1964). Generally, these forests are confined to major river bottoms, canyons, and floodplains. At least three series appear to be represented in this group.

Other riparian forests (or woodlands) may be dominated by *Acer*, *Alnus*, *Morus*, *Prosopis*, *Prunus*, *Populus augustifolia*, and/or *Salix*. Additional study will be required to determine climax and successional relationships within these latter types. Classification of riparian forests in the Southwest has been discussed in more detail by Pase and Layser (1977).

Another type of deciduous broad-leaved forest appears in southeastern New Mexico where *Quercus muhlenbergii* seems to be a climax dominant in local situations confined to mountain canyons.

A common deciduous forest type in the Southwest is *Populus tremuloides* (fig. 29). The successional role of aspen has long been open to debate (Pfister 1972). Where it is associated with *Pseudotsuga*, *Abies concolor*, or *Abies lasiocarpa*, it is clearly a seral species. However, there are situations where *Populus tremuloides* appears in relatively stable stands without conifer regeneration, and it has been proposed as climax in certain edaphic situations (Hoffman and Alexander 1976, Pfister 1972, Reed 1971, and Severson and Thilenius 1976). There is a clear opportunity for an aspen series in the Southwest when criteria for separating seral and climax aspen stands are described. The possibility for aspen to form edaphic climaxes is indicated by the broken heavy line in figure 9.

Computer Compatibility

The timber and range subsystem of INFORM[8] both require vegetation classification information for the PLANT-ASSOC table. This table is a three-part field (table 2). The first part consists of two columns where the subformation information could be loaded, providing room for 99 subformations. The second field is also two-part, so that up to 99 series could be loaded for any one subformation. The third part of the field contains a three-column entry for association or community type. This has the potential for 999 associations of a particular subformation and series being loaded. Retrieval of stored data from the system can be for all PLANT-ASSOC fields or for any one part. The approach is systematic and hierarchical, and allows for incorporation of additional data as the plant classification system evolves (table 3).

The data storage approach, as well as the classification method and categories, are wholly compatible and consistent with land classification and information systems—such as Modified ECOCLASS,[9] ECOSYM (Davis and Henderson 1976), Brown and Lowe (1974), or any others which could be utilized for national assessments under the Renewable Resources Planning Act of 1974.

Figure 29.—Aspen stand, San Francisco Peaks, Arizona. Criteria for separating seral from long-lived, stable aspen communities needs to be described.

Table 2.—Shows example of the field and columns into which the hierarchical classification information could be loaded

Field 1		Field 2		Field 3		
Col. 1	*Col. 2*	*Col. 1*	*Col. 2*	*Col. 1.*	*Col. 2*	*Col. 3*
Subformation		Series		Associaton		

[8]*Information for management (INFORM) is a system being developed by the USDA Forest Service to aid managers in data storage, retrieval, and analysis (Forest Service Manual 1390).*

[9]*Gallaher, W. B., and Committee (draft). Modified ECOCLASS–A method for classifying ecosystems. USDA Forest Service, Rocky Mountain and Southwestern Regions. Mimeo, October 1, 1975.*

Table 3.—Shows the classification categories and examples of how computer codes could be assigned for the timber subsystem of INFORM

1·0·0	CONIFEROUS FOREST SUBFORMATION
1·1·0	Engelmann spruce series
1·2·0	Subalpine fir series
1·3·0	Blue spruce series
1·4·0	White fir series
1·5·0	Douglas fir series
1·6·0	Ponderosa pine series
1·6·1	*Pinus ponderosa/Festuca arizonica* association
1·6·2	*Pinus ponderosa/Mulenbergia virescens* association
1·6·3	*Pinus ponderosa/Boutaloua gracillis* association
2·0·0	DECIDUOUS FOREST SUBFORMATION

SUMMARY AND CONCLUSIONS

This paper demonstrates how a preliminary classification for all natural vegatation in the Southwest might be accomplished to the series level with little additional research. Research by Hanks et al. (1977) and Moir and Ludwig (1979) will contribute to the classification of forest vegetation to the association level. Recent state-of-the-art papers on silviculture (Alexander 1974, Jones 1974, and Schubert 1974) have all identified the development and employment of habitat type classification as necessary to assure proper management of forests and sites in the southern Rocky Mountains.

Considerable additional research is needed to complete the classification at the association level for other than forest vegetation. However, concepts and methods to do this, as well as resulting applications to land management, are similar to those for forest vegetation (Daubenmire 1970, Hironaka 1977, and Shiflet 1973).

The method applied here, and proposed for the continued development of the classification, is described by Poore (1962). It consists of development of the classification through successive approximation by progressively more detailed investigations being conducted within a main framework.

Other research needs are suggested by this study. They are determining the successional and ecological relationships between: *Pinus strobiformis* and *P. flexilis*, *Abies lasiocarpa lasiocarpa* and *A. l. arizonica*, *Picea engelmannii* and *P. pungens*, *Cupressus arizonica arizonica* and *C. a. glabra*, and *Pinus ponderosa scopulorum* and *P. p. arizonica*. In addition, information on the successional and synecological roles of various junipers, oaks, and locust in forest stands is generally lacking. For example, tree growth in the Midwest has been found to be better on sites previously occupied by black locust because of improved soil structure and more foliar nitrogen (Carmena et al. 1976); does New Mexico locust play a similar successional role in the Southwest?

The classification approach proposed is computer compatible, and can be used with existing information systems such as INFORM. Since the method is systematic and hierarchical in design, it will allow incorporation of new or additional information as the vegetation classification system evolves.

If phytosociological studies are pursued by the methods suggested here, the plant associations for the Southwest eventually will be described systematically, their diagnostic species concisely defined, and their habitat, succession, and management implications described in detail.

Standardization of concepts and methods, as proposed here, is a major advantage, making the work of one author directly interpretable by, and useful to, another. Research findings reported within the site-based classification system will make those results more meaningful to management.

Development of a vegetative classification system, with concurrent training of personnel in its use, can result in a strong land management tool that expands knowledge about the forest and range and allow application of practices and prescriptions with due regard for environmental situations.

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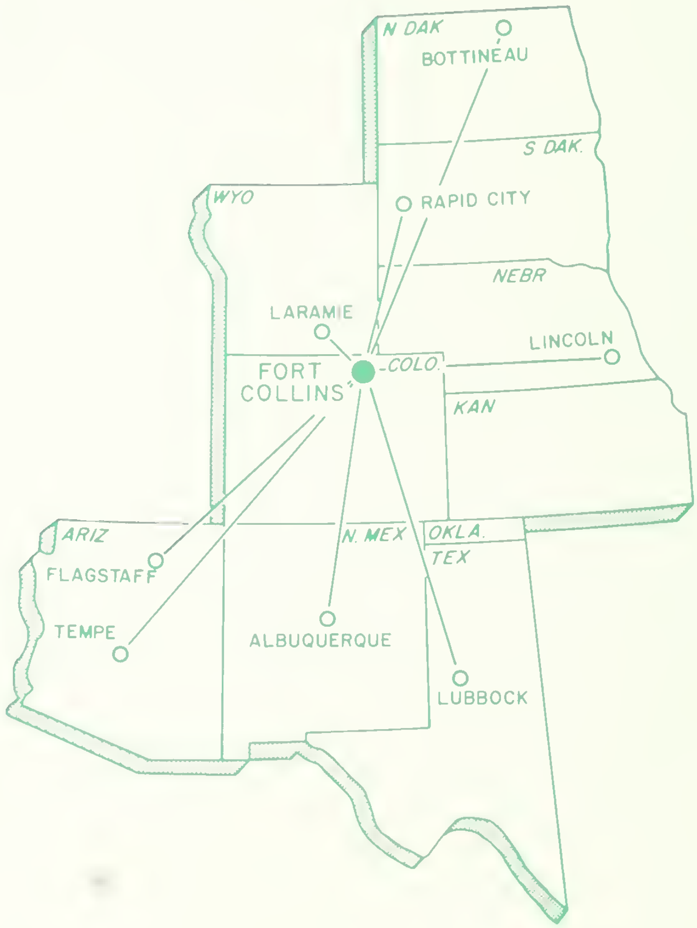
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Ecology of Arizona Cottontop

Dwight R. Cable

Research Paper RM-209
Rocky Mountain Forest and Range Experiment Station
Forest Service
U.S. Department of Agriculture

Abstract

This paper summarizes what is now known about the ecology and management of Arizona cottontop, *Trichachne californica*, a palatable, drought hardy, perennial grass that thrives under moderate grazing on semidesert ranges of the Southwest. Perennial culms that produce axillary shoots, favorable response to grazing, long life, and ability to grow both on warm- and cool-season moisture are valuable attributes of this species.

Keywords: Ecology, Arizona cottontop, grass

Research Paper RM-209 July 1979

Ecology of Arizona Cottontop

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Contents

Ecology of Arizona Cottontop

Dwight R. Cable

Management Recommendations

To be successful, grazing management must ·egulate the season and intensity of use of range plants ;o the plants maintain a healthy vigorous condition.)bviously, knowledge of the effects of partial lefoliation on plant growth processes is basic to the levelopment of a management strategy. Because the ·hythm of plant growth differs from species to species, ı management strategy suitable to one species may be ınsuitable to another.

The rhythm of plant growth of Arizona cottontop ınd its reactions to partial defoliation suggest this ;pecies is highly flexible in its adaptability to nanagement strategies. Cottontop's high palatability ıt all seasons, its tolerance of relatively heavy use, its ;rowth habit in which shoots in all stages of levelopment are present throughout most of the ;rowing season, its weak apical dominance and :onsequent prevalence of axillary shoot development, ınd the fact that axillary shoot growth is stimulated by ·emoval of the growing point (partial defoliation) ·egardless of stage of development, all suggest cottontop will thrive with any management strategy, provided only that the intensity of use is held to a reasonable level.

Because cottontop is more palatable than most other grasses with which it is associated, it will be used more heavily than the associated species, and thus could easily be subjected to destructive intensities of use. Two management practices are recommended to enable cottontop to maintain optimum productivity:

1. If cottontop is the dominant, the utilization objective should be based on 50% use of cottontop. Use of associated species under these conditions will probably average about 35% (Cable and Martin 1975). If cottontop is not the dominant grass, stock to obtain about 40% use of the major species; use of cottontop should average a little less than 60% at this stocking level.

2. Defer or lighten grazing by about 50% during the growing season, 2 years out of 3. This will lighten the grazing impact on cottontop during the summer, but still provide the stimulus for axillary sprouting and increased productivity.

Research Highlights

Arizona cottontop is an important native forage ;rass of southwestern ranges of the United States. ˜xtending southward to central Mexico, it is widely listributed within the semidesert shrub, desert ;rassland, chaparral, and oak-woodland types of the ˜ower and Upper Sonoran Life Zones. It grows on oils that vary in texture from clay loams to those that ıre loose and gravelly.

Cottontop is a climax dominant in the semidesert ;rassland type and, like other climax species, lecreases in abundance on abused ranges. Cottontop, ıowever, has several morphological and physiological haracteristics that enable it to tolerate severe onditions of climate or use and that enhance its alue as a range grass:

1. Individual culms and roots are long-lived, living for 3 years or more. Many individual plants live more than 15 years.

2. The culms exhibit low-level apical dominance. This, coupled with the large reservoir of buds at culm nodes on the elongated, as well as on the basal unelongated, portion of the culms, results in the sprouting of numerous axillary shoots. During its lifetime a basal culm can produce up to eight mature axillary shoots in addition to the terminal inflorescence.

3. Removing the growing point at the beginning of the summer growing season stimulates the sprouting and growth of axillary shoots, regardless of the stage of development of the shoot. The degree of stimulation is greatest during the first few weeks after treatment and decreases gradually during the remainder of the growing season.

4. Cottontop plants utilize both winter and summer precipitation. Although most herbage is produced during the summer growing period, essentially all basal culms produced in any given year sprout during the spring growing period; summer growth on most basal culms is merely a continuation of growth on shoots that sprouted in spring.

5. Shoots are produced throughout the growing season. New shoots are initiated from buds, both at

the base of the plant and on elongated internodes. New shoots on the upper part of the culms provide easily available green herbage relatively early in the growing period. Although sprouting of basal buds is normally confined to the spring growing period, axillary buds on the upper parts of the culms sprout throughout both spring and summer growing periods. Thus, most plants have shoots in all stages of development (from newly sprouting buds to those with a maturing panicle) at all times during the growing season.

6. Inflorescences mature throughout the summer growing period, starting about 3 weeks after growth begins (July or early August) and continuing as long as soil moisture is available (October in some years). Germinable "seed" will, therefore, be present whenever conditions are favorable for germination and establishment.

7. Cottontop is highly palatable to cattle and is preferred over most other species at all seasons of the year.

8. Cottontop tolerates relatively heavy grazing use over long periods. Dormant-season grazing averaging over 65% use for periods up to 15 years had no apparent effect on longevity, changes in basal area, or changes in plant height. However, continued heavy grazing during the growing season slows recovery following very dry years.

9. Cottontop, like most other semidesert species, extracts soil water rapidly when it is available, both in spring and summer. With its permanent root system in place, it can absorb soil water and begin growth quickly after an effective rain. It is also able to subsist for prolonged periods in soil with essentially no available water.

10. An established stand of cottontop competes strongly with velvet mesquite seedlings and, thereby, strongly deters the spread of mesquite into grasslands.

11. If a remnant stand of grass is present, marked improvement in production can be obtained by shrub control and lighter grazing use. Cottontop can be successfully reseeded on upland areas receiving at least 28 cm of annual precipitation, provided a good seed bed has been prepared. The use of cotton-box hoppers on seeding equipment is recommended for handling the fluffy cottontop seed. The recommended seeding rate is 5.6 kg/ha of hammermilled seed in the hulls.

12. Cottontop is only moderately affected by fires. If a wet summer follows a burn, cottontop will probably recover completely during the first growing season. If the burn is followed by a dry summer, complete recovery will probably require two summers.

13. Cottontop is highly flexible in its adaptability to management strategies, provided grazing intensity is held below 60%. Light summer use 2 years out of 3 is recommended to maintain optimum vigor while at the same time stimulating axillary sprouting to increase productivity.

Taxonomy

The type specimen for *Trichachne californica* (Benth.) Chase, (under the name *Panicum californicum* Benth.) was collected near Magdalena Bay, Lower California, in 1840. In the intervening years seven other names have been applied to this species: *Panicum lachnanthum, P. californicum, P. saccharatum, P. insulare* var. *lachnanthum, Valota saccharata, Digitaria californica,* and *Trichachne saccharata.* Under the International Rules of Botanical Nomenclature, published in 1933, *Trichachne californica* (Benth.) Chase was adopted as the valid name for this species (Hitchcock 1933 and 1950). Other authors (e.g., Gould 1968) now refer to this grass as *Digitaria californica.*

According to Fernald (1934), the genus *Valota* (*Trichachne* as used here) has existed for an extremely long time, as evidenced by the fact that the genus is found both in America and Australia, Australia having been cut off from its connection with other continents by mid-Cretaceous times. Fernald also states the species of the genus are few and stable (about 12), in contrast to the numerous unstable species of youthful genera of *Paniceae.*

Description

Arizona cottontop is a native, perennial, warm-season bunch grass with slender, erect stems from 30 to 100 cm tall (fig. 1). The culms are usually branched below, and arise from woolly, knotted, enlarged bases. The leaves are normally 8-13 cm or up to 25 cm long, with the upper leaves shorter than the lower. The outstanding physical characteristic of this grass is the slender silky-cottony seed head (composed of lance-shaped spikelets which grow in pairs) covered with long, silky, white (occasionally purplish) hairs (Judd 1962, Canfield 1934, U.S. Department of Agriculture 1937).

The cottontop root system is finely divided and much branched. It is concentrated mostly in the upper 20 cm of soil but extends downward to about 100 cm in coarse-textured soils (Blydenstein 1966). Average root diameter for 30 plants excavated was 0.6 mm. The number of secondary branches in the first 15 cm ıveraged 32 for grazed plants and 80 for protected ɔlants, and the number of roots per square centimeter, ːounted 8 cm below the base of the plant, averaged 'rom 1.5 to 2.2.

Distribution

The range of Arizona cottontop on the American ontinent is from the southwestern United States to entral Mexico (Hitchcock 1913). It has been collected rom nine states in Mexico as well as Arizona, New Mexico, Texas, Oklahoma, and Colorado. It is eported from South America (Hitchcock 1950).

The species is found in the desert shrub formation of he Lower and Upper Sonoran Life Zones. It is found n the oak-woodland, chaparral, and semidesert rassland types in Arizona between 300 and 1,800 m levation (Judd 1962, Humphrey 1960), where it grows n a variety of soils from clay loam to sandy loam and oose gravelly soils (Anderson et al. 1953, Schmutz nd Smith 1976, Cable and Martin 1975, Cable 1979).

Figure 1.—Mature Arizona cottontop plant (90 cm tall).

In New Mexico it is one of many important codominants with black grama (*Bouteloua eriopoda*) in the desert grassland (Castetter 1956). It is also common on the plains and foothills of the drier mountains throughout the state (Wooton and Standley 1911). In southern New Mexico it is found associated with *Larrea* on limestone ledges and porphyritic hills and in the yucca-cactus association (Fosberg 1940).

Arizona cottontop in Texas is distributed throughout the state except for the Gulf Coast and the piney woods and post-oak savannah of east Texas. It is more common on the Rio Grande Plains, Edwards Plateau, and the trans-Pecos areas than elsewhere (Walker 1954, Gould 1962, Cory and Parks 1937).

In northeastern Sonora, Mexico, Arizona cottontop has been collected in the oak-grassland type (above the mesquite zone) from 1,100 to 1,800 m in elevation (White 1948).

Growth and Development

Seedling Development

Every cottontop plant starts as a seedling, which develops into the primary shoot, and from which additional shoots develop by tillering. The sequence of development of the parts of the shoot, as the first foliage leaf pushes out through the tip of the coleoptile, is for the leaf blade to start elongating first, followed in a few days by the sheath. During the first 20 days of seedling development in the greenhouse, additional leaves appear at about 3-day intervals (Cable 1971b). The first internode to begin active elongation starts about the 14th day, and successive internodes start elongating at about 3-day intervals. By the 7th or 8th day, the first adventitious root appears (fig. 2), and by the 20th day most seedlings have three or four adventitious roots (the permanent root system of the shoot). Axillary buds at the base of the primary shoot sprout into basal tillers (two only) by the 20th day, the two second-order basal tillers are elongating by the 40th day. Generally, there are three unelongated internodes left below the lowest elongating internode on the primary shoot, four on the first-order tillers, and six on the second-order tillers. Blade, sheath, and internode lengths on the seedlings generally increase from the lowest through the 7th or 8th, but they differ between the primary shoot and the first- and second-order basal tillers in that the mature length of blade, sheath, and internode at any given culm position is longest on the primary shoot, intermediate on the first-order tiller, and shortest on the second-order tiller.

Shoot Growth

Although cottontop is a warm-season grass and grows mostly during the summer, new basal shoots normally start their development in the spring growing period, go dormant during the May-June drought, resume growth with the onset of summer rains, and produce an inflorescence. Most shoots also produce axillary shoots from axillary buds, primarily on the upper part of the culm; these axillary shoots may mature during the same summer or go dormant over winter and mature the following spring or summer.

Cottontop culms (both basal and axillary) live more than 1 year, some 3 or more. They may also use from one to four growing periods (spring or summer) to complete their development from sprouting bud to mature inflorescence, depending largely on the amount and distribution of rainfall and depending on when the initiating bud sprouted during the growing period. Growth made during successive growing periods is usually separated by one or two very short internodes. These short internodes result when elongation of new internodes stops at the end of a growing period.

Numbers of internodes on mature reproductive culms vary from 3 to 21. In addition, basal culms may have from 3 to 15 unelongated internodes (<2 mm) at the base of the culm, below ground level. In general, axillary culms have about one-third fewer internodes than basal culms, and multiple-growing-period culms average 1-1/2 to 2 times as many internodes as those only one growing period old. Numbers of internodes on axillary culms are inversely related to how high on the parent basal culm the axillary shoot is attached.

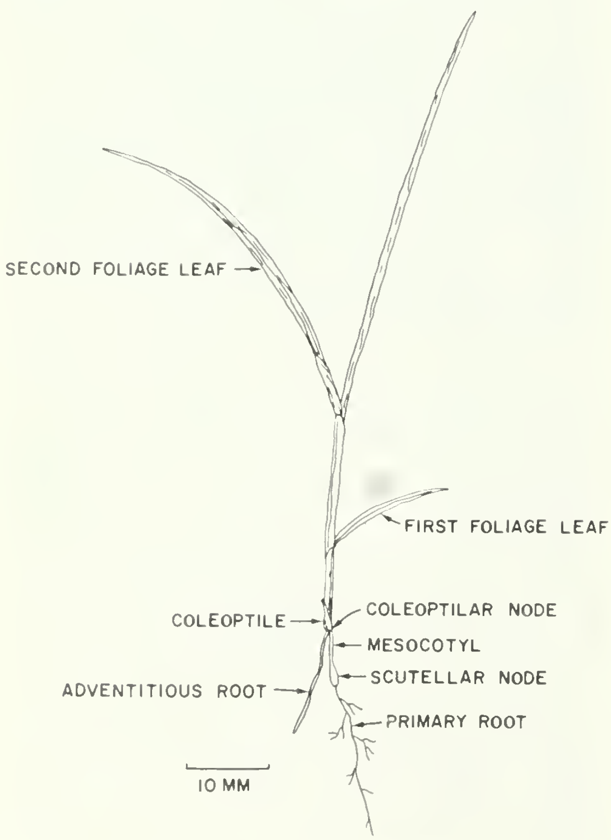


Figure 2.—Seven-day-old cottontop seedling.

Generally, the shortest internodes are at the base of the culm. Internode lengths increase gradually toward the top. The top two, especially the topmost (panicle internode), are greatly elongated. Variations in available soil moisture, however, affect these relations as, of course, does the number of growing periods required for the development of the culm. The length of the panicle internode is strongly correlated with the total length of the mature culm, because it comprises about 50% of that length.

In the field, new basal shoots elongate more or less uniformly for 5 or 6 weeks after summer growth starts (2.5-11 mm/day). Rate of growth then increases sharply (to 19-24 mm/day) for 7 or 8 days while the panicles are exserting and elevating, and then tapers off to zero within a few days.

From 13 to 18 days is normally required for the panicle internode to push the panicle out of the flag leaf sheath. About 70-80% of that elongation takes place in the first 7 days. Rate of elongation of the panicle internode is closely correlated with availability of soil moisture, but the internode will resume elongation if moisture is received within 3-4 days after elongation has stopped due to a moisture shortage. The maximum rate of elongation of the panicle internode measured on a single culm was 48.3 mm/day averaged over a 3-day period. Within any one 24-hour period, average hourly rates of elongation varied from a high of 1.95 mm/hour between 5 and 7 p.m., to a low of 0.27 mm/hour between 3 and 6 a.m. (fig 3).

Overall length of mature reproductive culms generally varies between 260 and 660 mm.

Buds

An axillary bud generally develops on each internode of the culm except two: the internode between the coleoptile and the first foliage leaf on the primary shoot, and that between the flag leaf and the panicle on all culms. Axillary buds on unelongated basal internodes (below ground level) differ markedly in appearance from those on elongated internodes of the culm. Basal buds are relatively short, circular in cross section, and not tightly appressed to the culm. Axillary buds are longer, slender, flattened, and tightly appressed to the culm. Basal buds are protected by dried scales and scale-leaves, with a short, dried rophyll at the base. The prophyll does not elongate. Axillary buds are enclosed only by the green prophyll and the sheath of the subtending leaf. The prophyll elongates for a time after the bud sprouts. The inner eaves of the basal bud are thickened and fleshy, while hose of the axillary bud are not.

Some buds live as long as the culms, 3 years or more; ome dry up, some are damaged by insects, and some reeze. Basal buds and axillary buds near the ground re most susceptible to damage. The average basal ulm will have eight live axillary buds and three live asal buds. By the time the basal buds sprout, they will verage 3.4 axillary buds per basal bud.

Basal buds sprout primarily in the spring, producing he year's crop of basal culms, most of which mature he following summer. Axillary buds can sprout hroughout both the spring and summer growing eriods and also in early fall, depending on the vailability of soil moisture.

Adventitious Roots

In the greenhouse adventitious roots start to develop from the lower internodes of the primary hoots within a week after seedling emergence (Cable 971b). By the time the seedlings are 3-1/2 to 4 weeks ld, they have an average of 4.8 adventitious roots. On asal buds, adventitious roots begin to develop about he time the bud sprouts in the spring. Additional adventitious roots appear throughout the spring growing period. Very few appear during the summer. Adventitious roots develop on some of the same internodes at the base of the culm from which basal shoots develop, although adventitious roots tend to develop more on the lower internodes and basal shoots on the upper internodes of the basal unelongated portion of the parent culm. Numbers of adventitious roots on mature basal culms varied from 0 to 12, averaging from 3.5 to 5 per culm. Live-tissue tests with tetrazolium chloride indicate many cottontop roots live 3 years; it is likely that some live longer. Active root systems of field-grown plants extend to at least 1-m depth (Cable 1979).

Leaves

New leaves are initiated by the apical meristem as nearly horizontal ridges partly encircling the growing point, and appearing alternately on opposite sides of the rudimentary axis. Each ridge soon develops into a collar-like structure. Only one or two such collar-like leaf initials are present at a given time. The newly developing leaf then grows up and over the apical meristem, forming a cowl-like hood over the growing point. Vertical elongation then raises the hood up away from the apical meristem. The ligule becomes visible as a row of bumps on the veins by the time the leaf is about 1 mm long. As soon as the ligule appears, the blade begins rapid elongation. The sheath begins

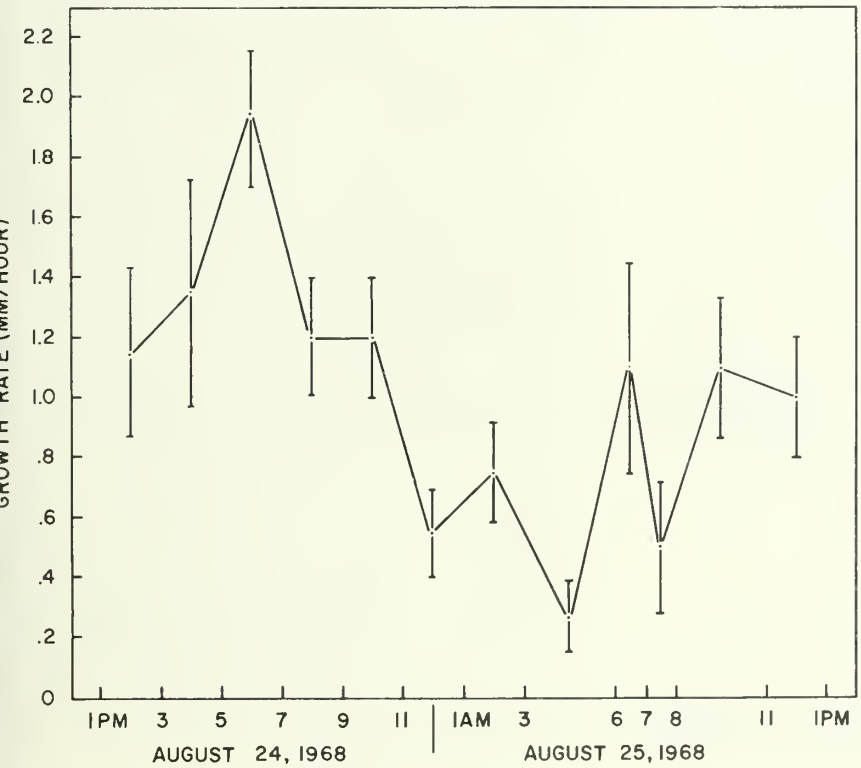


Figure 3.—Elongation of panicle internodes in millimeters per hour while panicles were exserting (means of 10 culms ±1 SE).

elongating when the blade has reached one-half to three-fourths of its mature length. The youngest six leaves are in the process of elongating at any one time (fig. 4). The youngest three or four of these are less than 1 mm long and are elongating very slowly. The other two or three exceed 1 mm in length and are elongating rapidly (all except the oldest are fully enclosed by the surrounding leaf sheaths). The blade is rolled during its elongating stage, but is fully expanded and elongated by the time it is fully emerged from the next lower sheath. In the field new leaves are initiated at the rate of one about every 4 days. Leaf blades remain fully green from 10 to 13 days. They start to dry in the same order in which they appear and require from 21 to 46 days to become fully dry. The rate of drying varies markedly: leaves 2 and 3 (below the flag leaf) consistently remain partly green much longer than any of the other blades.

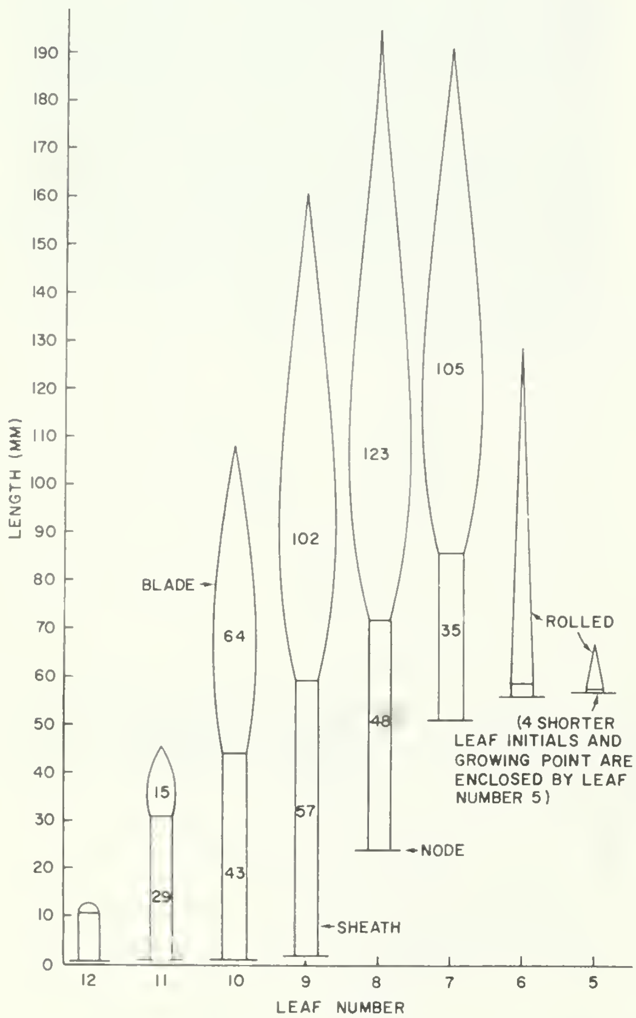


Figure 4.—Expanded diagrammatic view of vegetative shoot, showing relative positions and lengths of internodes, sheaths, and blades.

Lengths of leaf sheaths and leaf blades vary with position on the culm and whether the culm is basal or axillary. Also, taller mature culms tend to have longer leaves (sheath plus blade) than do shorter culms. The flag-leaf sheath is greatly elongated (to 202 mm), twice as long as the second sheath and three times as long as the third (fig. 5). Successively lower sheaths decrease slowly in length. Lengths of leaf blades are more variable than those of sheaths. Generally, the longest blade (up to 173 mm long) is on the third through sixth leaf from the top, with blade length decreasing toward both the top and bottom of the culm. However, on any given culm the longest blade can occur at any leaf position from the flag leaf to the seventh leaf. In the field differences in moisture availability at the time various leaves are elongating are responsible for the marked deviations from average lengths. Both sheaths and blades were shorter on axillary culms than on basal culms at all leaf positions. Leaf blades averaged 4.3 mm wide. Width was significantly related to blade length.

Inflorescences

The mature inflorescence of Arizona cottontop is a panicle consisting of a main axis with from four to nine erect branch racemes on which numerous spikelets covered with long, silky white hairs are borne. Normally, spikelets are borne in pairs, one short-stalked and one long-stalked, with each pair usually attached to the sinuous rachis at points of flexure. Panicles vary in length from about 50 mm to about 200 mm. The length of the panicle is strongly correlated with the length of the flag-leaf sheath, within which the panicle develops to its mature length before exserting.

The first indication that the vegetative growing point is about to become reproductive is an elongation of the growing point from the usual 0.07-0.09 mm to 0.15-0.20 mm long, accompanied by the formation of low ridges or swellings more or less circling the growing point (fig. 6). These are the primordia for the racemes. During the next 24 hours, while the young panicle is elongating to 3-5 mm, the raceme initials appear, and spikelet initials and glume primordia develop. By the time the panicle is ready to emerge from the enclosing sheath, it is fully elongated.

Most florets that reach anthesis (over half of cottontop florets are self-pollinated) exsert their anthers and stigmas during the first 3 hours after sunrise, on the part of the panicle that has emerged from the sheath during the previous 24 hours. By early afternoon flowering stops for the day. A few florets flower during the next week while the panicle is completing its exsertion and elevation. The last structure in the floret to complete its elongation is the ovary, or seed. The cottontop seed normally reaches its mature length of about 1.7 mm in the soft-dough stage after the panicle is well elevated. However, cottontop seed can mature even though lack of soil moisture at the end of the growing period prevents the panicle from emerging from the boot. The topmost spikelets usually begin falling within 5-8 days after the panicle has fully emerged from the sheath. Usually, all seed will fall within 7-8 days after the first shatter.

Normally, inflorescences begin emerging from the boot 2-3 weeks after growth starts in the summer. A few inflorescences are usually produced during the spring growing period. The first panicles to emerge are always on basal and axillary culms that started their development the previous fall or spring (multiple-growing-period culms). Ordinarily, panicles from culms not starting development until after the summer rains begin do not start to emerge from the boot until about 6 weeks after growth starts. New panicles continue to be produced as late in the fall as soil moisture is available (October in some years). Individual basal culms, during their 3-4-year life, can produce from one to nine panicles, of which all except one (or sometimes all) will be on axillary branches.

Meristematic tissue can change from vegetative to reproductive over a wide range of developmental stages—with culm length as short as 2.5 mm and only 1 internode elongated to 2 mm or more, or with culm length as long as 158 mm and 11 elongated internodes. Generally, few short shoots will be reproductive; the percentage increases as culm length and numbers of elongated internodes increase.

Seed Habits

No published information could be found on the seed yield of Arizona cottontop. Anderson et al. (1953) state that seed can be harvested with suction equipment or bug catchers. Anderson says harvesting and processing the chaffy seed is difficult, discouraging seed production.

The U.S. Department of Agriculture (1948) lists cottontop seed as follows: weight, 718,000 seed per pound (1,583 seeds/gm); average purity, 32%; average germination, 44%; and seed longevity, intermediate. Forty samples of seed collected on the Santa Rita Experimental Range in 1964 averaged 550,000 ± 5,527 seeds per pound (1,212/gm, ± 12) with rachises and glumes in place. Germination 6 months after collection ranged from 72 to 92%.

Seed longevity was tested by germination trials on seven batches of cottontop seed kept under uncontrolled storage conditions at the Santa Rita Experimental Range headquarters for periods varying from 3 to 30 years. These tests showed seed maintained a relatively high germination (over 80%) for about 3 years. Germination declined about 6% per year for the next 12-14 years, to less than 10%. Seed in

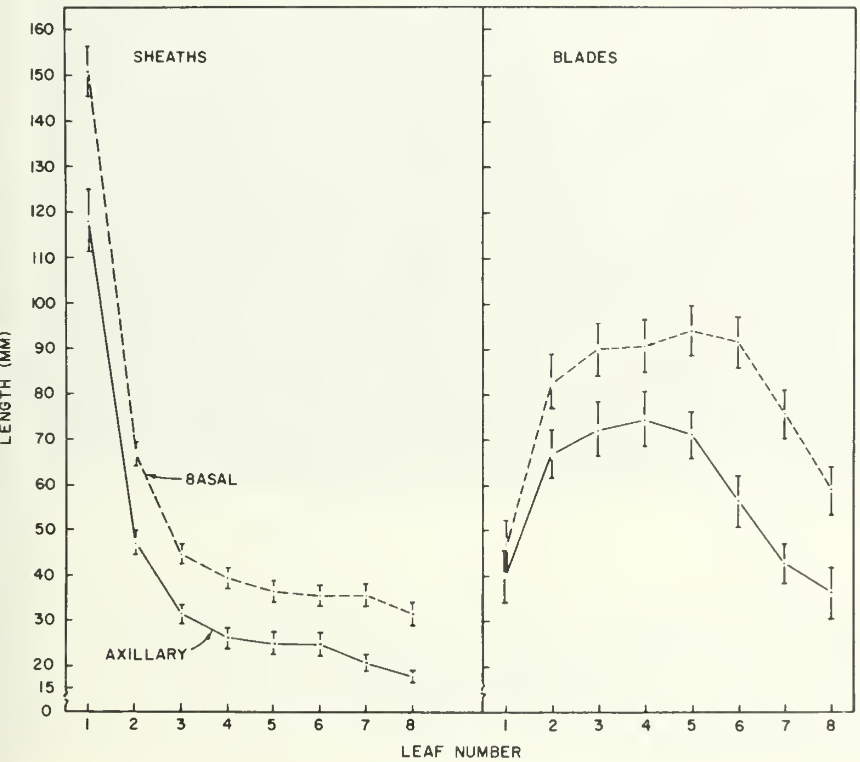


Figure 5.—Mean lengths of sheath and blade for upper 8 leaves on 28 mature basal culms and 14 mature axillary culms (±1 SE) (1 = flag leaf).

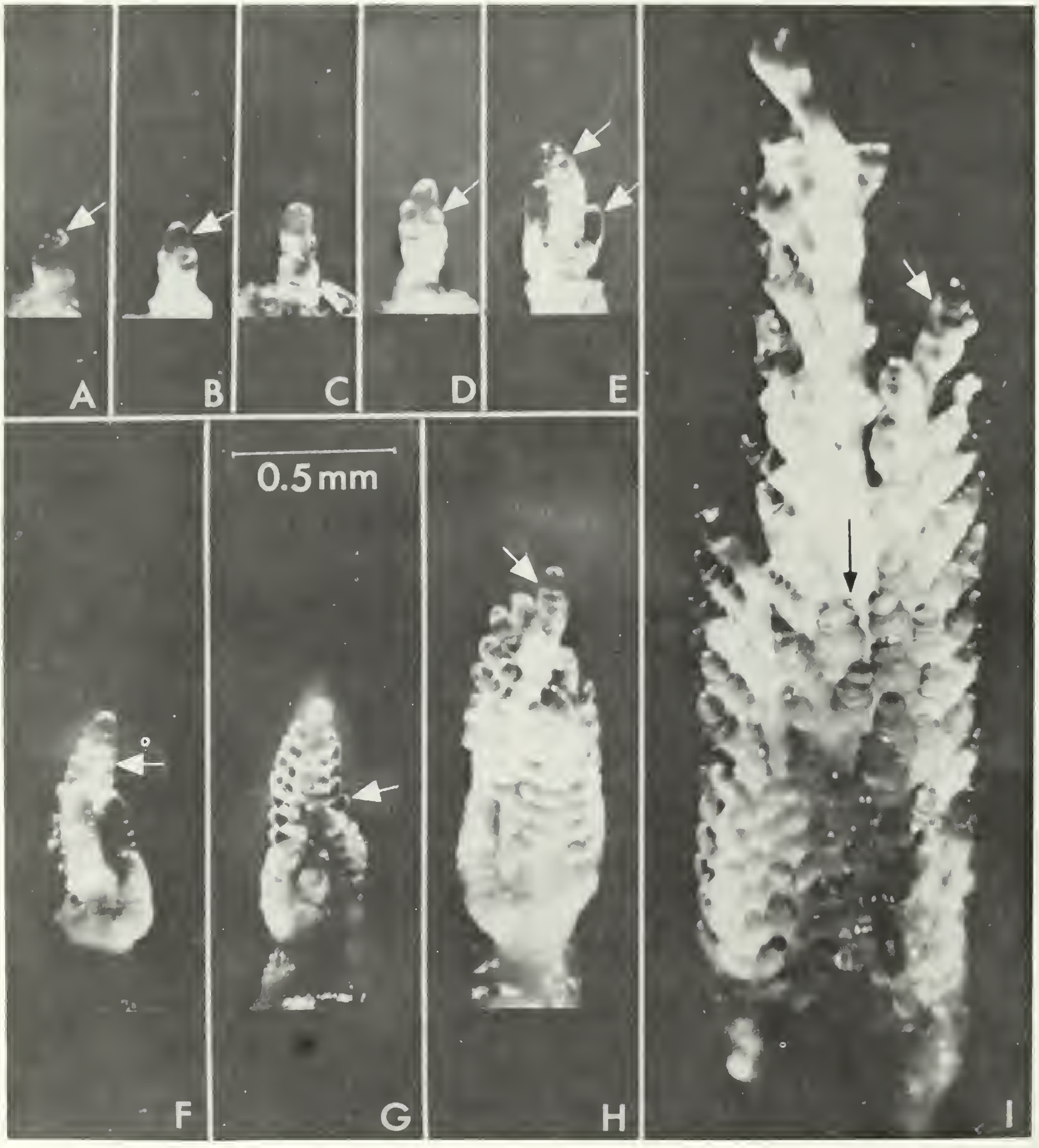


Figure 6.—Stages in the morphological development of shoot apices of Arizona cottontop: (A) vegetative growing point with cowl-like hood pushing up from far side; (B, C) vegetative growing points elongating preparatory to becoming reproductive; (D) raceme initials forming around reproductive growing point; (E) spikelet initials forming on upper part of main axis; branch racemes smooth; (F, G) spikelet initials showing on all branch racemes; (H) glume primordia on upper protuberances; (I) advanced stage of flower development, with floret protuberances in various stages of development.

uncontrolled storage at the Sierra Ancha Experimental Forest for 25 years showed 25% germination (Tiedemann and Pond 1967). Physiological and morphological differences and differences in storage conditions probably are responsible for the large differences in viability after prolonged uncontrolled storage.

Establishment and Longevity

Detailed 17-year records of seedling establishment on charted meter-square quadrats on the Santa Rita Experimental Range show that, although some cottontop seedlings were recorded in each of the 17 years, numbers of new plants averaged only 0.5 and 0.9 plants per meter-square quadrat on ungrazed and grazed quadrats, respectively. This was the lowest frequency for all species observed. However, first-season survival was relatively high, 46% on ungrazed quadrats, and 39% on grazed quadrats (Canfield 1957).

Arizona cottontop is a comparatively long-lived grass. Quadrat records from 17 years of charting on the Santa Rita show that some plants lived as long as 11 years (Canfield 1957). Arizona cottontop and sprucetop grama (*Bouteloua chondrosioides*) rated highest among 11 perennial grasses in survival during the first 4 years of life; from 17 to 21% of cottontop plants lived to 4 years of age. The percentage of plants surviving at any age was somewhat higher on ungrazed than on grazed quadrats through the fifth year; beyond that age survival was higher on grazed quadrats.

More recent records of cottontop longevity were obtained on the Santa Rita for 250 plants individually tagged in 1960 and 1961. Two hundred plants tagged in 1960 were in a pasture grazed annually during the winter-spring season. Fifty plants tagged in 1961 were in a permanent cattle exclosure. Basal diameter and height of each plant were measured twice yearly for 15 years. At the time of tagging, basal diameters of these plants varied from 1.2 to 14.0 cm. After 15 years, 31 of the 200 grazed plants (15.5%) were still alive, including one of the largest and one of the smallest plants originally tagged. Of the protected plants 17 of 50 (34%) were still alive, including the largest plants originally tagged. These results differ from those reported by Canfield (1957). Several of the grazed plants had their largest basal diameter at the end of the period. Obviously, some cottontop plants live considerably longer than 15 years. The protected plants that survived 15 years generally had much smaller basal diameters at the end than at the beginning of the period, and most were in poor vigor at the end.

Annual mortality rates show two major peaks (25.6% in 1963-64 and 27.2% in 1969-70) and two major lows (2.3% in 1967-68 and 1972-73) (table 1). These year-to-year differences in mortality may primarily reflect internal physiological conditions, because they are not correlated with observed changes in precipitation, intensities of utilization, or relative size of plant. It may be significant that the two major lows were in years with unusually high February-May rainfall. All longevity groups were grazed relatively heavily (45-55%) during the first 7 years and relatively lightly (20-30%) during later years.

Height-Weight Relations

Accurate determinations of the degree of utilization of grass plants are based on the height-weight relations characteristic of each species. From this relationship and records of actual use of individual plants on grazed range over a period of years, permissible levels of utilization can be determined. The height-weight relationship of Arizona cottontop was determined by air drying and weighing 2.54-cm segments of 15 cottontop plants. These 15 plants varied from 34 to 85 mm basal diameter, 66 to 99 cm total height, and 14.2 to 75.6 gm total weight. For these plants, the lower 40% of total height contained nearly 90% of the total weight (fig. 7). The long leafless panicle internode accounted for 34% of the average ungrazed plant height, but less than 2% of the plant weight.

To increase the usability of the height-weight data in determining utilization of individual plants, the data were converted into a nomograph (fig. 8) with which

Table 1.—Mortality among 200 tagged Arizona cottontop plants, 1961 to 1975

Year of death	Alive at start	Died during year		Mean use
		no.	*percent*	*percent*
1961-62	200	28	14.0	51
62-63	172	12	7.0	48
63-64	160	41	25.6	43
64-65	119	18	15.1	44
65-66	101	9	8.9	42
66-67	92	4	4.4	55
67-68	88	2	2.3	50
68-69	86	5	5.8	41
69-70	81	22	27.2	46
70-71	59	10	17.0	44
71-72	49	5	10.2	38
72-73	44	1	2.3	33
73-74	43	2	4.6	37
74-75	41	6	14.6	37
1975+	35	4	11.4	35

the percent use by weight can be determined directly from the ungrazed plant height and the grazed stubble height.

Ecological Relations

Successional Status

Early studies of perennial grass composition on the Santa Rita Experimental Range included areas heavily grazed, conservatively grazed for 5 years, and protected for 5 and 25 years, providing a basis for inferences on the successional status of cottontop and associated grass species (Canfield 1948).

On a relatively large segment of the Experimental Range, at elevations from 900 to 1,400 m with annual precipitation averaging from 30 to 55 cm, Canfield found that, after long periods of protection, the composition was dominated by tall, coarse-stemmed grasses such as Arizona cottontop, side-oats grama (*Bouteloua curtipendula*), and black grama. He concluded these species were probably "important members of the semidesert grassland climax vegetation." On the upper portion of the area studied, cottontop was the dominant species on protected areas, greatly surpassing every other grass in abundance and comprising one-third of the total composition. On the lower portion of the area cottontop and black grama were about equally abundant on protected areas and made up about one-half of the total cover. Canfield also noted that increasing abundance of Arizona cottontop was the most conspicuous sign of range recovery under either conservative grazing or total protection.

Response to Precipitation

Within its geographical range, cottontop grows in a wide variety of precipitation regimes, from a strongly bimodal type with spring and summer maxima separated by dry periods, as in southern Arizona, to a

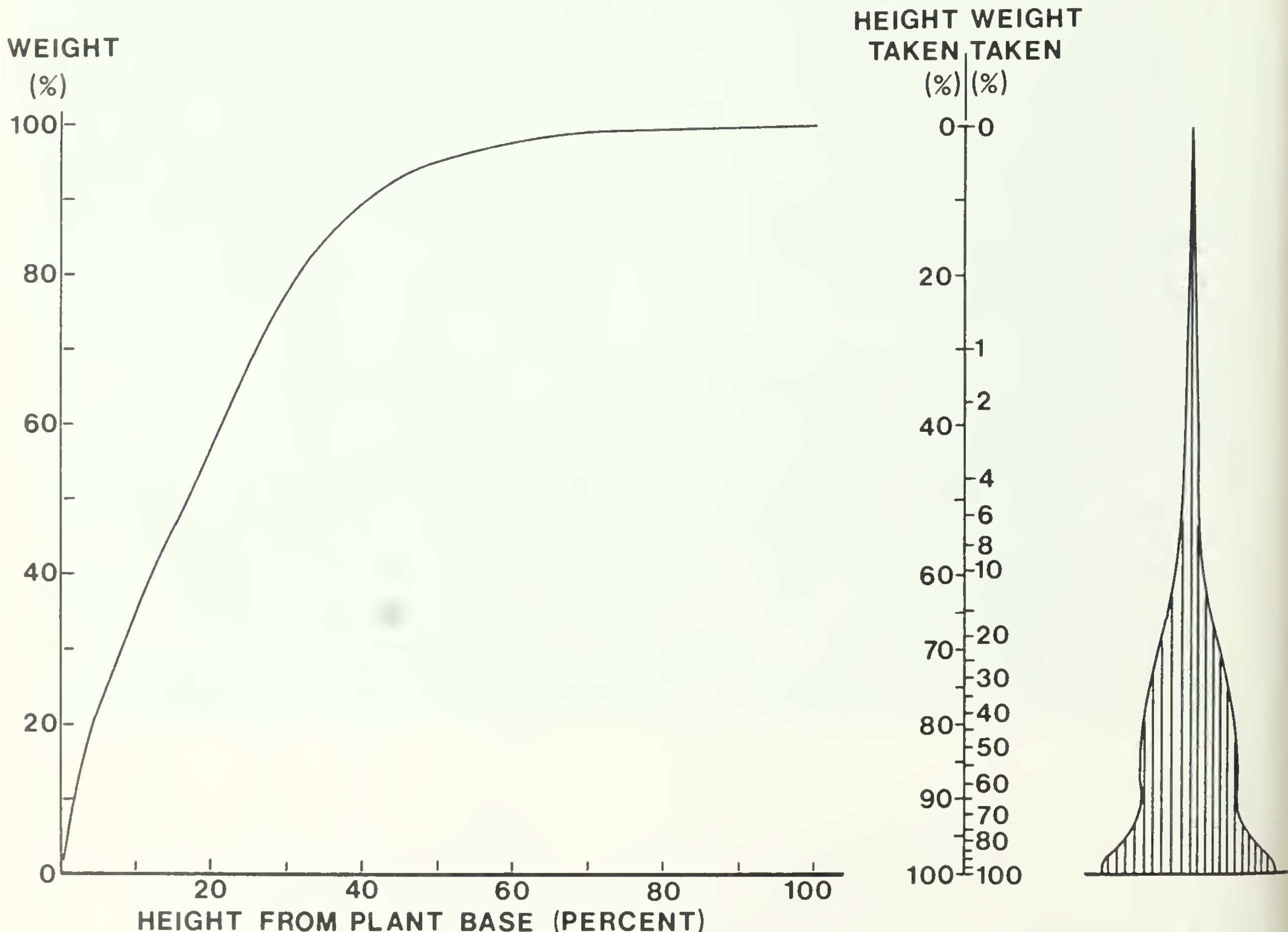
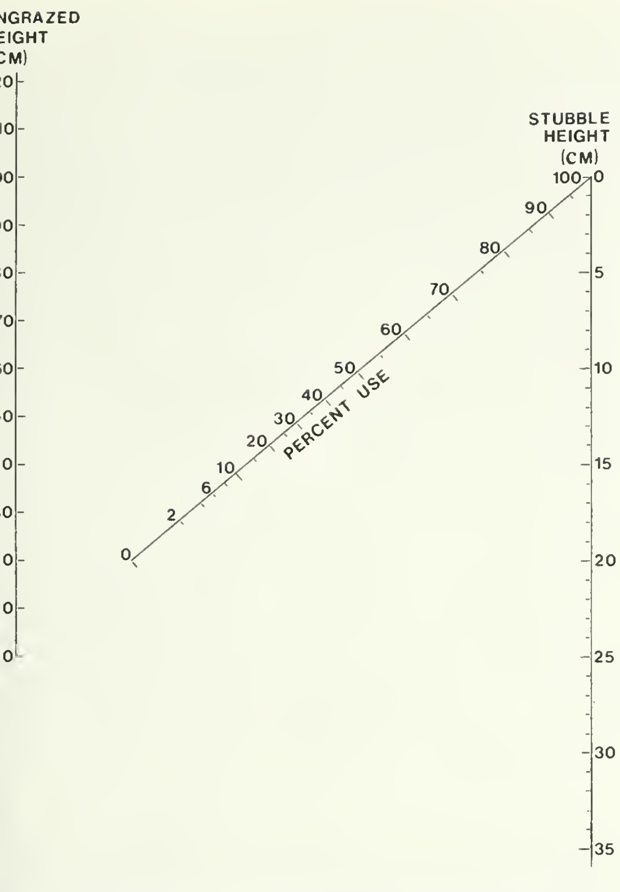


Figure 7.—Height-weight relationship and volume distribution in relation to height for 15 Arizona cottontop plants.



igure 8.—Percent use by weight of Arizona cottontop for ungrazed heights to 120 cm and stubble heights from 0 to 35 cm. To use, lay straight edge between ungrazed height and stubble height and read percent use on diagonal scale in center.

igh-summer, low-winter type, as in Texas, Okla-oma, and eastern New Mexico. Because cottontop is warm season grass, adequate summer rainfall would eem necessary for vigorous stands.

The specific influence of precipitation on produc-ion of perennial grasses, including Arizona cotton-op, was investigated for one precipitation regime on he Santa Rita Experimental Range (Cable 1975, Cable and Martin 1975). Over a 10-year period erennial grass production was most highly correlated vith rainfall for August of the current summer, and ext most highly with that for the current June-August eriod. However, rainfall for the June-September eriod of the previous summer also strongly affected rass production of the current summer—not directly, ut as an interaction: the product of current multiplied y previous summer's rainfall. Thus, the effectiveness f a given amount of current-summer rainfall in pro-ucing forage is strongly affected by the amount of ainfall received the previous summer. Changes in the roduct of previous June-September rainfall multi-lied by current August rainfall accounted for from 64 to 90% of the year-to-year changes in perennial grass production.

The influence of many other precipitation attributes on grass production was also investigated, including various expressions of winter precipitation (alone and in combination with summer rainfall) as well as expressions involving size and spacing of storms. None of these variables was as closely correlated with production as the interaction rainfall term alone.

Response to Light

Arizona cottontop and several other semidesert grasses grow better in full sunlight than they do under artificial shade (Tiedemann et al. 1971). Artificial shade treatments which reduce full sunlight by 20% increments show that each successive 20% reduction in light, from 100 to 20% of full sunlight reduces herbage yield of cottontop by about 20% of the full sunlight yield. Yields of black grama are reduced more than those of cottontop; yields of bush muhly (*Muhlenbergia porteri*) and plains bristlegrass (*Setaria macrostachya*) less. The reductions in herbage yield are accompanied by corresponding reductions in root weight, but levels of total available carbohydrates are not affected. Length of leaf blades of cottontop increase about one-third in shade, and numbers of inflorescenses decrease. In a previous study, however, Tiedemann (1970) found production of cottontop and two other species was higher for plants growing under mesquite trees than in the open. Thus, while shade by itself reduces herbage production of cottontop, apparently the growth stimulating effect of higher nutrient levels in the soil under the trees than in the open, more than makes up for the restrictive influence of shade on production.

Response to Soil

Soil texture.—Arizona cottontop grows on a wide variety of soils, from clay loam to sandy loam and loose gravelly soils. It is also found on limestone ledges and porphyritic hills. However, it grows better on some soils than others. On the Santa Rita Experimental Range cottontop is abundant and very productive on Whitehouse and Comora soils, slightly favoring the Comora. It is much less abundant on Coronado soils (Cable and Martin 1975). Whitehouse is characterized by clayey subsoils and well developed horizons; Comora, by sands or sandy loams in the subsoil and weak profile development. Coronado is a shallow, stony, and cobbly soil of the steeper slopes.

Soil water.—The use of soil water by Arizona cottontop coincides with the two main periods of plant growth; one in the spring, using accumulated winter precipitation, and one in the summer, using current summer rainfall (Cable 1979).

Although summer is the main period of perennial grass growth, soil water is readily used in the spring when available. Above normal water supplies in the spring of 1973 provided 9.6 cm of available water in the upper 1 m of soil for the cottontop plants studied. During the 70-day depletion period from March 22 to May 30, the plants used 76% of the available water. Water was extracted uniformly within the upper 75 cm, 0.11% by volume per day, slightly slower at 100 cm (table 2). Bare soil losses were about half as great, highest at 25 cm and decreasing at deeper depths, especially at 100 cm.

In the summer, evapotranspiration demand is higher than in spring, extraction rates are higher, and soil water is depleted faster. During both spring and summer growth periods, available soil water is reduced to 1-2% by volume throughout the profile by the end of most depletion periods, and to essentially no available water after unusually dry periods.

Thus, cottontop is able to use water rapidly when available. It is also able, when necessary, to exist for relatively long periods with little or no available water. During such periods, which may last for several months during dry spring or summer growing periods, water loss at cottontop plants is essentially the same as water loss from bare soil.

Response to Burning

Cottontop is intermediate among semidesert grasses in its susceptibility to damage from burning (Reynolds and Bohning 1956, Cable 1967). Basal intercept of perennial grasses decreased during the relatively dry growing season immediately following burning, but had essentially recovered by the end of the second growing season. A second fire 3 years after the first did not adversely affect the grass plants because of low fuel accumulation in the interim and a wet growing season following the fire.

Competitive Interactions

An established stand of cottontop competes strongly with velvet mesquite (*Prosopis juliflora* var. *velutina*) seedlings. In a study of 100 velvet mesquite seeds planted per treatment, only 7 seedlings became established in a stand of cottontop, compared with 56 on an adjacent bare area (Glendening and Paulsen 1955). One year after planting, mesquite seedling survival averaged 18% on the cottontop plot and 80% on the bare area. The situation is reversed, however, in mature stands of velvet mesquite. The reduction in cottontop production caused by competition from mesquite is most clearly shown by the large increases in cottontop production that result when an existing stand of mesquite is controlled. On one study area native perennial grass production (mostly cottontop) increased from less than 224 kg/ha in the year that the mesquite were first sprayed with herbicide to over 896 kg/ha (mostly cottontop) in the fall of the second year, after the second spraying (Cable 1971a, 1976). In another study, in which existing stands of mesquite were thinned to four levels (62, 40, 22, and 0 trees/ha), native perennial grass production (mostly cottontop) was five to six times higher by the end of the second growing season (fig. 9) on plots where all mesquite was killed than on plots where no mesquite was killed. Grass production was significantly higher with each successive level of thinning (Parker and Martin 1952). Cottontop production increased much less following mesquite control on areas with initially less dense mesquite and more dense grass cover (Cable and Martin 1975) and on areas with less than 33 cm of annual precipitation (Martin and Cable 1974).

Competition from burroweed (*Haplopappus tenuisectus*) reduces cottontop production comparatively little. Stands of 25,000-30,000 burroweed plants/ha reduced cottontop production by about 25% (Cable 1969). The relatively small impact of burroweed on cottontop was attributed to the relatively few burroweed feeder roots in the upper 15-

Table 2.—Soil water use (percent by volume) by Arizona cottontop between March 22 and May 30, 1973, following good winter recharge on the Santa Rita Experimental Range

At plants				Bare soil			
Depth	Available water	70-day use	Rate per day	Depth	Available water	70-day use	Rate per day
cm	*percent by volume*			*cm*	*percent by volume*		
25	9.20	7.60	0.110	25	9.10	5.30	0.080
50	9.40	7.80	.110	50	9.00	4.10	.060
75	9.70	7.50	.110	75	9.20	3.80	.050
100	10.20	6.40	.090	100	6.70	1.00	.010
Mean	9.63	7.33	.105	Mean	8.50	3.55	.051

Figure 9.—Effect of mesquite removal on perennial grass cover: (A) Undisturbed stand of 340 mesquite per ha, September 1945; (B) Adjacent area where mesquite were eliminated in March 1945, showing striking first season increase in Arizona cottontop, September 1945.

20 cm of soil where grass roots are concentrated, and to the fact that the primary period of growth of burroweed is in the spring. Summer growth of burroweed usually does not begin until cottontop growth is well advanced. In fact, because of its earlier summer growth, cottontop competes with burroweed enough to reduce crown cover increase of burroweed during the summer by about one-half.

Competition between summer annual grasses and cottontop follows a pattern similar to that with burroweed, in that annual grass production is about two-thirds less with cottontop competition than without. Annual grass competition can reduce cottontop production by about one-fourth (Cable 1969).

Among the various associated native perennial grasses, competition does not appear to be a dominant factor; the species coexist on many kinds of sites and in many mixtures. The evidence is compelling, however, that introduction of some exotic grasses can drastically upset the relative stability of the native perennial grass stand in the semidesert. On the Santa Rita on ranges between 1,100 and 1,400 m elevation and receiving 33-43 cm of annual rainfall, Lehmann lovegrass (*Eragrostis lehmanniana*) has almost completely replaced the former native grass stand, including cottontop within 10-12 years after seeding (Cable 1971a, 1976). It will eventually invade and replace adjacent unseeded native stands. None of the native perennial grasses, including cottontop, can compete successfully over the years with Lehmann lovegrass on areas to which it is well adapted.

Response to Insects

Schuster (1967) lists Arizona cottontop as one of 38 native and introduced grasses affected by rhodesgrass scale (*Antonina graminis*). In greenhouse tests Schuster found the yield of glabrous cottontop plants was reduced 88.3% by the scale infestation. The scale killed 85% of the plants during the test. Pilose cottontop plants, on the other hand, decreased only 28.6% in yield, and no plants were killed. No indication of actual field occurrence or damage to cottontop from rhodesgrass scale was given.

Physiological Relationships

Osmotic Relations

Osmotic value is a measure of the total osmotic pressure found in plant cells, including turgor pressure and suction pressure. As such, it reflects the climate, soil, and especially the moisture supply characteristics of the environment.

Love (1934) studied the osmotic value of foliage of several grasses, including Arizona cottontop, at three locations on the Santa Rita Experimental Range from June until December 1933. He found osmotic values varied inversely with variation in precipitation, although diurnal fluctuations in osmotic values were influenced also by air and soil temperatures, wet-bulb depression, and solar radiation. The highest and lowest osmotic values recorded for Arizona cottontop were 42.97 and 11.60 atmospheres. Consistently lower values were recorded at the location where greater amounts of water were available. Grasses at this location also produced a greater amount of growth than those at either of the other stations.

Love also found total weekly precipitation of at least 5 cm was required to initiate growth of perennial grasses (including cottontop). From measurements of soil moisture and wilting point, he concluded grasses apparently "do well with the total soil moisture below the calculated wilting coefficient."

Water Requirement

McGinnies and Arnold (1939) determined the quantity of water required for the production of a unit weight of dry matter, exclusive of roots, for a variety of grasses, forbs, and shrubs typical of the semidesert grassland on the Santa Rita Experimental Range. They found two periods of growth during the year. The main period of growth was in the summer, from late June into September. With optimum conditions plants often developed to full bloom stage in from 10 to 30 days. The second period of growth, occurring sometime between November and April, was very indifinite as to beginning and ending, depending on the occurrence of favorable combinations of soil moisture and temperature.

Arizona cottontop was found to have a generally moderate water requirement, with a tendency for high production in late spring and during summer months of moderate temperatures and moderate to low humidity. It made poor growth during excessively hot dry weather and only moderate growth under hot humid conditions. The lowest water requirement was recorded in July and early August of 1936, a relatively moist period with average summer temperatures.

A more recent study of soil water use by several semidesert grasses and shrubs showed that cottontop extracted water from a 100-cm profile at an average rate of 0.105% by volume/day during a 70-day depletion period following good winter recharge, and 0.099% by volume/day during a wet summer. Rates of loss were similar at 25-, 50-, and 75-cm depths during the spring depletion period (table 2). At 100-cm extraction was slower during the early part of the period and more rapid during the latter part (Cable 1979). These semidesert species are able to extract water rapidly from soil when it is available, and to subsist for prolonged periods in soil with essentially no available water.

Economic Considerations

Abundance and Yield

Abundance.—Generally, abundance of Arizona cottontop has been referred to in qualitative terms, as being "common," but seldom as "abundant" (Anderson et al. 1953; Wooton and Standley 1911). Griffiths et al. (1915) stated, however, "In many situations, especially in the moister places in the desert foothills of Arizona and the plains of Texas, it grows almost pure over large areas and makes a striking appearance."

Early descriptions of the vegetation of the Santa Rita Experimental Range by Griffiths (1901), Wooton (1916), and Hensel[2] in 1917 either made no mention of Arizona cottontop or indicated it was a minor species. Griffiths (1904) does mention the presence of cottontop in the open foothills at the upper edge of the Experimental Range "growing under the protection of bushes along the arroyos." He also states cottontop "sometimes covers considerable areas of open land" and includes a photograph taken in the fall of 1902 south of the Range "in McCleary's pasture" (the south-central part of present pasture 8), showing a good stand of cottontop headed out. In the legend to this photo accompanying his annual report of 1902, Griffiths[3] refers to this stand as "one of the best growths of cottontop I have ever seen."

In ensuing years the relative importance of cottontop on most of the Santa Rita increased greatly, apparently in direct response to gradually decreasing grazing pressure. Between 1915 and 1935, cottontop made up only 2% of the composition on depleted ranges, compared to from 19 to 26% on areas grazed conservatively or protected from grazing (Canfield 1948). In 1941 McGinnies et al.[4] ranked Arizona cottontop eighth of 14 perennial grasses in relative abundance on the Santa Rita. Reynolds in 1959 showed cottontop as third in abundance on ranges between 1,200 and 1,500 m elevation, tied for sixth place on ranges between 1,000 and 1,200 m, and tied for second place on ranges below 1,000 m.

During the 10 years from 1957 to 1966, on ranges between 900 and 1,200 m on the Experimental Range, cottontop was the dominant perennial grass, accounting for 36% of the total perennial grass production, over twice that of the next species (Martin and Cable 1974). During the same period, on ranges between 1,200 and 1,500 m, cottontop was the second most productive species, below slender grama (*Bouteloua filiformis*) (Cable and Martin 1975).

Apparently, the heavy grazing and drought to which southern Arizona was subjected immediately before and after the turn of the century (Griffiths 1901, 1910) had nearly eliminated Arizona cottontop as a component of the grass cover, except on more favored sites or protected spots. More conservative management in recent years has permitted cottontop to regain its former dominance on the Santa Rita. A similar recovery of cottontop has been noted on other areas. Near Oracle, Ariz., on ranges 1,100 m elevation and 38-40 cm precipitation, cottontop was nearly absent in 1941 (Schmutz and Smith 1976). By 1969 cottontop was present in small amounts on a grazed range and was the most abundant grass on a protected range. Schmutz and Smith concluded cottontop "is one of the most important climax grasses on this site."

Yield.—Arizona cottontop has produced over 672 kg/ha on favorable sites in wet years on the Santa Rita. Long-time averages over larger areas are, of course, much lower. On six large pastures covering 11,000 ha between 900 and 1,200 m elevation, receiving from 25 to 36 cm annual precipitation, cottontop was the most productive species, averaging 21.3 kg/ha during a 10-year period, and constituting 36% of the total perennial grass production. Production varied from year to year, with changes in rainfall, but the relative variation was low: a coefficient of variation of 40% compared to a range of from 35 to 86% for associated species. On four small pastures totaling about 1,300 ha, at 1,200-1,500 m elevation, and with 38-43 cm annual precipitation, cottontop production averaged 70 kg/ha during the same 10-year period. This constituted 14% of the total perennial grass production, and was next to the highest production by a single species. Productivity of cottontop in terms of weight of herbage per acre per 0.01% of basal intercept, was intermediate between the smaller bunchgrasses and the tall larger bunchgrasses (table 3) (Cable and Martin 1975).

[2]*Hensel, R. L. 1917. Natural revegetation of the Santa Rita Experimental Range. (Typewritten report on file at USDA For. Serv., Rocky Mt. For. and Range Exp. Stn., Tempe, Ariz.*

[3]*Griffiths, David. 1902. A report upon range work in Arizona in 1902. (Typewritten report, plus supplement containing 78 figures, on file at USDA For. Serv., Rocky Mt. For. and Range Exp. Stn., Tempe, Ariz., 76 p)*

[4]*McGinnies, W. G., K. W. Parker, and G. E. Glendening. 1941. Southwestern range ecology. U.S. Dep. Agric., For. Serv., Southwest. For. and Range Exp. Stn. (mimeo), 201 p.*

Nutritive Quality and Palatability

The protein content of young and early-mature cottontop herbage averaged 8-10%, nearly twice that of mature material. The protein content of young cottontop material reported by Fudge and Fraps (1945) was next to the lowest of 23 species of grasses tested. Phosphoric acid and lime content of cottontop was also near the bottom of the list. Fudge and Fraps rated the average protein and phosphorus content of young cottontop as "fair" and calcium content as "good."

Crude protein content of cottontop foliage clipped at approximately monthly intervals on the Santa Rita varied between 3.6 and 5.7% from November to June, but rose to 12.8% in the middle of the summer growing season (Cable and Shumway 1966).

A comparison between nitrogen content of the soils and protein content of the grasses showed very little relation between the two variables. Protein in 54 samples from soils containing less than 0.061% nitrogen was as high as in those produced on soils which contained more than 0.18% nitrogen. In another study Fudge and Fraps found protein in the grasses was significantly related to total nitrogen in the soil in 15 out of 44 comparisons. Content of phosphorus and lime in the grasses tended to vary with phosphoric acid and active lime content of the soils.

The available published analyses of cottontop herbage are summarized in table 4.

Moisture content of herbage of Arizona cottontop collected on the Santa Rita at monthly intervals between September 5, 1956, and June 3, 1957, varied from a high of 45.2% on September 5 to a low of 15.6% on May 1, with a 10-month average of 23.7% (Cable and Bohning 1959). Moisture content followed the rainfall pattern: highest in summer, with a smaller high in winter, separated by periods of low moisture content (lowest in early summer).

Table 3.—Average production and average productivity per unit of basal intercept for the 17 most common species on 4 study pastures on the Santa Rita Experimental Range, 1957-66

Species	Average production	Productivity index[1]
	kg/ha[3]	
Curlymesquite (*Hilaria belangeri*)	6.4	1.04
Sprucetop grama (*Bouteloua chondrosioides*)	24.6	1.23
Hairy grama (*B. hirsuta*)	12.1	1.87
Santa Rita threeawn (*Aristida glabrata*)	9.5	1.86
Slender grama[2] (*Bouteloua filiformis*)	96.0	2.15
Sideoats grama[2] (*B. curtipendula*)	66.0	2.52
Black grama[2] (*B. eriopoda*)	58.7	2.93
Rothrock grama (*B. rothrockii*)	8.1	3.30
Tall threeawns[2] (*Aristida hamulosa*) (*A. ternipes*)	62.4	3.65
Arizona cottontop[2] (*Trichachne californica*)	70.6	4.17
Plains lovegrass (*Eragrostis intermedia*)	10.4	4.57
Lehmann lovegrass (*E. lehmanniana*)	3.8	4.98
Bush muhly (*Muhlenbergia porteri*)	4.5	5.90
Green sprangletop (*Leptochloa dubia*)	23.7	7.78
Tanglehead (*Heteropogon contortus*)	18.0	9.23
Plains bristlegrass (*Setaria macrostachya*)	8.1	9.26
Cane bluestem (*Andropogon barbinodis*)	10.0	9.63

[1]Weight of herbage per hectare per 0.01 percent of basal intercept.
[2]Major species.
[3]Kg/ha = 1.12 (lb/acre).

Table 4.—Chemical composition of Arizona cottontop herbage in percent on a water-free basis

Stage of growth	Authority	Water	Ash	Crude protein	Crude fiber	N-free extract	Ether extract
Young	Fudge and Fraps (1945)	7.49	10.59	8.22	33.39	38.56	1.75
Early mature	Griffiths et al. (1915)	7.85	11.96	9.97	29.97	45.72	2.38
Green mature	Wilson (1931)	3.79	7.98	4.92	32.22	49.43	1.85
Dry	Catlin (1925)	2.81	8.46	4.62	32.62	50.11	1.36
2-3 yrs old	Catlin (1925)	2.47	8.67	4.00	34.33	50.58	1.11

Palatability.—Arizona cottontop has been rated by ·esearchers as moderately high in palatability. For ·xample, McGinnies et al.,[4] based on the work of ·ister (1939), ranked cottontop sixth in preference out ›f 14 perennial grasses for yearlong grazing by cattle, ·arying by seasons from second for July-September ;razing to thirteenth for December-January grazing. ·rnold (1942) rated cottontop eleventh out of 19 ;rasses for cattle. Culley (1937), however, reported hat cottontop was definitely selected by cattle hrough most of the year—more consistently than any ›ther of the 10 most important perennial grasses on he Santa Rita. Canfield (1942) concluded that Arizona cottontop is a preferred grass in spite of its elatively coarse stems."

More recent data on palatability support the high ›reference rating indicated by Culley and Canfield. In 10-year study (Cable and Martin 1975), average use ›f cottontop was 57%, second highest of all species. ·he average for all species was 41%. Although ottontop contributed only 13.6% of the total erennial grass production during the 10-year period, early one-fourth (22.4%) of the total perennial grass ·se consisted of cottontop. In the same study, on hose transects on which use of all species averaged 0%, use of cottontop averaged 36%, a further ndication cattle strongly prefer cottontop.

Response to Grazing

Dormant-season grazing.—Degree of use of 200 ndividually tagged plants was determined annually on ·e Santa Rita for 15 years from the height-weight ·elationship, using the ungrazed height at the end of ·e summer growing season, and the grazed stubble eight the following June. All grazing by domestic vestock occurred during the winter-spring season. ·ntensity of use varied widely among plants and mong years. For example, for the 172 plants that ved 2 or more years after tagging, mean use varied mong plants from 16 to 71%. One plant was grazed ·om 68 to 72% by weight for seven successive winter ormant seasons and was alive and healthy 16 years fter tagging. These widely varying intensities of use uring the 15-year period had no apparent effect on (1) ·e number of years the plants lived after tagging, (2) ·hanges in basal area of individual plants, or (3) ·hanges in ungrazed plant height from year to year. ·ormant season grazing of Arizona cottontop, at high s well as low intensities, appears to have no etrimental influence on vigor or longevity of ·dividual plants.

Growing-season grazing.—Consistent heavy graz-·g during the summer growing season adversely ·fects vigor and productivity of cottontop. It was reviously noted that continued heavy grazing reduces Arizona cottontop to a minor component of the perennial grass stand, even where cottontop is well adapted (Canfield 1948). Canfield also reported that an increase in abundance of cottontop is the most conspicuous, if not the first, sign of range recovery under either conservative grazing or total protection. Under good management, cottontop made up 19-31% of the total perennial grass stand. Overgrazing caused a tendency toward dominance of short-lived and short-statured perennial grasses.

Arizona cottontop is apparently as able to maintain itself or increase on conservatively grazed year-long ranges as it does on summer-deferred ranges. Reynolds (1959) reports an increase in cottontop from 0 to 6.1% of total stand between 1937 and 1948 on a summer-deferred range on the Santa Rita Experimental Range, compared to an increase from 3.1 to 15.5% on a yearlong-range grazed conservatively.

More recent data indicate the degree of recovery following a dry year is strongly linked to the average level of grazing use. Thus, on transects where utilization during a 10-year period was heavy (52-59%), increases in perennial grass production following a dry year were greatly suppressed compared to increases where plants were lightly used (21-28%) (Cable and Martin 1975). In terms of absolute production (pound per acre), however, cottontop showed larger increases where use was heavy. This suggests recovery of cottontop was not affected adversely by heavy use. There were wide differences in the levels of herbage production among the four groups of transects, however. The more heavily used groups were also the higher producing groups. When the production data are more properly expressed as percent of production in the initial year, the cottontop data are consistent with those for the other species: largest percentage increases in production following a dry year occurred on transects where plants were used most lightly, and smallest percentage increases on transects used most heavily (fig. 10). The data also suggest that the heavily grazed plants were not able to respond fully to higher rainfall for at least 2 years following a very dry year.

Restrictions in root development caused by heavy grazing are probably involved in the variable rates of recovery following a dry year on plants grazed at different intensities. In an examination of root branching on grazed versus protected cottontop plants, Blydenstein (1966) found grazed plants had 32 root branches on the first 15.2 cm of length, compared to 80 branches on ungrazed plant roots.

Effect of removing the growing point.—A recent study in which growing points of individual culms were removed at different stages of culm development helps to explain the response of cottontop to grazing.

Thirty-two individual culms on field grown plants were selected in July, at the start of the summer rainy season, in each of the following stages of development:

1. Vegetative growing point
2. Early reproductive - panicle less than 5 mm long
3. Early boot - flag leaf blade just fully exposed
4. Late boot - panicle fully developed, ready to exsert
5. Panicle exserted - no axillary shoots visible
6. Panicle exserted - axillary shoot tips showing

The growing points were removed from half the culms in each stage. Lengths of axillary shoots developing on each culm were measured weekly for the following 11 weeks. Numbers and growth rates of axillary shoots increased significantly at all stages of development on culms with growing points removed. Twice as many new axillary shoots appeared on treated culms as on intact culms during the first 4 weeks after treatment (fig. 11). Total length of axillary shoots on treated culms averaged about three times the length on intact culms during the same period, varying from an additional 72 mm/culm for culms treated in the early boot stage to 113 mm/culm for culms treated in the early reproductive stage. By the end of the summer growing season numbers of axillary shoots on intact culms had caught up with those on treated culms, about 1.5 shoots/culm for both, but total

Figure 10.—Arizona cottontop production, as percent of production in 1957, on transects used at different levels for the period 1957-66. Mean 10-year use of cottontop for groups 1, 2, 3, and 4 were 48, 52, 65, and 71 percent, respectively.

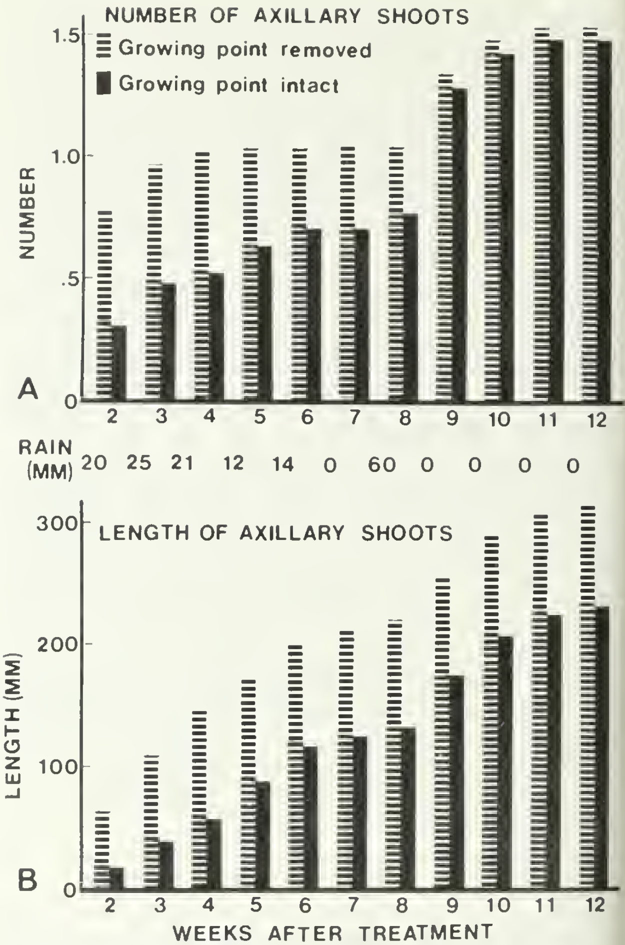


Figure 11.—Number (A) and total length (B) of axillary shoots per culm on successive weeks from July 29 to October 5, for culms with growing points removed and for intact culms.

length of axillary shoots on treated culms averaged 314 mm, well above the 232 mm for intact culms.

The inherently weak apical dominance of cottontop permits axillary shoot development even on intact culms, but the growth of axillary shoots is stimulated if the growing points are removed. Hence, cottontop can tolerate relatively heavy grazing use because accelerated growth of axillary shoots after grazing soon offsets the initial loss of leaf surface.

Response to Fertilization

Little information is available on the effect of fertilization on cottontop. Fertilization of semidesert grasslands generally has shown little benefit unless rainfall is above normal in the following summer growing season. In these wetter years, fertilization increases production, protein content, and palatability, and extends the green feed period (Stroehlein et al.

)68, Herbel 1963, Honnas et al. 1959, Holt and 'ilson 1961). In one study on the Santa Rita, plots rtilized with 224 or 448 kg/ha of ammonium iosphate produced Arizona cottontop plants 50% ller than on unfertilized plots in a year of above-'erage summer rainfall. With no fertilizer, plants 'eraged 7.8 grams per plant; with 224 kg/ha of rtilizer, plants averaged 23.6 grams per plant. Cattle 'eferred plants fertilized at 224 and 448 kg/ha over ose fertilized at 112 kg/ha or not fertilized. There as no difference in the time of seed set, but the seed ipeared to be heavier at the higher fertilizer rates 'ixier 1959).

eseeding

Arizona cottontop has been recommended for seeding by Cassady and Glendening (1940) on arren or almost barren sheet-eroded gravelly ridges, iaracterized by fairly heavy clay soils" and for leteriorated grassland areas receiving 35 cm or more rainfall annually." They recommend seeding on intour furrows and covering by raking. They also port cottontop can be successfully transplanted in ily, August, February, and March.

Earlier work by Wilson (1931) in New Mexico dicated 6-7 kg/ha of seed planted not deeper than 1.2 n should give a good stand if the area can be kept latively weed free. He recommended drilling in the tter part of June, and reported Arizona conttontop ve the best germination of all native forage plants sted. Wilson also noted cottontop seedlings made ower growth than most other plants, especially the inuals. Quicker growing plants soon overtopped and aded the cottontop seedlings to their detriment.

Glendening (1942), in a study of the effect on rmination and emergence of different methods of vering the seed, concluded cultivation was not sential where the soil could be covered with some rm of litter. Best germination and emergence was otained where the ground was covered with open-esh gauze. About two-thirds as many seedlings were otained where cut burroweed branches were attered over the ground surface or where the ground as raked and covered with open-mesh gauze. overing the soil surface consistently increased soil oisture content and lowered soil temperature.

Anderson et al. (1953) consider Arizona cottontop one of the more easily established native grasses, if a iod seedbed is prepared. It was the most persistent ecies tested on a droughty site with loose gravelly il near Nogales, spreading fairly rapidly by ilunteer seeding. Anderson et al. reported the fluffy ed can be planted with cotton box hoppers on the eding equipment. The recommended seeding rate is 6 kg/ha of hammermilled seed in the hulls.

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Metric-English Conversion Factors

1 mm	= 0.039 inches
1 cm	= 0.394 inches
1 m	= 39.37 inches
1 ha	= 2.47 acres
1 ka/ha	= 0.89 pounds/acre

Cable, Dwight R. 1979. Ecology of Arizona cottontop. USDA For. Serv. Res. Pap. RM-209, 21 p. Rocky Mt. For. and Range Exp. Stn., For. Serv., U.S. Dep. Agric., Fort Collins, Colo.

This paper summarizes what is now known about the ecology and management of Arizona cottontop, *Trichachne californica*, a palatable, drought hardy, perennial grass that thrives under moderate grazing on semidesert ranges of the Southwest. Perennial culms that produce axillary shoots, favorable response to grazing, long life, and ability to grow both on warm- and cool-season moisture are valuable attributes of this species.

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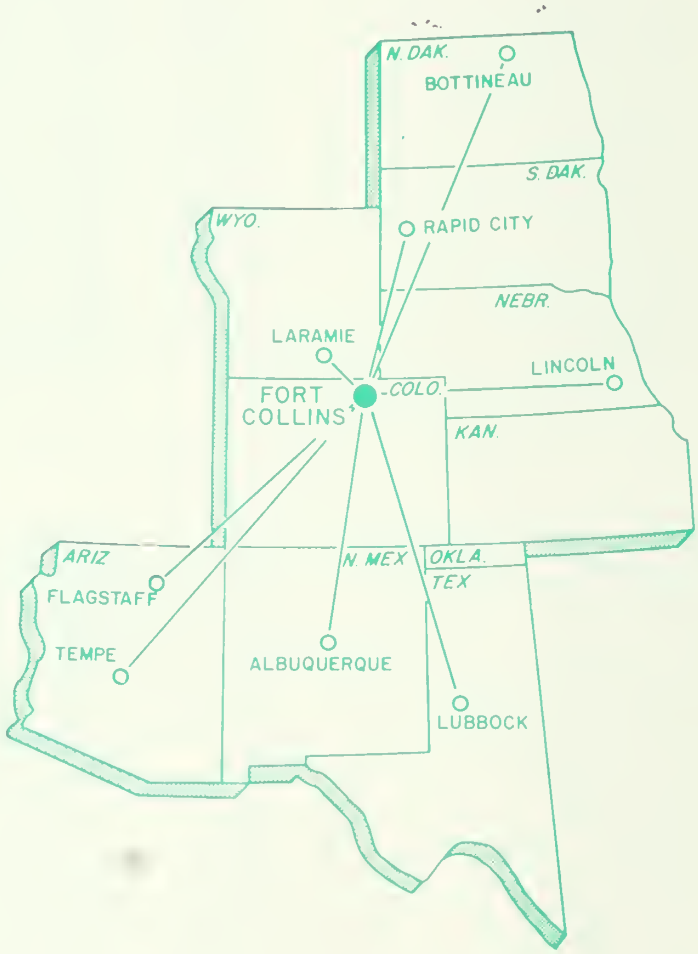
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Germination Requirements of 19 Species of Arid Land Plants

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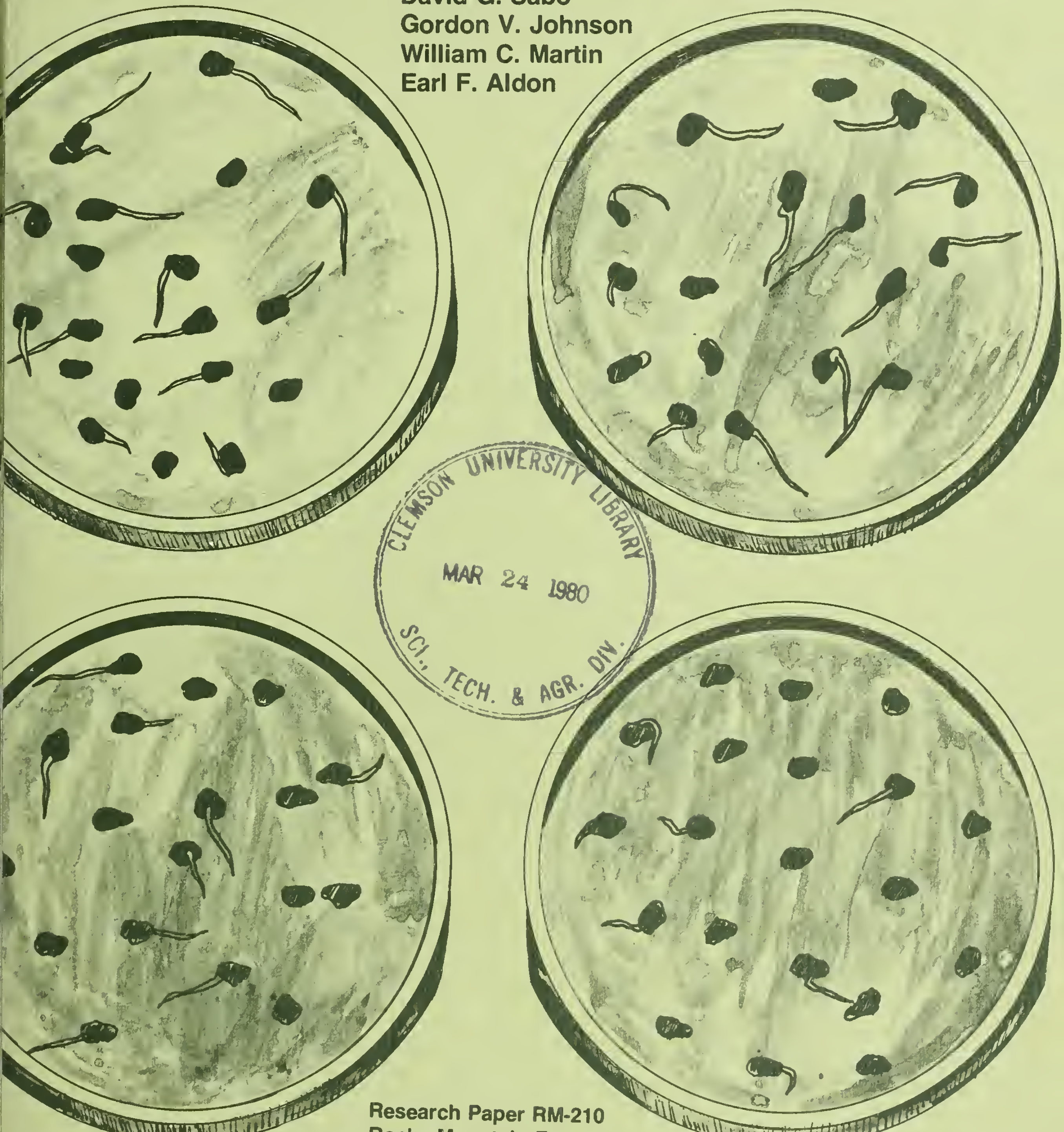

Research Paper RM-210
Rocky Mountain Forest
and Range Experiment Station
Forest Service
U.S. Department of Agriculture

Abstract

A laboratory experiment revealed (1) the optimum germination temperature(s) by means of a thermal gradient plate; (2) effects of levels of moisture stress at the optimum germination temperature, and (3) reaction to the presence or absence of light in ten species of shrubs and nine species of grasses tested for indications of their suitability for strip mine reclamation.

Keywords: Strip mine reclamation, grass germination, shrub germination.

SURFACE ENVIRONMENT & MINING

SEAM

USDA FOREST SERVICE PROGRAM

esearch Paper RM-210 October 1979

Germination Requirements of 19 Species of Arid Land Plants[1]

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Gordon V. Johnson, Associate Professor
William C. Martin, Professor
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and

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[1]The research reported here is a contribution to the SEAM program. SEAM, an acronym for Surface Environment and Mining, is a USDA Forest Service program to research, develop, and apply technology that will help maintain a quality environment and other surface values while helping meet the Nation's mineral requirements.

[2]Research reported here was conducted at the Station's Research Work Unit at Albuquerque, N. Mex.; central headquarters maintained at Fort Collins, in cooperation with Colorado State Unviersity.

Contents

Germination Requirements of 19 Species of Arid Land Plants

David G. Sabo, Gordon V. Johnson, William C. Martin, and Earl F. Aldon

Management Implications

Information on the germination requirements of these species can be helpful to seed technologists as well as to land managers. Those faced with revegetating disturbed areas of all kinds, for example, road cuts, severely depleted ranges, or mine spoil areas, can use these data for proper species selection, time of planting, conditions required for successful germination, and as a guide to seed viability standards.

Introduction

Areas of the Southwest with the potential for strip mining, due to the extreme climatic conditions, are poised in a delicate ecological balance. Success in reclaiming devastated land depends on knowledge of many parameters, including conditions for optimum seed germination (Aldon and Springfield 1973, Aldon et al. 1973).

The objectives of this study were to determine: (1) optimum temperatures for germination of seed of the various candidate species of grasses and shrubs; (2) the effects of moisture stress applied to seeds at an optimum temperature for germination; and (3) the effects of light, if any, on germination.

Materials and Methods

Collection, Cleaning, and Storage of Seeds

Collection areas were chosen as representative of the natural habitats in which each species occurs in New Mexico to minimize ecotypical variation in germination (table 1). Seeds were collected by hand from healthy, reproducing populations. After allowing ample time for the material to dry, seeds were threshed and separated from chaff in a seed scarifier with the scarification surface removed. Seed was then cleaned using a seed cleaner.

Seeds were stored at room temperature for most of the species except *Chrysothamnus nauseosus*, which was stored at 2° C in airtight containers to retain viability.

Selections of seed pretreatments to eliminate dormancy were based on the literature, the anatomical features of the seed being tested, and a knowledge of the ecology and habitat of the species in general.

Thermal Gradient Plate for Temperature Tests

The thermal gradient plate (TGP) (Scientific Systems, Baton Rouge, La.)[3], which closely approximates the plans given by Larsen (1971), is essentially a 2-inch-thick aluminum plate with a gradient of temperatures maintained across the surface (fig. 1). Located along each side of the aluminum plate are separate watertight canals. These canals are attached to refrigeration or heating pumps which

[3]*The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others which may be suitable.*

maintain a constant supply of water to each canal. At any one time, only two canals on opposite sides of the aluminum plate are in use. One canal has a flow of refrigerated water, and the opposite canal is maintained with the heated flow. This creates the gradient of temperatures across the surface of the plate.

An alternation of temperatures is provided by activating the other two canals through a series of automatically activated valves. The valves are attached to a timer unit so that one temperature gradient is maintained for 8 hours and the other for 16 hours out of every 24-hour day, roughly approximating a variety of naturally occurring daily temperature patterns.

Table 1.—Sources of seed and dates of collection of each species tested

Grasses

Western wheatgrass, *Agropyron smithii* — USDA Forest Service source, no location or date of collection given

Little bluestem, *Andropogon scoparius* — USDA Forest Service source, no location or date of collection given

Sideoats grama, *Bouteloua curtipendula* — 15 miles east of Gallup, N. Mex., along U.S. Highway 44 — August 1975

Blue grama, *Bouteloua gracilis* — USDA Forest Service, Lovington, Ark., Valley Source Lot No. 2172 — no date given

Desert saltgrass, *Distichlis stricta* — north of San Ysidro, N. Mex., along Highway 4 — August 1975 and August 1976

Galleta, *Hilaria jamesii* — Commercial dealer, Los Lunas, N. Mex. — collected 1972

Spike muhly, *Muhlenbergia wrightii* — USDA Forest Service source, no location or collection data given

Spike dropseed, *Sporobolus contractus* — south of San Ysidro, N. Mex., along Highway 44 — June 1975

Sand dropseed, *Sporobolus cryptandrus* — USDA Forest Service source, no location or date of collection given

Shrubs

Fringed sagebrush, *Artemisia frigida* — 7 miles south of Interstate 40 on Highway 14 — November 1975

Big sagebrush, *Artemisia tridentata* — 25 miles west of San Luis, N. Mex.— November 1975

Shadscale saltbush, *Atriplex confertifolia* — 25 miles west of San Luis, N. Mex. — November 1975

True mountainmahogany, *Cercocarpus montanus* — foothills north of Santa Fe, N. Mex., elevation 7,300 ft — 1974

Rubber rabbitbrush, *Chrysothamnus nauseosus* ssp. *consimilis*—north of San Ysidro, N. Mex., along Highway 4— November 1975

Bigelow rubber rabbitbrush, *Chrysothamnus nauseosus* ssp. *bigelovii* — north of San Ysidro, N. Mex., along Highway 4 — November 1976

Cliffrose, *Cowania stansburiana* — 12 miles north of Thoreau, N. Mex., along Highway 56 — November 1975 and November 1976

Apacheplume, *Fallugia paradoxa* — 60 miles west of Albuquerque, N. Mex., along Interstate 40 — June 1975

Rough menodora, *Menodora scabra*—USDA Forest Service source — by the P. and M. Mine, McKinley County, N. Mex. — 1975

Greasewood, *Sarcobatus vermiculatus* — USDA Forest Service source — by the P. and M. Mine, McKinley County, N. Mex. — November 8, 1973

Globemallow, *Sphaeralcea incana* — 25 miles west of Albuquerque, N. Mex., along Highway 44 — August 1975

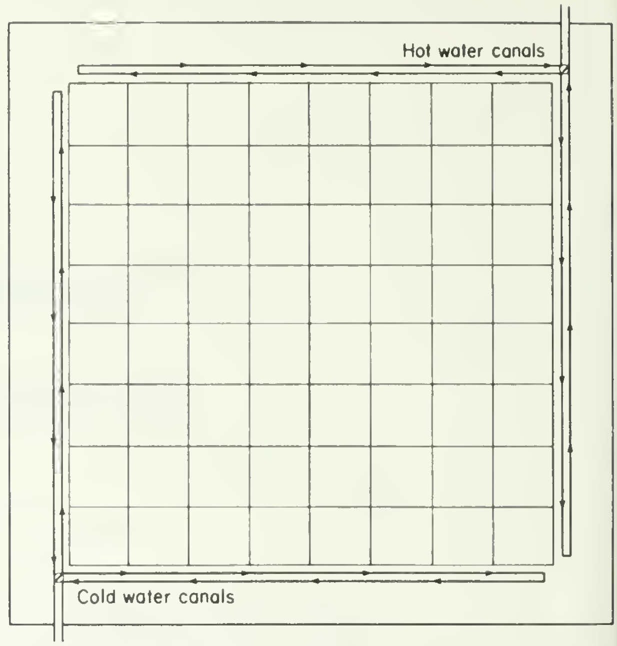

Figure 1.—Diagram of the surface of the thermal gradient plate, showing locations of watertight canals for maintenance of temperatures. In each 24-hour cycle, the hot canal at top and cold canal at bottom are activated for 8 hours. Then the hot canal at right and the cold canal at the left are activated for 16 hours.

The aluminum plate is mounted on a tilting mechanism. The plate is tilted so the edge with the heated water flow is raised above the edge with the cool flow. The angle of the plate can be adjusted to allow for control of the temperature gradient between rows of petri dishes situated on the surface of the plate.

Petri dishes used on the plate were of the 95-mm-diameter, commercially available, glass Felsen type, with an extra heavy base to allow for a more uniform spreading of the temperature across the surface of the dish.

The plate is furnished with a heavy plexiglass cover to decrease evaporation from the open dishes. Additionally, each of the 64 dishes was covered with a piece of 6-mil clear polyethylene film to further prevent desiccation.

Substrate for germination was two thicknesses of Whatman No. 3 filter paper, cut to fit the petri dishes. Redistilled water, the only moistening agent used, was applied to the point of glistening on the substrate. Water was added as needed during the germination tests. Light was held constant 24 hours a day.

Temperatures for each of the 64 positions were read with a Yellow Springs tele-thermometer[3] with an attached thermistor probe. The probe was placed against the surface of the moist filter paper-substrate in each petri dish; these temperatures are indicated for the TGP throughout this publication.

Additionally, to detect unforeseen fluctuations occurring during a test, an automatic temperature recorder monitored 10 positions along the water-tight canals.

Moisture Stress Response Tests

Moisture stress tests were conducted in a diurnal growth chamber. Temperature cycles used for the individual tests were the cycles previously determined to be beneficial for germination of the species.

All tests were conducted in covered petri dishes. One petri dish was used for each replicate. All petri dishes for each test were placed in sealed plastic boxes to further prevent desiccation. A moist blotter was enclosed in the box to retard evaporation. No significant water loss occurred from petri dishes.

Polyethylene glycol 4000 (PEG) in redistilled water was used as the osmotic agent for moisture stress. Dilutions to approximate 0, −2, −4, −7, −10, −13, and −16 bars were used, based on Mexal and Reid (1973). Water potentials of PEG solutions were verified using a thermocouple psychrometer. Substrate for germination was two thicknesses of Whatman No. 3 filter paper of the 95-mm-diameter size moistened with 7 ml of the solutions.

Use of the osmotic agent PEG-4000 requires one caution. A fresh solution of PEG should always be prepared prior to testing seeds to avoid fungal problems.

Light Response Tests

Light response tests were conducted on each species by placing the seeds to be tested in light-tight, black plastic boxes. Fluorescent light was admitted to half the boxes for approximately 8 hours per day. The temperature cycle for germination tests without light was 8 hours at 25° C and 16 hours at 14° C.

If no difference between the two tests was noted, it was inferred that light did not play a substantial role in germination. If a difference was noted, the test was rerun with a black plastic hood placed over the TGP to exclude all light. The effects and interactions of temperature and light could then be determined.

Seed Numbers and Germination Count

The number of seeds used and the duration varied with each type of test. Tests on the TGP used approximately 3,200 seeds, with 50 seeds at each of 64 positions; however, 25 seeds per position were used in some tests (table 2). The percentage of filled seed was considered for species on which it was practical to make a determination. Sources which evidenced the highest rate of fill for each species were utilized. Moisture stress and light tests utilized 100 seeds per treatment, with at least two replicates for each treatment. All data reported are for tests conducted during 1975 and 1976.

Table 2.—Number of shrub and grass seeds per position, the total number used, and the duration for each test on the TGP

Species	Seed/ position	Total seeds	Duration
			(days)
A. Shrubs			
Artemisia frigida	50	3,200	30
Artemisia tridentata	50	3,200	30
Atriplex confertifolia	25	1,600	36
Cercocarpus montanus	25	1,600	32
Chrysothamnus nauseousus ssp. *biglovii*	25	1,600	21
Chrysothamnus nauseosus ssp. *consimilis*	25	1,600	15
Cowania stansburiana	50	3,200	36
Fallugia paradoxa	50	3,200	30
Menodora scabra	50	3,200	26
Sarcobatus vermiculitus	50	3,200	26
Spheralcea incana	50	3,200	30
B. Grasses			
Agropyron smithii	50	3,200	24
Andropogon scoparius	50	3,200	31
Bouteloua curtipendula	50	3,200	28
Bouteloua gracilis	50	3,200	21
Distichlis stricta	50	3,200	21
Hilaria jamesii	50	3,200	15
Muhlenbergia wrightii	50	3,200	24
Sporobolous contractus	50	3,200	26
Sporobolous cryptandrus	50	3,200	26

Counts of germinated seed for all tests were conducted daily for the first 2 weeks, and every 4 days thereafter. Germinated and fungal-infected seeds were removed at the time of each count. Seeds were considered to have germinated when either the radical and/or the plumule emerged and the seedling was believed capable of continuing growth.

Tests conducted in the dark were evaluated under a green safe-light, supplied by two thicknesses of green cellophane placed over a fluorescent light.

Presentation of TGP Results

The results of all experiments are presented under the subheading of each species. A figure representing the surface of the thermal gradient plate with the 64 germination positions is given.

The mean day of germination (MD) is calculated as:

$$MD = \frac{\Sigma(\text{no. seeds germ./position X day of germ.})}{\text{Total seeds germ./position}} \quad [1]$$

The percentage of germination in each position is calculated as:

$$\% = \frac{\text{no. seeds germ./position X 100}}{\text{Total seeds/position}} \quad [2]$$

Conclusions as to the optimum temperature range for a species are based on a comparison of percentage germination and the mean day of germination. In most cases the combination of most rapid germination (the least mean day value) with the highest percentage of germination was considered optimum. However, in a few cases, recommendations for germination are made on the additional, somewhat subjective, observation of relative vigor of the germinated seedlings.

Summary

Tables 3 and 4 summarize temperature, moisture, and procedural recommendations for germination of the 19 species of grasses and shrubs. It is important to note that these recommendations are valid for seeds collected in the areas noted in this study. Subsequent testing of seed collected from various locations has indicated a high degree of ecotypic variability in optimum temperatures for most species. Various articles discussed lend support to this observation.

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Table 3.—Recommendations for optimum germination of nine species of grasses

Species	Temperatures or ranges of temperatures (circadian)	Moisture requirement [1,2]	Remarks
		(bars)	
Agropyron smithii	18.5° C (8 hr) and 10° C (16 hr)	-7	Light reported to be necessary
Andropogon scoparius	27° C (8 hr) and 16.5° C (16 hr)	nd	—
Bouteloua curtipendula	23° C constant, 12° C (8 hr) and 31° C (16 hr)	-10	—
Bouteloua gracilis	27° to 37° C (8 hr) and 35° to 37° C (16 hr)	-10	—
Distichlis stricta	40° C (8 hr) and 36° C (16 hr)	-13	Abrasive scarification necessary
Hilaria jamesii	29° C constant	-7	—
Muhlenbergia wrightii	12° to 34.5° C constant or alternating	-4	—
Sporobolus contractus	15.5° to 19° C (8 hr) and 26.5° to 29.5° C (16 hr)	-2	Acid-scarify, light required by some sources
Sporobolus cryptandrus	11° to 27° C (8 hr) and 35° to 37° C (16 hr)	-4	Acid-scarify, light required

[1]Point at which germination percentages are adversely effected.
[2]nd=not determined.

Table 4.—Recommendations for optimum germination of 10 species of shrubs

Species	Temperatures or ranges of temperatures (circadian)	Moisture requirement [1,2]	Remarks
		(bars)	
Artemisia frigida	17° C constant, 13° to 17° C (8 hr) and 23.5° C (16 hr)	-2	—
Artemisia tridentata	18.5° C constant	-7	—
Atriplex confertifolia	12° C constant, 16° C (8 hr) and 12° C (16 hr)	-4	Seedcoat must be removed or fissured
Cercocarpus montanus	23° C (8 hr) and 11.5° to 15.5° C (16 hr)	-2	—
Chrysothamnus nauseosus ssp. *bigelovii*	20.5° C (8 hr) and 30° C (16 hr)	nd	—
Chrysothamnus nauseosus ssp. *consimilis*	13° C (8 hr) and 23° C (16 hr)	-4	Light required
Cowania stansburiana	25° C constant	nd	Stratified for 30 days at 14° C
Fallugia paradoxa	22° C constant	nd	—
Menodora scabra	24° C (8 or 16 hr) and 17° C (16 or 8 hr)	nd	—
Sarcobatus vermiculatus	11° C constant	-16	—
Spheralcea incana	24° C (8 hr) and 17° C to 20.5° C (16 hr)	-4	Abrasive scarification enhances germination

[1]Point at which germination percentages are adversely effected.
[2]nd=not determined.

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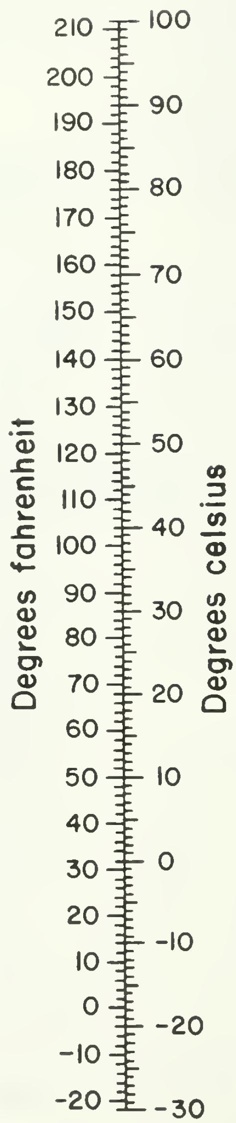

Germination Requirements of Grasses

Western wheatgrass

Agropyron smithii Rydb.

Range.—Moist, usually alkaline soil; Ontario to Alberta and British Columbia; New York; Michigan to Washington, south to Tennessee, Texas, Arizona, and northeastern California; mostly introduced east of Iowa and Kansas.

Past work.—Long considered as one of the most important range grass species in the United States, *A. smithii* is a rhizomatous, long-lived perennial, with a high soil-stabilizing potential. It is adapted to alkaline soils, and its seedlings are vigorous and develop rapidly (Knipe 1973).

Germination studies have been conducted by a number of researchers (Delouche and Bass 1954, Knipe 1973, and Toole 1976). Results have been remarkably similar, indicating that germination is best with alternating temperatures of 15° C and 30° C. Delouche and Bass (1954) and Toole (1976) declared light played no significant role in germination tests. Toole (1976) found incandescent and far-red illumination to actually inhibit germination at certain temperatures, as would be expected if a photoreactive system were present.

Tests have also been conducted for germination ability at varying stresses, with findings indicating a relationship between temperature and moisture stress conditions (Knipe 1973). Moisture stresses greater than −1 bar were shown to be severely limiting in all cases.

Temperatures (°C) during 16-hour part of cycle	10.0	14.0	18.5	21.5	25.5	30.5	36.5	39.5
39.5								
36.5	50% 11.5	24% 27.3	38% 18.0	24% 21.5	4% 25.0			
30.5	74% 7.8	78% 7.4	66% 13.7	40% 16.3	4% 22.0	4% 8.5	1% 11.0	1% 18.0
25.5	66% 12.0	76% 11.5	54% 14.7	14% 31.5	4% 24.5	20% 24.6	20% 12.1	
21.5	74% 9.8	38% 15.1	22% 14.5	24% 18.5	68% 20.2	50% 21.0	42% 16.8	4% 23.5
18.5	56% 10.0	26% 10.5	28% 18.4	54% 18.9	82% 11.2	60% 8.9	24% 10.3	2% 18.0
14.0	34% 12.7	42% 8.5	82% 16.2	80% 15.0	78% 11.3	48% 11.0	10% 13.6	4% 18.0
10.0	18% 14.7	60% 18.2	94% 11.8	68% 13.8	52% 14.4	40% 14.8		

Temperatures (°C) during 8-hour part of cycle

Figure 2.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Agropyron smithii* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Knipe (1973) reported a significant interrelationship between water stress and temperature. Increases in temperature increased the effective moisture stress and decreased germination percentages. Knipe (1973) also reported that moisture stress below −1 bar resulted in a strong downward trend in germination percentage. His study temperatures were slightly higher temperatures than used here, which may account for the high germination percentages at −2 and −4 bars.

Toole (1976) states that good germination of *A. smithii* is achieved without light and at alternating temperatures. She also mentions that germination percentages are depressed at constant temperature without light. Germination of *A. smithii* is poor at constant temperatures whether light is present as in this temperature response study or absent (Knipe 1973, Toole 1976).

Collection and preparation.—Cleaned seed was received from the USDA Forest Service (table 1). Extra plant material had been removed and inflorescences were fractured so that the individual caryopsis could be studied.

Test Results

Temperature response test (fig. 2).—Temperatures above 30.5° C. retarded germination with negligible germination being obtained at the highest temperatures. Alternating temperatures produced more favorable results than constant temperatures. The peak response was 94% germination at 18.5° C (8 hr) and 10° C (16 hr) with a mean germination time of 11.8 days. Good germination was also noted at alternations of 18.5° to 25.5° C (8 hr) and 14° C (16 hr) which corresponds with literature previously published (Knipe 1973, Toole 1976).

Moisture stress response test.—Increase in the moisture stress appears to have little effect on *A. smithii* germination until a potential below −4 bars is reached. Total percentage germination and time to reach 75% of total germination for *A. smithii* at seven levels of water stress with alternating temperatures at 22° C (8 hr) and 14° C (16 hr) ($\underline{N}$ = 2) were as follows:

Water potential (bars)	Total germination (%)	Time to reach 75% of total germination (days)
0	86a[1]	15
−2	83a	15
−4	84a	16
−7	22b	21
−10	7c	—
−13	2c	—
−16	0c	—

[1]Any two means not followed by the same letter are significantly different (0.05 level, Newman Keuls multiple range test, Zar 1974).

Light response test.—No light response was noted.

Range.—Prairies, open woods, dry hills and fields; Quebec and Maine, south to Florida and Arizona.

Past work.—*Andropogon scoparius* is regarded as a good forage grass in the Southwest, but at maturity the culms become woody and the forage value is decreased. Little bluestem is a common constituent of wild hay.

Germination recommendations for *A. scoparius* (AOSA 1970) are alternating temperatures of 20° to 30° C in the presence of light. Potassium nitrate should be used in the substrate solution. Additionally, it is recommended that the seeds be prechilled for 2 weeks at 5° C.

Collection and preparation.—Seed was received from the USDA Forest Service. Seed was threshed in the seed scarifier with the abrasive material removed. All extra plant parts were removed from the seed when it was passed through the commercial seed cleaner.

Temperatures (°C) during 16-hour part of cycle	13.0	16.5	19.5	23.0	27.0	31.5	36.0	40.0
40.0	2% 4.0		2% 3.5	10% 4.5	6% 4.0	14% 4.0	6% 4.0	8% 3.5
36.0	16% 4.3	26% 4.5	26% 3.5	4% 5.0	18% 3.8	10% 4.2	24% 3.0	4%
31.5	18% 4.2	20% 7.1	34% 5.5	22% 3.7	34% 3.9	20% 4.1	18% 3.5	20% 4.8
27.0	34% 6.0	54% 7.2	54% 8.5	24% 6.4	46% 4.1	40% 3.8	24% 3.7	30% 5.4
23.0	54% 7.4	44% 7.0	34% 9.0	34% 7.3	40% 4.3	18% 4.3	28% 3.8	14% 6.0
19.5	48% 12.8	52% 11.1	52% 9.4	60% 8.8	40% 10.2	28% 8.1	16% 4.5	6% 5.0
16.5	26% 13.6	34% 13.4	58% 14.4	42% 12.7	74% 8.7	40% 7.3	14% 5.0	6% 5.0
13.0	2% 26.0	14% 23.5	62% 16.7	66% 10.8	14% 9.8	14% 10.0	6% 14.0	5% 7.5

Temperatures (°C) during 8-hour part of cycle

Figure 3.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Andropogon scoparius* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Test Results

Temperature response test (fig. 3).—Germination of seed of *A. scoparius* was optimum (74%) with alternating temperatures of 27° C (8 hr) and 16.5° C (16 hr), but good germination was also obtained at a few nearby positions. Both extremes of heat and cold inhibited germination to some extent. In the cooler ranges of temperatures, times to germinate were lengthened considerably.

Moisture stress response test.—A moisture stress response test is not included for *A. scoparius*. Germination was satisfactory with the control (0 bars), but variability between replicates at other stresses was greater than allowed (AOSA 1970).

Light response test.—Germination of *A. scoparius* seed was not affected by either the presence or absence of light.

Range.—Plains, prairies, and rocky hills, Maine and Ontario to Montana, south to Virginia, Texas, Arizona, and southern California; Mexico to Argentina.

Past work.—One of the foremost range species in the Southwest, *Bouteloua curtipendula* is widely distributed and much used for grazing and hay (Hitchcock 1950). *B. curtipendula* is extremely vigorous, often forming tufts or clumps and producing stout rhizomes (Gould 1951). In the Southwest, *B. curtipendula* is commonly found on rocky open slopes, woodlands, and forest openings, at elevations of 2,500 to 7,000 feet.

A considerable number of seed germination studies have described parameters and conditions which influence *B. curtipendula:* dormancy (Coukos 1944), temperature (Toole 1938, Cole et al. 1974), germination inhibitors (Sumner and Cobb 1962), and relationships of seed weight to germination (Green and Hansen 1969). Procedures for germination recommended by the Association of Official Seed Analysts (1970) include use of alternating temperatures of 15° C and 30° C, 8 hours of light administered daily, and KNO_3 in the germination medium.

Studies by Cole et al. (1974) on various sources and ages of *B curtipendula* seed showed that optimum temperatures for maximum germination for each differed depending upon year of seed production and duration of the specific temperature.

Collection and preparation.—Seed of *B. curtipendula* was collected 15 miles east of Gallup, N. Mex., along U. S. Highway 44 during August 1975. Seed was cleaned of all other plant material by threshing and passing it through the commercial seed cleaner.

Temperatures (°C) during 16-hour part of cycle								
37.0	56% 2.5	28% 2.0	16% 2.0	16% 2.0	12% 2.0	32% 2.0	32% 2.0	20% 2.0
35.0	36% 2.0	40% 2.0	24% 2.6	36% 2.4	44% 2.0	44% 2.5	32% 2.0	40% 2.0
31.0	92% 2.0	60% 3.0	40% 2.0	56% 2.0	52% 2.0	36% 2.0	44% 3.0	32% 2.0
27.0	40% 3.4	48% 2.6	60% 2.6	48% 2.6	32% 2.7	60% 2.5	36% 3.0	52% 2.6
23.0	76% 4.0	36% 4.0	56% 4.1	92% 2.9	56% 3.6	36% 3.3	32% 2.7	56% 2.7
20.0	80% 4.9	68% 4.7	72% 4.7	72% 4.3	60% 4.0	60% 3.6	60% 3.2	60% 2.7
16.0	72% 8.3	44% 6.0	68% 7.0	56% 6.0	84% 5.0	80% 4.0	40% 4.4	90% 4.0
12.0	48% 16.0	40% 15.0	72% 9.2	72% 7.8	48% 7.2	48% 6.0	78% 4.5	40% 4.4
	12.0	16.0	20.0	23.0	27.0	31.0	35.0	37.0

Temperatures (°C) during 8-hour part of cycle

Figure 4.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Bouteloua curtipendula* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Test Results

Temperature response test (fig. 4).—Germination of *B. curtipendula* seed could at best be termed variable. Peak germination responses of 92% were achieved at two TGP positions. The first was a constant temperature of 23° C, and germination time was 2.9 days. The second, alternating temperatures of 12° C (8 hr) and 31° C (16 hr), had a mean germination time of 2.0 days.

Temperatures above 31° C decreased germination, but cooler constant temperatures also limited germination.

Moisture stress response test.—Germination of *B. curtipendula* seeds is not greatly affected by moisture stress levels through −10 bars. Total percentage germination and time to reach 75% germination for *B. curtipendula* at seven levels of moisture stress at a constant temperature of 23° C ($\underline{N}$ = 2) were as follows:

Water potential (bars)	Total germination (%)	Time to reach 75% of total germination (days)
0	100a	2
−2	100a	2
−4	100a	3
−7	96ab	4
−10	88bc	4
−13	80cd	4
−16	70d	5

The greater levels of stress, −13 and −16 bars, hindered germination somewhat but not to the extent of most other species. Percentage germination at stress levels of 0 bars through −13 bars was 80% or higher and at −16 bars had only dropped to 70%.

Light response test.—Neither the presence nor absence of light appeared to have any influence on the germination of seed of *B. curtipendula*.

Range.—Wisconsin to Alberta, south to Missouri, Texas, southern California and Mexico.

Past work.—The most valuable of the grama grasses for soil stabilization and forage, *Bouteloua gracilis* is adapted to varying habitats and occurs naturally on all major soil types within its range. Morphologically somewhat variable in height depending on habitat, *B. gracilis* tends to be taller in Arizona and somewhat tufted, while in the Great Plains region, the plants are lower and more mat forming (Gould 1951). Among the species' chief assets are a high palatability rating, resistance to heavy grazing and extreme drought conditions, and rhizomatous growth (Hitchcock 1950).

Seed experiments have been conducted on ecotypes of *B. gracilis* to determine the influence of temperature (Knipe 1967), moisture stress (Knipe 1968), and the relationship of seed size (Green and Hansen 1969) to germination. Knipe (1967) showed *B. gracilis* germinates extremely well at constant temperatures in a range of 60° to 90° F (15.5° to 32.5° C) and at alternating temperatures whose weighted means are 64° to 90° F (15.5° to 35.0° C). Effects of moisture stress were not inhibitory to germination until tensions were below −7 bars (Knipe 1968). Green and Hansen (1969) found heavy seeds (3.0-4.0 mg) of *B. gracilis* germinate significantly better than light seeds (0.5-1.0 mg).

Collection and preparation.—The seed source was Lovington, Ark., Valley Lot No. 2172. Seed of *B. gracilis* was threshed to remove all other plant material, and caryopsis were blown free with a commercial seed cleaner.

Temperatures (°C) during 16-hour part of cycle	12.0	16.0	20.0	23.0	27.0	31.0	35.0	37.0
37.0	84% 2.0	100% 2.0	88% 2.0	68% 2.4	88% 2.0	100% 2.0	100% 2.0	100% 2.0
35.0	64% 2.1	96% 2.7	88% 2.1	68% 2.0	96% 2.0	92% 2.0	96% 2.0	92% 2.0
31.0	84% 2.0	88% 2.0	88% 2.0	76% 2.2	76% 2.0	84% 2.0	100% 2.0	92% 2.0
27.0	88% 2.6	68% 3.0	80% 2.1	68% 2.0	100% 2.4	80% 2.1	100% 2.0	64% 2.2
23.0	92% 3.6	68% 3.3	80% 3.2	80% 2.8	80% 2.2	76% 2.4	80% 2.0	72% 3.2
20.0	84% 4.4	72% 4.3	80% 4.1	100% 4.0	80% 2.8	76% 2.5	88% 3.1	76% 3.0
16.0	80% 8.7	100% 6.0	96% 5.0	80% 4.6	100% 4.0	100% 4.0	100% 4.0	100% 4.0
12.0	64% 11.0	72% 7.7	100% 6.0	100% 6.0	100% 6.0	100% 4.6	100% 4.0	100% 4.4

Temperatures (°C) during 8-hour part of cycle

Figure 5.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Bouteloua gracilis* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Test Results

Temperature response test (fig. 5).—Germination times and percentages for *B. gracilis* seed are excellent at most positions on the TGP, with the only exception being the coolest constant temperature position which had a longer mean germination time.

Some variation was evident between positions in replicate tests on the TGP, but good patterns of temperatures for optimum germination can be noted. Peak germination (above 88%) in the shortest period of time was obtained with a range of alternating temperatures of 27° to 37° C (8 hr) and 35° to 37° C (16 hr) with a mean time of 2 days. Excellent germination (above 80%) also occurred with a range of alternating temperatures of 20° to 37° C (8 hr) and 12° to 16° C (16 hr) requiring from 4 to 6 mean days. Constant temperatures of 16°, 27°, and 37° C resulted in 100% germination in mean times of 6, 2.4, and 2 days, respectively.

Moisture stress response test.—Moisture stress did not inhibit germination of *B. gracilis* until stress exceeded −10 bars. Total percentage germination and time to reach 75% of total germination for *B. gracilis* at seven levels of moisture stress and temperatures maintained at 27° C (N = 3) were as follows:

Water potential (bars)	Total germination (%)	Time to reach 75% of total germination (days)
0	100a	2
−2	100a	2
−4	100a	2
−7	98ab	2
−10	96b	2
−13	82c	2
−16	78c	5

These results show slightly more germination during water stress than those published by Knipe (1968), probably due to ecotypic variation. Knipe's results show a gradual, significant decrease in germination below −7 bars and at −16 bars achieved only 42.25% germination.

Light response test.—Seeds of *B. gracilis* did not respond to either the presence or absence of light.

Range.—Alkaline soils, Saskatchewan to eastern Washington, south to California and Texas; Mexico.

Past work.—Desert saltgrass, as *D. stricta* is commonly called, is a dioecious, perennial grass with extremely stout rhizomes. Generally found in low areas with high moisture content and often high salinity, it is of little value for forage (Hitchcock 1950). Interest in saltgrass has lately been stimulated by its possible use as a recovery plant on mine tailings (Pavlicek et al. 1977). Use as a revegetation plant would probably depend on an abundant supply of moisture in an area (Pavlicek et al. 1977). Its stout rhizomes and firm culms make it important for erosion control.

Collection and preparation.—Seed of *D. stricta* was collected during August 1975, and August 1976, from a large, naturally occurring population adjacent to State Highway 4, north of the village of San Ysidro, N. Mex.

Prior to germination, the seeds were scarified for 4 minutes, using a coarse grade of sandpaper in the seed scarifier.

After scarification, germination occurred equally well with seeds both 1 year old and less than 2 weeks old.

Temperatures (°C) during 16-hour part of cycle	13.0	16.5	19.5	23.0	27.5	31.5	36.0	40.0
40.0	92% 5.4	84% 4.1	100% 4.8	84% 6.9	76% 5.7	96% 3.6	88% 3.0	72% 3.2
36.0	88% 5.9	72% 7.0	92% 5.1	72% 3.7	92% 3.8	84% 5.6	88% 3.8	100% 2.0
31.5	72% 6.1	72% 7.7	76% 5.5	76% 5.0	60% 5.4	68% 7.5	96% 4.6	80% 4.8
27.5	44% 10.8	80% 7.3	52% 7.0	60% 7.2	48% 7.5	68% 4.3	96% 3.5	96% 3.8
23.0	20% 8.4	56% 7.0	48% 7.8	40% 9.1	80% 8.6	84% 7.3	80% 7.1	92% 5.6
19.5	40% 13.8	44% 11.4	56% 12.1	28% 8.0	84% 8.2	92% 7.3	88% 7.0	92% 5.6
16.5			4% 18.0	32% 11.0	84% 11.6	92% 8.2	88% 7.4	84% 7.1
13.0			4% 14.0	40% 15.5	96% 10.0	72% 12.4	64% 8.9	100% 7.3

Temperatures (°C) during 8-hour part of cycle

Figure 6.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Distichlis stricta* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Test Results

Temperature response test (fig. 6).—Good germination percentages of *D. stricta* seeds are highly dependent on warm temperatures. Temperatures of 27.5° C or above produced the best germination in the shortest time periods. Seeds at a number of positions germinated at 90% or higher, but alternating temperatures of 40° C (8 hr) and 36° C (16 hr) produced the healthiest appearing seedlings. Mean time for germination at this position was only 2 days, and germination was 100%.

Cooler temperatures slowed germination and depressed the percentage of seeds germinated. No seeds germinated at the coolest positions (below 19.5° C).

Moisture stress response test.—Germination percentages of *D. stricta* are only slightly affected until a stress of −13 bars is reached. Total percentage germination and time to reach 75% of total germination at seven levels of water stress and alternating temperatures maintained at 40° C (8 hr) and 36° C (16 hr) (N = 2) were as follows:

Water potential (bars)	Average total germination (%)	Time to reach 75% of total germination (days)
0	98a	3
−2	98a	3
−4	88b	6
−7	94ab	9
−10	93ab	10
−13	60c	10
−16	40d	14

Lengths of time to reach 75% of the total seeds germinated demonstrate the effect of increasing moisture stress.

Light response test.—Germination of *D. stricta* seeds did not appear to be affected by either the presence or absence of light.

Range.—Deserts, canyons and dry plains; Wyoming and Utah to Texas and Inyo County, California.

Past work.—A common range grass of the western United States, *H. jamesii* has the ability to resist close grazing and withstand xeric conditions of deserts and dry sandy plains (Hitchcock 1950). In northeastern Arizona *H. jamesii* is the dominant grass on sandy plateaus of Navajo County (Gould 1951). The culms, although usually erect, are often decumbent at the base or rhizomatous, features which would lend stability as a soil binder for the recovery of devastated lands.

Knipe (1967, 1968) has shown *H. jamesii* to be both a good species for germination in a wide range of temperatures and to be strongly drought tolerant. Germination percentages were 85% and above with constant temperatures of 60° to 90° F (15.5° to 32° C) and alternating temperatures whose weighed means were 64° to 90° F (17° to 32° C). The maximum germination percentages were achieved with a constant temperature of 90° F (32° C) and alternating temperatures of 75° to 95° F (24.5° to 35° C). Moisture stress tests utilizing media representing a range of moisture tensions of 0 to −16 bars were conducted. At a sustained temperature of 77° F (25° C) germination was not significantly reduced until a tension of −10 bars was reached. According to Knipe's (1968) data, fairly good germination was also achieved at tensions of −13 and −16 bars.

Knipe (1967) recommended a constant temperature of 90° F (32° C) or alternating temperatures of 75° to 95° F (24° to 35° C) for maximum germination.

Temperatures (°C) during 16-hour part of cycle	14.0	17.0	21.0	24.0	29.0	33.0	37.0	40.5
40.5	44% 3.1	62% 2.1	62% 2.1	50% 2.1	76% 2.3	76% 2.0	56% 1.8	22% 1.9
37.0	86% 2.0	72% 2.2	52% 2.0	66% 2.0	76% 1.7	84% 1.3	72% 1.7	42% 2.0
33.0	96% 3.1	54% 2.3	56% 2.5	84% 2.0	78% 2.0	68% 1.6	84% 2.1	74% 2.2
29.0	90% 3.2	92% 2.5	78% 2.4	76% 2.1	100% 1.9	84% 1.9	70% 2.0	58% 2.1
24.0	58% 3.6	78% 3.2	88% 2.5	94% 2.2	88% 2.0	76% 1.8	44% 2.0	58% 2.1
21.0	54% 4.7	76% 3.3	76% 3.5	88% 2.6	76% 2.2	96% 2.2	78% 2.0	14% 2.0
17.0	64% 6.9	42% 5.4	74% 3.9	76% 3.9	66% 3.6	40% 3.0	48% 3.0	24% 3.2
14.0	62% 10.7	80% 6.5	78% 4.6	82% 4.3	82% 5.2	48% 4.2	68% 3.3	66% 4.4

Temperatures (°C) during 8-hour part of cycle

Figure 7.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Hilaria jamesii* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Collection and preparation.—The seed was collected in 1972 from a commercial dealer in Los Lunas, N. Mex. Caryopsis had been cleaned of all other plant material.

Test Results

Temperature response test (fig. 7).—Good germination results were achieved at all positions but the warmest. Alternating temperatures resulted in excellent germination (above 90%) at 14° C (8 hr) and either 29° or 33° C (16 hr), and also at 17° C (8 hr) and 29° C (16 hr). The peak response was 100% at a constant temperature of 29° C with a mean germinating time of 1.9 days. Excellent germination was also noted at the constant temperature of 24° C.

Knipe's (1967) temperatures are somewhat different than optimum temperatures indicated by data from the TGP. A number of explanations are possible. No date for collection is given by Knipe (1967), and age of seed could be a factor; also, no location of collection is given and ecotypical variations may be evident.

Water stress response test.—Germination of *H. jamesii* was depressed as moisture stress increased, dropping to a low average of 19% at −16 bars. The control and water potential of −2 bars gave average germination percentages of 92% each. Total percentage germination and time required to reach 75% of total germination for *H. jamesii* at seven levels of moisture stress with temperatures maintained at 30° C ($\underline{N}$ = 4) were as follows:

Water potential (bars)	Total germination (%)	Time to reach 75% of total germination (days)
0	92a	1
−2	92a	3
−4	85ab	3
−7	74b	3
−10	58c	4
−13	37d	4
−16	19e	4

Knipe (1968) indicated much higher germination percentages (72.25, 71.25, and 65.5%) at greater stresses (−10, −13, and −16 bars) than results mentioned above. No explanation can be given for such a large variation in results; however, different seed sources were probably used.

Light response test.—No initial response to light was noted; thus light probably plays no substantial role in germination.

Range.—Plains and open slopes, sandy or rocky, at elevations of 5,000-8,000 feet. Oklahoma, Colorado, Utah, New Mexico, Arizona and northern Mexico.

Past work.—*Muhlenbergia wrightii* is considered to be one of the most important range grasses of arid and semi-arid lands, forming a sizeable proportion of the grass flora of the Southwest (Hitchcock 1950).

Experiments on *M. wrightii* to define germination parameters have thus far been scant or are nonexistent.

Collection and preparation.—Cleaned seed was received from the USDA Forest Service. No pretreatments were administered prior to germination tests.

Temperatures (°C) during 16-hour part of cycle	12.0	17.0	20.0	23.5	27.5	31.0	34.5	37.0
37.0	60% 3.6	60% 3.7	48% 4.0	32% 3.1	30% 3.0	34% 2.6	32% 4.0	32% 4.7
34.5	94% 4.9	98% 4.5	96% 3.1	96% 2.4	100% 2.7	96% 3.6	92% 3.1	90% 3.3
31.0	90% 8.0	100% 5.2	100% 3.6	92% 3.6	92% 2.7	94% 2.2	96% 2.9	96% 3.0
27.5	88% 8.7	94% 5.2	100% 4.4	94% 4.1	88% 2.9	98% 2.5	100% 2.7	100% 2.7
23.5	94% 10.8	98% 10.0	100% 6.9	94% 5.9	94% 5.3	100% 3.4	100% 3.4	94% 4.5
20.0	88% 14.3	88% 10.8	100% 10.0	96% 8.8	92% 5.5	100% 4.3	100% 3.8	100% 5.0
17.0	100% 14.4	100% 12.4	100% 10.0	100% 10.0	94% 5.9	94% 5.5	78% 6.3	60% 8.5
12.0			100% 10.0	100% 10.6	100% 10.2	100% 8.3	94% 9.2	70% 12.0

Temperatures (°C) during 8-hour part of cycle

Figure 8.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Muhlenbergia wrightii* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Test Results

Temperature response test (fig. 8).—*M. wrightii* germinates well at all temperatures in a range from 12° to 34.5° C. Germination percentages were depressed at a constant temperature of 12° C and alternating temperatures of 12° C (16 hr) and 17° C (8 hr). Mean germination time ranged from 2.2 days at a constant 31° C to 14.4 days at alternating temperatures of 12° C (8 hr) and 17° C (16 hr). Generally, the warmer temperatures produced the more rapid germination times.

Moisture stress response test.—Increases in moisture stress appear to have little influence on germination percentages of *M. wrightii* until a water potential of −13 bars is reached. Total percentage germination and time required to reach 75% of total germination for *M. wrightii* at seven levels of water stress with temperatures maintained at 31° C ($\underline{N}$ = 3) were as follows:

Water potential (bars)	Total germination (%)	Time to reach 75% of total germination (days)
0	90a	3
−2	85ab	5
−4	83b	5
−7	83b	7
−10	80b	8
−13	45c	8
−16	25d	9

As water stresses are increased, the time required for 75% total germination increases slightly. Water potentials above −4 bars appeared to have little influence on seedling vigor, while potentials at or below −4 bars noticeably reduced vigor.

Light response test.—No response to either the presence or absence of light was noted in germinating seeds of *M. wrightii*.

Range.—Mesas, dry bluffs, and sandy fields; Arkansas, Colorado to Nevada, south to western Texas; southern California and Sonora.

Past work.—*Sporobolus contractus* is a common grass in the southwestern United States. It is found primarily in dry, open areas, usually on open, sandy, or rocky slopes and washes, and is frequently found alongside roads (Gould 1951). The value of spike dropseed as a forage or browse plant is not mentioned in the literature, but cattle have been noted grazing indiscriminately on both *S. cryptandrus* and *S. contractus*.

V. K. Toole (1941) determined the most appropriate methods of obtaining optimum germination percentages. After acid scarification of the seeds, germination was optimum with alternating temperatures of 15° and 35° C with light.

Collection and preparation.—Seed of *S. contractus* was collected south of the village of San Ysidro, N. Mex., along State Highway 44. Collection date was June 1975, while the heads were still intact. Seed heads were pulled apart by hand and the chaff floated off in water. Seed was scarified by soaking for 4 minutes in 71% sulfuric acid and then washed for 30 minutes with tap water (Toole 1941).

Temperatures (°C) during 16-hour part of cycle								
36.0	16% 7.0							
32.5	12% 3.7	52% 5.5	62% 5.7	22% 5.0	28% 6.0	38% 6.0	26% 5.5	24% 5.0
29.5	52% 4.0	76% 3.3	66% 3.7	54% 3.3	54% 3.6	38% 5.0	44% 5.3	36% 6.0
26.5	72% 4.4	78% 4.8	64% 4.9	48% 5.0	36% 5.4	28% 3.4	34% 3.5	13% 5.0
23.0	56% 6.0	54% 5.1	50% 5.0	52% 5.3	48% 5.0	56% 3.9	44% 5.1	40% 6.4
19.0	42% 5.0	42% 5.1	64% 6.8	54% 7.0	68% 6.0	68% 4.6	72% 4.3	56% 6.2
15.5	44% 8.0	48% 10.2	58% 7.7	66% 8.1	72% 7.3	68% 6.6	74% 6.0	54% 5.7
12.0	2% 20.0		12% 12.0	50% 7.0	50% 7.5	50% 7.3	48% 6.0	12% 7.1
	12.0	15.5	19.0	23.0	26.0	29.5	32.5	36.0
	Temperatures (°C) during 8-hour part of cycle							

Figure 9.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Sporobolus contractus* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Test Results

Temperature response test (fig. 9).—Germination of *S. contractus* was best within two ranges of alternating temperatures: 15.5° to 19° C (8 hr) and 26.5° to 29.5° C (16 hr), and 26° to 32.5° C (8 hr) and 15.5° to 19° C (16 hr). Mean times for germination at the first set of temperatures range from 3.3 to 4.9 days with the highest germination percentage (78%) occurring with a mean of 4.8 days. Mean times in the second set of temperatures were slightly longer, ranging from 4.3 days to 7.3 days.

Results of this test compare favorably with results of Toole (1941). The ranges of temperatures for optimum germination are similar, but the percentages of seed germinated are lower than those reported by Toole.

Moisture stress response test. —All moisture stress levels below 0 bars were found to decrease germination of *S. contractus*. Total percentage germination and time required to reach 75% of total germination at seven levels of moisture stress and alternating temperatures of 30° C (8 hr) and 15° C (16 hr) were (N = 2) as follows:

Water potential (bars)	Total germination (%)	Time to reach 75% of total germination (days)
0	80a	3
−2	71b	3
−4	71b	3
−7	60c	6
−10	33d	6
−13	0e	—
−16	0e	—

Light response test.—Germination of *S. contractus* seeds was determined not to be affected by either the presence or absence of light.

Toole (1941) mentions that germination of *S. contractus* seed is best with light, and this was substantiated in further testing of *S. contractus* seed from other New Mexican sources. However, the light response phenomenon may depend on ecotype since source and light was not required by the seed source used in these temperature and moisture stress studies.

Range.—Sandy, open ground; Maine and Ontario to Alberta and Washington; south to North Carolina, Indiana, Louisiana, southern California, and northern Mexico.

Past work.—*Sporobolus cryptandrus* is a widely distributed polymorphic species. Occurring in most areas of the United States, it is found primarily on exposed sites in sandy soil. Sand dropseed is highly adaptable to differing environments but exhibits numerous growth forms in differing situations (Gould 1951). While green, it is highly palatable to domestic livestock and large game animals. Due to its high palatability, sand dropseed has been used extensively in grass mixtures for range reseeding work.

Considerable work on determination of the best methods and temperatures for germination of the *Sporobolus* species has been done by Toole (1941), who reported germination of *S. cryptandrus* to be optimum with alternating room temperatures (24.5° to 35° C) in the presence of light. Previous testing of *S. cryptandrus* seed indicated a pretreatment scarification with 71% sulfuric acid was necessary to achieve maximum germination. A high degree of ecotype variability was noted by Toole and should be taken into account when determining optimum temperatures for certain collection sources.

Collection and preparation.—Cleaned seed was received from the USDA Forest Service. Seed of *S. cryptandrus* was scarified by soaking in 71% sulfuric acid for 3 minutes and then washed for 30 minutes in tap water prior to germination tests (Toole 1941).

Temperatures (°C) during 16-hour part of cycle	11.0	16.0	20.0	23.0	27.0	31.0	35.0	37.0
37.0	88% 5.2	82% 2.9	64% 3.4	58% 3.3	42% 5.4	12% 2.8	20% 3.0	12% 4.0
35.0	62% 4.5	74% 4.4	80% 2.7	64% 2.6	60% 5.8	56% 3.0	78% 2.7	62% 3.0
31.0	84% 6.0	88% 3.9	80% 2.8	82% 4.2	64% 3.9	56% 6.0	72% 5.4	80% 2.9
27.0	74% 12.0	64% 5.0	52% 3.2	52% 3.0	74% 2.9	68% 3.6	90% 3.3	88% 2.9
23.0	42% 14.0	38% 10.3	42% 4.7	60% 3.5	54% 4.7	72% 8.9	94% 5.6	100% 6.0
20.0	12% 12.0		12% 10.0	34% 6.0	60% 6.8	78% 7.0	100% 5.2	100% 5.3
16.0			6% 12.0	32% 10.0	60% 6.9	78% 5.1	100% 5.0	100% 6.6
11.0				50% 11.8	64% 8.7	92% 6.7	84% 7.0	100% 6.0

Temperatures (°C) during 8-hour part of cycle

Figure 10.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Sporobolus cryptandrus* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Test Results

Temperature response test (fig. 10).—Alternating temperatures had the most pronounced effect on germination of *S. cryptandrus*. Alternating temperatures of 35° to 37° C (8 hr) and 11° to 27° C (16 hr) produced the best germination percentages. Mean germination times at these temperatures were from 2.9 to 7.0 days.

Constant temperature produced much lower germination percentages, and temperatures of 20° C or lower (either constant or alternating) resulted in very low germination percentages or inhibited germination altogether.

Germination percentages obtained in this experiment are similar to those published by Toole (1941).

Moisture stress response test.—Germination percentages of *S. cryptandrus* seed were affected by moisture stress levels below −2 bars. Total percentage germination and time required to reach 75% of total germination for *S. cryptandrus* at seven levels of moisture stress and alternating temperatures of 15° C (8 hr) and 30° C (16 hr) were (N = 2) as follows:

Water potential (bars)	Total germination (%)	Time to reach 75% of total germination (days)
0	83a	3
−2	89a	3
−4	69b	3
−7	64b	4
−10	52c	6
−13	35d	8
−16	0e	—

Moisture stress of −16 bars totally inhibited germination.

Light response test.—Germination of *S. cryptandrus* benefited from the presence of light. Tests were run on the TGP in light and in darkness to explore this phenomenon further. The test without light produced sporadic germination with no germination percentages exceeding 10% at any position. This type of response was also described by Toole (1941).

Germination Requirements of Shrubs

Fringed sagebrush *Artemisia frigida* Willd.

Range.—Dry, stony soil to elevations of 7,000 feet; widely distributed in western Texas, New Mexico, Arizona, Colorado, Utah, North and South Dakota, Nebraska, and Idaho, north to Canada and Alaska.

Past work.—A perennial mat-forming herb, *A. frigida* is one of the most characteristic autumnal societies of the mixed grass prairie, ranking second only to *Gutierrezia sarothrae* in abundance. The abundance of *A. frigida* is partly due to its response to overgrazing and is considered as a primary indicator of overgrazing on the Great Plains. It usually mixes with *Gutierrezia* in the central portion, exceeding it in the north, and falling far below it in abundance in the south (Hall and Clements 1923). *A. frigida* is reported by stockmen and foresters to be an important forage in the late fall, winter, and early spring (Vines 1960).

Its ability to occupy devastated areas, low growth form, high palatability value, and broad ecological amplitude are important factors in the selection of *A. frigida* in devastated land revegetation.

Temperatures (°C) during 16-hour part of cycle	13.5	17.0	20.5	24.0	27.5	31.0	34.0	37.0
37.5				4% 8.0				
34.0	48% 11.7	28% 11.0	20% 7.2	16% 9.2	16% 11.0			
31.0	100% 9.9	92% 7.4	100% 8.4	36% 7.4	76% 11.0			
27.5	72% 6.2	96% 6.0	96% 5.6	92% 5.1	92% 5.3	76% 9.3	28% 7.4	16% 8.5
23.5	100% 5.3	100% 5.3	100% 5.4	100% 6.6	64% 8.8	96% 5.8	48% 9.0	16% 4.5
20.5	56% 6.6	96% 6.0	84% 5.0	92% 5.3	100% 4.8	84% 4.1	64% 5.8	8% 7.5
15.5	68% 5.7	100% 5.4	92% 6.1	40% 5.0	68% 5.0	64% 6.5	64% 7.7	12% 13.7
11.5	64% 7.9	88% 12.0	92% 7.8	100% 7.2	92% 6.9	52% 7.3	56% 10.1	8% 11.0

Temperatures (°C) during 8-hour part of cycle

Figure 11.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Artemisia frigida* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Collection and preparation.—Seeds of *A. frigida* were collected along New Mexico Highway 14, 7 miles south of the junction of Interstate 40 in November 1975.

Achenes of *A. frigida* are small; to satisfactorily clean them, the heads must be threshed and the extra plant material sifted and blown off. No other pretreatment is necessary for germination.

Test Results

Temperature response test (fig. 11).—Achenes of *A. frigida* germinated very well over most of a range of temperatures from 17° to 24° C (8 hr) and 11.5° to 31° C (16 hr). Temperatures of 34° C or higher strongly depressed percentages and lengthened mean germination times. Optimum germination was at a constant temperature of approximately 17° C with a mean germination time of 5.4 days, and alternating temperatures of 13.5° to 17° C (8 hr) and 23.5° C (16 hr) with mean germination times of 5.3 days.

Water stress response test.—Germination of achenes of *A. frigida* is strikingly affected by increase in moisture stress. Total percentage germination and time required to reach 75% of total germination at seven levels of moisture stress with a constant temperature of 17° C were (N = 2) as follows:

Water potential (bars)	Total germination (%)	Time to reach 75% of total germination (days)
0	98a	5
−2	85b	5
−4	49c	8
−7	41c	10
−10	18d	11
−13	0e	—
−16	0e	—

Solutions of PEG equivalent to −4 bars resulted in only one-half the amount of germination of the controls. Stress conditions below −10 bars gave no germination.

Light response test.—No response to either the presence or absence of light was noted in germinating seeds of *A. frigida*.

Range.—Widely distributed in the West, especially on the semi-arid lands of the Great Basin, but ranging up to the timberline in mountains; British Columbia to Mexico; Texas, New Mexico, Arizona, Colorado, California, North Dakota, Montana, Wyoming, and Washington.

Past work.—The literature indicates considerable variation in germination of *A. tridentata* seeds. Vines (1960) mentions that germination of 35% or less is normal, whereas the U.S. Department of Agriculture (1974) indicates 80% germination was acceptable. Variation in germination has been noted when the seeds of one subspecies, *A. tridentata* subsp. *tridentata* were collected from the same plant at different times of the year (Harniss and McDonough 1976). The U.S. Department of Agriculture (1974) indicates a great deal of geographical variability in height (0.5 to 5 m), palatability, seed production, and resistance to insect attack. Variability in seed germination probably could be included in this list.

Up to 85% germination has been obtained in 100 days at stratification temperatures of 32° to 38° F (0° to 3° C) (U.S. Department of Agriculture 1974). Variation among subspecies and ecotypes plays a significant role in optimum germination temperatures and times (McDonough and Harniss 1974, Harniss and McDonough 1976).

Temperatures (°C) during 16-hour part of cycle	11.5	15.0	18.5	22.5	26.0	29.5	32.5	36.0
36.0	12% 4.0			4% 8.0			8% 4.0	
32.5	30% 5.0	28% 3.6	40% 3.9	36% 5.2	32% 7.0	24% 4.6	12% 4.0	4% 4.0
29.5	64% 4.6	68% 3.4	76% 4.3	60% 3.4	44% 4.7	60% 3.4	44% 5.5	12% 3.6
26.0	100% 4.2	68% 4.3	88% 3.7	72% 4.9	76% 4.6	52% 3.9	44% 3.0	12% 5.5
21.5	76% 3.6	96% 3.3	92% 3.5	84% 3.5	100% 3.5	68% 4.6	80% 3.6	84% 3.2
18.5	100% 3.4	88% 3.3	100% 3.6	80% 3.1	84% 3.6	80% 3.6	72% 3.8	48% 6.7
15.5	84% 10.5	96% 4.3	92% 3.6	92% 4.0	92% 3.8	100% 4.4	56% 5.1	92% 5.6
11.5	96% 8.9	68% 11.2	68% 6.7	100% 4.6	100% 6.3	76% 5.5	52% 7.1	92% 6.5

Temperatures (°C) during 8-hour part of cycle

Figure 12.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Artemisia tridentata* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Collection and preparation.—*A. tridentata* seeds were collected in November 1975, from plants located well within a large population of the species, approximately 25 miles west of the village of San Luis, N. Mex.

Seeds were prepared by threshing to break up the heads and separate plant material, then cleaning with a commercial blower-type seed cleaner. No other pretreatments were administered.

Test Results

Temperature response test (fig. 12).—Achenes of *A. tridentata* germinate well in a broad range of temperatures from 11.5° to 26° C (8 hr) and 11.5° to 26° C (16 hr). Peak germination with respect to both germination time and percentage was at the constant temperature of 18.5° C; mean germination time was 3.6 days.

Moisture stress response test.—Moisture stress appears to have little effect on germination percentages until −10 bars is reached, when germination is reduced to 52%. Times to obtain 75% of total germination are lengthened as stress is increased. Total percentage germination and time required to reach 75% of total germination at seven levels of moisture stress when temperatures were maintained at 18.5° C ($\underline{N}$ = 3) were as follows:

Water potential (bars)	Total germination (%)	Time to reach 75% of total germination (Days)
0	92ab	4
−2	90ab	4
−4	98a	6
−7	85b	9
−10	52c	9
−13	5d	—
−16	0d	—

Light response test.—No response to either the presence or absence of light was noted with *A. tridentata* seed.

Range.—On hard, stony, alkaline soils with a high clay content, at elevations of 4,000 to 6,000 feet. From extreme western Texas and New Mexico to southern California, north to Oregon and Wyoming.

Past work.—Investigations of germination have been somewhat hampered by the extremely hard seed coat of *A. confertifolia*. Because the seed coat is essentially impermeable to water and much too hard for rupture by a germinating embryo, tests have taken as long as 1,460 days to obtain germination (U.S. Department of Agriculture 1974). Salisbury and Ross (1969) describe an interesting symbiotic relationship in which a fungus uses the seed coat of *A. confertifolis* as a substrate for growth, at the same time scarifying it so germination can occur. The fungus grows only when temperature and moisture conditions are suitable.

Collection and preparation.—Seed for germination experiments was collected in November 1975 from a large stand growing approximately 25 miles west of San Luis, N. Mex. The extreme hardness of the seedcoat required repeated scarification that either removed the seedcoat entirely, or fissured and made it thin enough to allow the penetration of water.

The technique of repeated scarification required a commercial seed scarifier and a blower-type seed cleaner. The seed scarifier was used without the normal abrasive surface in place; instead the roughness of the seedcoat itself was used as the abrasive. The seeds were scarified for 2-minute intervals. As the seeds rubbed against each other, their coats were uniformly reduced in thickness; those seeds with thinner coats were freed first. After 2 minutes the seeds were run through the cleaner, which removed seeds with very thin coats left and with coats removed. The remaining seeds were placed back in the scarifier and the process repeated. With the seedcoat removed, germination proceeds rapidly.

Temperatures (°C) during 16-hour part of cycle	12.0	16.0	20.0	23.9	27.9	31.0	35.0	37.0
36.5								
31.5	6% 4.0		20% 4.0	20% 4.7	27% 4.0		6% 6.0	
29.0	6% 4.0	6% 4.0	6% 4.0	13% 2.0	27% 2.0	6% 2.0	20% 2.0	
26.0	6% 2.0	27% 9.0	20% 2.0	47% 2.5	40% 2.5	47% 2.5	27% 3.0	20% 4.7
23.0	47% 5.7	13% 2.0	33% 3.6	13% 2.0	47% 2.8	53% 4.0	40% 5.7	6% 4.0
19.0	60% 3.8		27% 6.0	13% 16.0		27% 10.0	13% 4.0	13% 4.0
17.0	33% 12.0	13% 6.0	60% 5.8	20% 6.6	73% 11.7	6% 5.9	80% 6.8	13% 4.0
12.0	100% 7.5	86% 9.7	73% 7.2	66% 7.2	73% 11.2	40% 13.7	47% 6.0	6% 22.0

Temperatures (°C) during 8-hour part of cycle

Figure 13.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Atriplex confertifolia* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Test Results

Temperature response test (fig. 13).—*A. confertifolia* germinates well at only the cooler temperatures; as the temperatures are increased, germination percentages drop markedly. The most optimum germination temperatures were either a constant temperature of 12° C or an alternating temperature of 16° C (8 hr) and 12° C (16 hr). At the constant temperature the mean germination time was only 7.5 days; at the alternating temperature it was 9.7 days.

Results obtained here are far more practical than the U.S. Department of Agriculture (1974) observations of temperatures of 32° to 38° F (0° to 3° C) in moist paper for 1,460 days. With that procedure, a germinative capacity of only 25% was recorded, as compared to a maximum of 100% on the TGP. The increase was probably because of the removal of the seedcoat which acts as a barrier to water penetration and germination, and rejection of seeds without an embryo.

Moisture stress test.—Increases in moisture stress strongly depress germination percentages. Total percentage germination and time required to reach 75% of total germination at seven levels of water stress when temperatures were maintained at 11° C (N = 2) were as follows:

Water potential (bars)	Total germination (%)	Time to reach 75% of total germination (days)
0	86a	6
−2	80a	6
−4	46b	6
−7	10c	8
−10	0d	—
−13	0d	—
−16	0d	—

Stress beyond −7 bars gave no germination.

Light response test.—No response to either the presence or absence of light was noted on germinating seeds of *A. confertifolia*.

Range.—Dry, rocky bluffs or mountainsides at elevations of 3,500 to 9,000 feet; New Mexico, Arizona, northward to Wyoming and South Dakota.

Past work.—*Cercocarpus montanus* is an important browse shrub for southwestern big game. Found primarily on arid mountain slopes, it has the ability to survive very dry conditions. *C. montanus* has received considerable attention for revegetation studies (Heit 1970, Piatt 1976). Additionally, mountain-mahogany has been reported to form root nodules and fix nitrogen (Hoeppel and Wollman 1971).

Conditions for germination of *C. montanus* seed as recommended by the U.S. Department of Agriculture (1974) were 32° to 38° F (0° to 3° C) for 70 days; this resulted in 92% germination. Heit (1970) recommends fluctuation of 10° to 30° C for optimum germination. No data were given to demonstrate how this temperature regime affected germination. The U.S. Department of Agriculture (1974) recommends stratification to achieve optimum germination.

Collection and preparation.—Seeds were collected during summer 1974 from plants on the northern edge of Santa Fe, N. Mex., at an elevation of 7,300 feet. Seeds were cleaned of all other plant parts, but no other pretreatments or stratification were administered.

Temperatures (°C) during 16-hour part of cycle	13.0	16.5	19.5	23.0	27.0	31.5	36.0	40.0
37.5	2% 11.0							
35.2	40% 13.4	10% 9.6	0% 0	4% 6.0				
31.5	40% 10.6	46% 9.4	30% 8.3	28% 8.0	8% 16.0			
27.0	54% 10.9	58% 9.6	66% 7.5	20% 7.4	20% 8.2			
23.5	42% 12.2	52% 7.8	58% 6.6	52% 6.6	38% 10.0	14% 6.7	4% 5.0	2% 21.0
20.0	38% 12.0	60% 9.6	64% 7.5	38% 10.5	52% 7.0	18% 6.1		
15.5	38% 14.0	50% 12.3	64% 9.0	70% 8.8	60% 9.7	16% 8.0	8% 7.0	
11.5	42% 14.4	62% 13.6	32% 11.5	72% 9.3	34% 11.8	24% 10.4	2% 9.0	

Temperatures (°C) during 8-hour part of cycle

Figure 14.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Cercocarpus montanus* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Test Results

Temperature response test (fig. 14).—Germination of *C. montanus* was strongly influenced by temperatures across the TGP. Warmer temperatures inhibited germination altogether, while cooler temperatures resulted in a slight decrease in germination percentages. The optimum temperature response was with alternating temperatures of 23° C (8 hr) and 11.5° to 15.5° C (16 hr). At these temperatures, 70 to 72% germination was obtained with a mean time of about 9 days. An alternation of 10° and 30° C recommended by Heit (1970) was too high for this particular ecotype of *C. montanus*.

Moisture stress response test.—Increasing moisture stress gradually depressed germination percentages. Total percentage germination and time to reach 75% of total germination for *C. montanus* at seven levels of moisture stress with alternating temperatures of 23° C (8 hr) and 15° C (16 hr) were (N = 3) as follows:

Water potential (bars)	Total germination (%)	Time to reach 75% of total germination (days)
0	74a	9
−2	68a	9
−4	48b	11
−7	29c	12
−10	15d	13
−13	0e	—
−16	0e	—

Stresses greater than −10 bars inhibited germination altogether. Times for germination were also increased as stresses were increased.

Light response test.—Light or the absence of it was determined to have no substantial effect on the germination of *C. montanus*.

Rubber rabbitbrush

Bigelow rubber rabbitbrush

Range.—Texas through New Mexico, Colorado to the Dakotas, Washington, British Columbia and Alberta, Canada; westward to California and south to Mexico.

Past work.—*C. nauseosus* is an important codominant in the sagebrush subclimax association. These two subspecies are typically considered to be somewhat halophytic in nature, often occurring either along or in saline washes and arroyos. The deep root system, heavy litter production, and ability to become established on severely exposed sites make rabbitbrush useful for erosion control (U.S. Department of Agriculture 1974). The value of these shrubs as a browse plant for animals depends largely upon local conditions. Throughout most of its range, rabbitbrush is only lightly browsed, except under very unusual circumstances. The species is poisonous to stock under certain conditions, at least in Nevada (Hall and Clements 1923) and Arizona (Parker 1972).

Germination recommendations by Vines (1960) indicate that seed viability is low (20 to 40%), whereas the U.S. Department of Agriculture (1974) lists *C. nauseosus* as having a germinative capacity of 63% on the average. The latter report also indicates that some stratification treatments enhance germination rates, and stratification temperature recommendations were for 33° to 38° F.

Literature related to seed germination of *Chrysothamnus nauseosus* (Vines 1960, U.S. Department of Agriculture 1974) generally does not define the subspecies. The importance of the identification of the subspecies is evidenced by the great variation in germination requirements mentioned below.

Collection and preparation.—Seeds of both subspecies were collected north of the village of San Ysidro, N. Mex., in an area adjacent to State Highway 4. Seeds of subspecies *consimilis* were collected in November 1975, of subspecies *bigelovii* in November 1976. No pretreatment was administered prior to germination tests, however, larger, filled seeds were selected.

Temperatures (°C) during 16-hour part of cycle	13.0	16.5	19.5	23.0	27.5	31.5	36.0	40.0
40.0								
36.0								
31.5	7% 5.0							
27.5		27% 7.0						
23.0	14% 6.0	27% 6.0	41% 4.0	20% 6.0	14% 5.0	20% 5.0		
19.5	54% 9.0	41% 5.0	54% 5.0	27% 6.0	7% 5.0		7% 5.0	
16.5	48% 10.0	60% 6.0	41% 11.0	82% 8.0	27% 9.0			
13.0	60% 13.0	20% 8.0	34% 8.0	54% 8.0	14% 6.0	7% 13.0		

Temperatures (°C) during 8-hour part of cycle

Figure 15a.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Chrysothamnus nauseosus* ssp. *consimilis* germinated on thermal gradient plate with a 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination. Test conducted under dark conditions.

Temperatures (°C) during 16-hour part of cycle	13.0	16.5	19.5	23.0	27.5	31.5	36.0	40.0
40.0								
36.0	26% 3.5	2% 3.6	2% 3.4	18% 4.0	30% 3.8			
31.5	42% 4.1	44% 3.9	38% 3.8	36% 3.7	34% 4.0	40% 4.0	6% 4.0	
27.5	72% 4.5	68% 3.9	62% 3.6	68% 3.4	48% 3.3	52% 3.5	20% 4.2	2% 4.0
23.0	76% 5.9	68% 5.9	72% 4.3	68% 4.5	72% 3.8	62% 3.8	24% 3.3	
19.5	56% 6.5	54% 5.6	52% 4.9	44% 5.1	54% 3.8	44% 4.5	12% 4.6	
16.5	58% 8.9	54% 7.3	54% 7.3	44% 6.3	54% 3.9	44% 4.7	12% 5.0	
13.0	60% 20.0	46% 19.3	50% 19.2	56% 18.0	14% 8.0	8% 5.0	10% 6.4	

Temperatures (°C) during 8-hour part of cycle

Figure 15b.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Chrysothamnus nauseosus* ssp. *consimilis* germinated on thermal gradient plate with a 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination. Test conducted under continuous light.

Chrysothamnus nauseosus (Pallas) Britton ssp. *consimilis* (Greene) H. M. Hall

Chrysothamnus nauseosus (Pallas) Britton ssp. *bigelovii* (Gray) H. M. Hall

Test Results

Temperature response tests (figs. 15 and 16).—*C. nauseosus* ssp. *consimilis* (fig. 15): Seeds of ssp. *consimilis* germinated well vith a peak percentage of 76% at alternating temperatures of 13° C (8 hr) and 23° C (16 hr); mean germination time was 5.9 days. Alternating temperatures of 13° to 27.5° C (8 hr) and 23° to 27.5° C 16 hr) gave the best range of responses, with germination times peing only slightly increased at the cooler temperatures.

Temperatures above 27.5° C inhibited most germination. Time o germinate was considerably lengthened at the coolest tempertures.

C. nauseosus ssp. *bigelovii* (fig. 16): Germination of seed of ssp. *igelovii* was excellent at temperatures at or below 32.5° C. Peak ermination percentage in the shortest time occurred at alterating temperatures of 20.5° C (8 hr) and 30° C (16 hr) with a nean germination time of 2.7 days. No changes in germination ercentages were noted at the cooler temperatures, but germinaon required considerably more time.

Moisture stress response test.—Seeds of ssp. *consimilis* were erminated at alternating temperatures of 20° C (8 hr) and 24° C 16 hr) with light supplied during the 16-hour periods to simulate daylight period.

Germination was strongly affected at even moderate stresses. Total percentage germination and time to reach 75% germinaion for ssp. *consimilis* at seven levels of moisture stress with lternating temperatures, 13° C (8 hr) and 23° C (16 hr) (N = 2) vere as follows:

Water potential (bars)	Total germination (%)	Time to reach 75% of total germination (days)
0	74a	3
−2	68a	3
−4	38b	10
−7	34b	13
−10	7c	16
−13	2d	—
−16	2d	—

Water potentials of −4 and −7 bars decreased the germination per entage to half that of the control. Times for germination were lso increased by an increase in moisture stress.

Light response tests.—*C. nauseosus* ssp. *consimilis:* Light pronoted germination of subspecies *consimilis* at alternating temperatures maintained above 23° C (8 hr) or above 19.5° C (16 hr). Below those temperatures, germination progressed with very ittle difference between tests in light or darkness.

Two differences should be noted in comparing germination at he lower temperatures in dark and light. Germination times at he coolest temperatures were considerably longer in the presence of light than in the dark. This could be due to the seed peing more than a month older in the dark test. Secondly, at alternating temperatures of 23° C (8 hr) and 16.5° C (16 hr) 82% germination was recorded in the dark compared to 44% in the light. No explanation can be given for this apparent anomaly.

C. nauseosus ssp *bigelovii:* No appreciable response to either the presence or absence of light was noted.

The results graphically demonstrate the high degree of variability found in *C. nauseosus* subspecies. A wide range of temperatures strongly decrease germination in subspecies *consimilis*, while *bigelovii* is only affected at the warmer extremes. This is important to note since these subspecies were collected from the same area, where the plants of each subspecies were growing next to each other.

Light plays a major role in the germination response of subspecies *consimilis* but does not appear to be a factor in germination of *bigelovii*. This response of subspecies *consimilis* to light is not surprising since a great many other species respond similarly. A light and temperature interaction study with the Grand Rapids cultivar of lettuce indicated that, at higher temperatures, a great percentage of seeds are dependent on red light exposure for germination (Devlin 1966).

Temperatures (°C) during 16-hour part of cycle \ Temperatures (°C) during 8-hour part of cycle	13.0	17.0	20.5	23.0	26.5	30.0	32.5	36.0
36.0	64% 2.8	48% 3.3	36% 2.0	56% 2.0				
32.5	96% 2.8	100% 3.6	84% 3.3	72% 4.0	56% 3.0	72% 3.7	80% 2.3	8% 2.0
30.0	84% 2.3	76% 4.5	100% 2.7	80% 3.6	88% 3.9	64% 3.5	72% 2.1	48% 3.5
26.5	72% 3.7	80% 4.2	56% 3.7	76% 2.8	64% 2.6	76% 2.9	84% 2.0	68% 2.0
23.0	76% 4.2	80% 8.7	76% 7.7	56% 7.5	76% 5.0	96% 3.9	96% 2.4	36% 7.7
20.5	60% 9.0	76% 8.7	76% 9.9	88% 6.2	68% 10.0	72% 4.5	52% 2.4	64% 2.9
17.0	72% 16.9	16% 16.0	88% 16.9	76% 9.0	92% 3.7	88% 3.0	72% 2.1	40% 2.7
13.0	76% 17.6	76% 17.4	68% 16.9	64% 10.2	76% 11.9	88% 3.5	92% 2.0	64% 4.2

Figure 16.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Chrysothamnus nauseosus* ssp. *bigelovii* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Range.—On sunny, dry soils of slopes, mesas, or washes at elevations of 3,500 to 5,000 feet; New Mexico, west through Arizona to California and north to Colorado, Utah, and Nevada.

Past work.—*Cowania stansburiana* is a valuable plant for the restoration of depleted big game ranges (U.S. Department of Agriculture 1974) and also is a considerable value as browse on winter ranges for domestic animals (Vines 1960). Cliffrose grows in exposed, rocky situations, such as south-facing slopes and canyons in the arid Southwest. It is reported that it will withstand grazing of as much as 65% of its mass and still recover (Vines 1960).

Work on propagation of cliffrose seeds is somewhat limited. The U.S. Department of Agriculture (1974) mentions that it is not known whether pretreatment other than stratification of the seeds is necessary. Temperatures simulating daily fluctuations under field conditions of 0° to 29.5° C, and 0° to 3° C gave germinative capacities of 89 to 99%, respectively, differences which were determined not to be significant (Plummer et al. 1970). Natural seedings of cliffrose have been successful in areas such as roadcuts, gullies, south slopes, and other difficult sites, particularly in pinyon-juniper associations and on southerly exposures in the lower montane associations (U.S. Department of Agriculture 1974).

Collection and preparation.—Seeds were collected in August 1975 and 1976 from a population of the species occurring 12 miles north of Thoreau, N. Mex., on Highway 56. Collected material was allowed to dry, and seeds were then picked clean. No other pretreatment was administered.

Temperatures (°C) during 16-hour part of cycle								
40.5								
37.0		4% 17.0	4% 17.0			4% 17.0		
33.0		8% 30.0						
29.0	16% 22.5	20% 18.2	4% 13.0	24% 16.5	20% 27.0			
24.0	28% 21.0	24% 21.0	28% 12.7	40% 15.5	20% 19.4			4% 22.0
21.0	24% 20.5	28% 17.7	44% 22.0	44% 15.0	28% 7.0	16% 12.0		
17.0	24% 21.0	28% 20.0	32% 18.0	36% 21.9	44% 18.8	16% 14.5		4% 34.0
14.0	12% 30.6	16% 20.0	28% 27.0	48% 21.8	40% 20.0	20% 14.0	4% 22.0	
	14.0	17.0	21.9	24.0	29.0	33.9	37.9	40.0

Temperatures (°C) during 8-hour part of cycle

Figure 17.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Cowania stansburiana* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Test Results

Temperature response test (fig. 17).—Germination at first appeared to be only poor to fair; 48% germination was the peak response, with a mean germination time of 21.8 days. The test was conducted for 36 days before the apparatus was shut down, allowing the surface to return to room temperature. After 2 days at room temperature, all seeds that had been at constant temperatures of 14° to 17° or both alternations of 14° and 17° C germinated. The additional germination did not occur at any other positions. Subsequent testing in a growth chamber, with temperatures set at a constant 14° C for 30 days and then raised to 25° C for 2 days, resulted in 100% germination for filled seeds.

Additional tests conducted on replicates of seed stratified between moist blotter paper at 0° to 3° C for 2 months produced 80 to 100% germination of filled seed during that time period.

Experiments described by U.S. Department of Agriculture (1974) support the observations of the importance of stratification. Seeds germinated under simulated field conditions at a level of 89 to 99%. Time for germination was given as 90 days with two sets of temperature alternations, 0° to 29° C and 0° to 3° C; however, significant differences were observed between temperatures. They also state, "The length of time over which germination takes place indicates the possibility of varying embryo dormancy, and the response to temperature suggests that cold stratification may be helpful."

Moisture response test.—Because of the quantity of seed used during the previously mentioned tests, there was not enough to satisfactorily conduct a valid test on moisture stress situations.

Light response test.—No effect of either the presence or absence of light was noted on germination of seed of *C. stansburiana*.

Range.—Along dry arroyos of deserts or on rocky or gravelly lopes; central, west, and northwest Texas; usually at elevations of 3,000 to 8,000 feet; New Mexico west to California, north to Colorado, Utah, and Nevada, south to Mexico.

Past work.—*Fallugia paradoxa* is found throughout the drier reas of the Southwest. This species is an important forage plant hat, on many ranges, furnishes browse to both domestic and vild animals (U.S. Department of Agriculture 1974). *F. paradoxa* s an excellent shrub for erosion control, and for that reason has been planted in many areas of the Southwest.

Considerable ecotypic variation has been noted in the height of *F. paradoxa*, which ranges from 2 to 7 feet. Important physiological differences have also been observed in tolerance to extremes of heat and cold (U.S. Department of Agriculture 1974).

Recommendations for germination conditions vary considerably. The U.S. Department of Agriculture (1974) mentions hat 4-month-old seed from two sources germinated at 73 and 50%, respectively, when placed between moist papers and kept at 32° to 38° F (0° to 3° C) for 60 days. Vines (1960) reported 19 to 55% germination in 4 to 10 days when seed was sown in a prepared seed bed.

Collection and preparation.—Seeds were collected from a population occurring along Interstate 40, 60 miles west of Albuquerque, N. Mex., in June 1975. To select only filled, healthy seeds, all material collected was placed in the commercial seed scarifier without the abrasive surface, and allowed to rub against itself. Resultant achenes were free of pericarp and style appendages. Achenes of *F. paradoxa* less than 1 month old were used in each test.

Temperatures (°C) during 16-hour part of cycle	11.5	16.0	19.5	22.5	25.0	29.0	31.5	36.0
36.0	12% 8.0	16% 7.5						
31.5	20% 7.8	32% 7.5	36% 10.4					
29.0	72% 5.2	84% 5.4	56% 4.8	64% 6.1	36% 6.3	36% 7.3	28% 6.0	12% 6.0
25.0	84% 5.2	100% 4.3	80% 4.4	76% 4.6	68% 6.8	60% 8.2	48% 8.7	8% 9.0
22.5	96% 4.4	100% 5.1	96% 5.6	100% 4.0	76% 4.4	52% 5.0	32% 7.0	32% 6.0
19.5	80% 5.4	100% 6.2	100% 6.0	92% 5.0	52% 4.7	56% 7.4	72% 5.2	16% 8.2
16.0	100% 9.7	76% 5.7	76% 7.9	80% 7.0	96% 7.1	100% 6.0	76% 6.8	48% 9.5
11.5	60% 16.3	68% 12.0	76% 9.6	52% 8.7	100% 6.0	96% 6.5	72% 7.1	28% 9.0

Temperatures (°C) during 8-hour part of cycle

Figure 18.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Fallugia paradoxa* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Test Results

Temperature response test (fig. 18).—*F. paradoxa* germinates well in a range of temperatures from 11.5° to 22.5° C (8 hr) and 19.5° to 25° C (16 hr) with an average mean germination time of 5 days. Best germination (100%) when compared with mean germination time (4 days) was at a constant temperature of 22.5° C. Germination is adversely affected by temperatures above 31.5° C (8 hr) or 29° C (16 hr). These results compare favorably for germination time with Vines (1960), in which he states planted seed germinated in 4-10 days. Percentages observed in these tests are considerably higher than reported by the U.S. Department of Agriculture (1974) or Vines (1960), probably due to the method of cleaning in which unfilled seed was removed.

Moisture stress test.—Tests using PEG-4000 as the osmotic agent with *F. paradoxa* achenes were repeatedly unsatisfactory. Controls using water germinated well, but the variability between replicates was greater than allowed by the Association of Official Seed Analysts (1970); hence, the results of moisture stress tests have been omitted.

Light response test.—No light response was noted in tests of *F. paradoxa*.

Range.—Dry, rocky mesas or in oak woodland at elevations of 1,500 to 7,000 feet. In western Texas and New Mexico; west to California, north to Utah and Colorado and south to Mexico.

Past work.—*Menodora scabra* is a native of rocky areas and desert grasslands from 1,500 to 7,000 feet, and supplies a useful browse for livestock and game animals (U.S. Department of Agriculture 1974). Due to the nature of the habitat in which it is commonly found, *M. scabra* should readily adapt to strip-mined land, and act somewhat as a soil binder.

Literature references to seed propagation mention that good seed crops usually occur each year. In one sample, purity was 41% and soundness 98% (Vines 1960). A more recent reference mentioned that seeds apparantly need no treatment prior to germination; 70 and 99% germination was obtained in two tests of untreated seeds (U.S. Department of Agriculture 1974). The U.S. Department of Agriculture (1974) shows values of 70 and 99% in two tests of untreated seed; however, no temperature recommendations were given.

Collection and preparation.—*M. scabra* seed was collected in summer of 1975 around the Pittsburg and Midway Coal Mine, McKinley County, N. Mex. Seed, as received, was free of all chaff, and no pretreatment was administered.

Temperatures (°C) during 16-hour part of cycle	14.0	17.0	21.0	24.0	29.0	33.0	37.0	40.0
40.5								
37.0	12% 17.3	34% 17.7	10% 16.4	42% 6.9	14% 11.0	32% 7.6	10% 9.4	6% 7.0
33.0	34% 21.0	46% 14.4	48% 9.6	22% 14.8	26% 12.8	10% 7.6	20% 7.2	
29.0	40% 9.3	30% 11.9	44% 8.3	42% 8.7	40% 11.0	34% 7.1	32% 7.8	16% 4.5
24.0	46% 7.3	76% 5.6	56% 5.1	66% 8.3	36% 6.4	44% 4.6	18% 12.5	14% 6.0
21.0	56% 10.6	62% 8.1	56% 8.7	56% 7.2	22% 12.4	66% 7.6	54% 7.4	2% 9.0
17.0	66% 13.4	62% 12.0	56% 10.4	**80% 10.1**	36% 8.7	52% 14.2	70% 8.7	
14.0	16% 18.0	40% 18.0	54% 14.5	54% 10.6	34% 12.5	40% 17.2	26% 21.0	

Temperatures (°C) during 8-hour part of cycle

Figure 19.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Menodora scabra* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Test Results

Temperature response test (fig. 19).—The best germination percentages with this seed were 80% at alternating temperatures of 24% C (8 hr) and 17° C (16 hr) and 76% at 17° C (8 hr) and 24° C (16 hr). The mean germination times were somewhat different, requiring 10.1 days and 5.6 days, respectively.

This species appears quite variable in percentage of germination.

Moisture stress response tests.—Because of an apparent interaction between *M. scabra* and polyethylene glycol 4000, no germination occurred at any stress level below 0 bars.

Light response test.—No response was noted to either the presence or absence of light.

Range.—On alkaline or saline soils of dry plains and slopes of grasslands; northwestern Texas and New Mexico; west to California, north to Canada.

Past work.—A predominant plant species of the Great Basin, *S. vermiculatus* is an indicator of moist, saline, or alkaline soils (McDougall 1973). It provides valuable forage for livestock in fall and winter, but concentrated feeding on young stems and leaves has caused poisoning. Vines (1960) mentions its use as wildlife food for porcupine, jackrabbit, Zuni prairie dog, painted chipmunk, and western chipmunk.

No references were found for requirements for germination of *S. vermiculatus*.

Collection and preparation.—Seeds were collected at the Pittsburg and Midway Coal Mine, McKinley County, N. Mex., November 8, 1973. Prior to germination, the seed was rubbed to remove the membranaceous wings and destroy any empty seed.

Temperatures (°C) during 16-hour part of cycle	11.0	15.5	19.0	22.5	26.0	29.0	32.5	37.0
37.0								
32.5								
29.0			8% 2.0		4% 3.0			
26.0	20% 4.0	12% 3.6	28% 3.0	8% 4.0	2% 3.0			
22.5	24% 2.4	38% 3.2	28% 3.0	32% 6.0	44% 5.0	12% 3.0	2% 3.0	
19.0	40% 3.2	46% 4.0	38% 4.0	34% 3.0	22% 3.8	20% 4.2	8% 3.0	
15.5	84% 6.0	88% 4.5	74% 4.9	44% 5.1	40% 3.0	32% 4.0		
11.0	100% 5.5	94% 8.3	82% 5.5	56% 5.0	44% 5.4	30% 4.5	4% 5.0	2% 3.0

Temperatures (°C) during 8-hour part of cycle

Figure 20.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Sarcobatus vermiculatus* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Test Results

Temperature response test (fig. 20).—*S. vermiculatus* germinated well at only the colder temperatures. Optimum germination (100%) was at a constant temperature of 11° C, with a 5.5 day mean time; 94% germination was obtained with 15.5° C (8 hr) and 11° C (16 hr). Germination percentages dropped considerably at higher temperatures.

Moisture stress response test.—Increases in moisture stress levels appeared to have an inverse effect on germination of *S. vermiculatus* until a stress exceeding −10 bars was reached. Total percentage germination and time to reach 75% total germination for *S. vermiculatus* at seven levels of moisture stress when temperatures were maintained at 11° C (N = 3) were as follows:

Water potential (bars)	Total germination (%)	Time to reach 75% of total germination (days)
0	88cd	4
−2	98a	4
−4	99a	4
−7	96ab	4
−10	92bc	4
−13	90c	9
−16	80d	12

Time to germinate was lengthened considerably at stresses exceeding −10 bars.

Light response test.—No appreciable difference was noted in response to the presence or absence of light.

Range.—On grassy rocky slopes, sandy soils, among boulders, and on gravelly clay flats from Texas to Arizona and northern Mexico.

Past work.—A common subshrub or suffrutescent perennial in the arid Southwest, *Sphaeralcea incana* is well adapted to xeric conditions. Often found on dry, rocky slopes and around boulders, it is able to obtain moisture by plunging its thick perennial root down to regions of higher water content. Although the herbaceous upper portions of these plants die back in winter, the woody stem bases persist.

Because *S. incana* is adapted to xeric conditions and is a browse plant (Correll and Johnston 1970), this species is valuable in erosion control and possibly revegetation of strip-mined lands.

Collection and preparation.—Seeds were collected along U.S. Highway 44, 25 miles west of Albuquerque, N. Mex., in August 1975. Seeds were scarified for 3 minutes using a medium grit sandpaper. This roughening of the surface seemed to enhance germination by making the seedcoat more permeable to water.

Temperatures (°C) during 16-hour part of cycle	13.5	17.0	20.5	24.0	27.5	31.0	34.0	37.0
37.5	20% 15.0	10% 15.0		4% 8.0		4% 4.0		
34.0	4% 14.0	84% 15.1	40% 9.1	36% 8.5	44% 14.4	12% 17.0		
31.0	76% 12.6	84% 10.5	96% 8.6	84% 12.5	36% 7.3	52% 13.2	24% 7.6	24% 13.8
27.5	80% 11.0	88% 11.8	80% 8.7	96% 11.0	48% 11.0	56% 9.0	44% 10.4	24% 17.3
23.5	76% 13.4	88% 9.9	72% 8.8	92% 11.9	76% 7.9	72% 12.8	76% 10.7	44% 11.0
20.5	84% 14.6	72% 13.4	68% 10.3	100% 10.5	68% 11.5	72% 11.7	84% 11.7	68% 10.1
17.0	100% 14.3	84% 11.2	88% 13.4	100% 11.5	88% 10.7	68% 12.0	68% 11.9	44% 12.3
13.5	52% 14.3	48% 11.2	72% 13.4	68% 11.5	80% 10.7	76% 12.0	72% 11.9	72% 12.3

Temperatures (°C) during 8-hour part of cycle

Figure 21.—Percentage germination and mean day of germination for 64 cells (50 seeds each) of *Sphaeralcea incana* germinated on thermal gradient plate with an 8-hour/16-hour alternating temperature pattern. Shaded areas represent cells having 80% or higher germination.

Test Results

Temperature response test (fig. 21).—*S. incana* germinates well when alternating temperatures range from 17° to 31° C (8 hr) and 13.5° to 27.5° C (16 hr). Peak germination responses (100%) were obtained with alternating temperatures of 24° C (8 hr) and 17° to 20.5° C (16 hr), taking only 11.5 and 10.5 days to germinate.

Warmer temperatures surpressed germination, especially where temperatures were 34° C or above for 16 hours. The coolest temperatures appear to slow germination.

Moisture stress response test.—Germination of *S. incana* is affected directly by increasing moisture stress. Total percentage germination and time to reach 75% germination for *S. incana* at seven levels of moisture stress when temperatures were maintained at 23.5° C (N = 2) were as follows:

Water potential (bars)	Total germination (%)	Time to reach 75% of total germination (days)
0	83a	4
−2	72a	4
−4	42b	10
−7	30c	12
−10	5d	12
−13	0d	—
−16	0d	—

Stress of only −2 bars noticeably decreased germination. Time to germinate to 75% of the total was also affected as stress was increased.

Light response test.—No effects of either the presence or absence of light were noticeable on the germination of seed of *S. incana*.

Sabo, David G., Gordon V. Johnson, William C. Martin, and Earl F. Aldon. 1979. Germination requirements of 19 species of arid land plants. USDA For. Serv. Res. Pap. RM-210, 26 p. U.S. Dep. Agric., For. Serv., Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

A laboratory experiment revealed (1) the optimum germination temperature(s) by means of a thermal gradient plate; (2) effects of levels of moisture stress at the optimum germination temperature, and (3) reaction to the presence or absence of light in ten species of shrubs and nine species of grasses tested for indications of their suitability for strip mine reclamation.

Keywords: Strip mine reclamation, grass germination, shrub germination.

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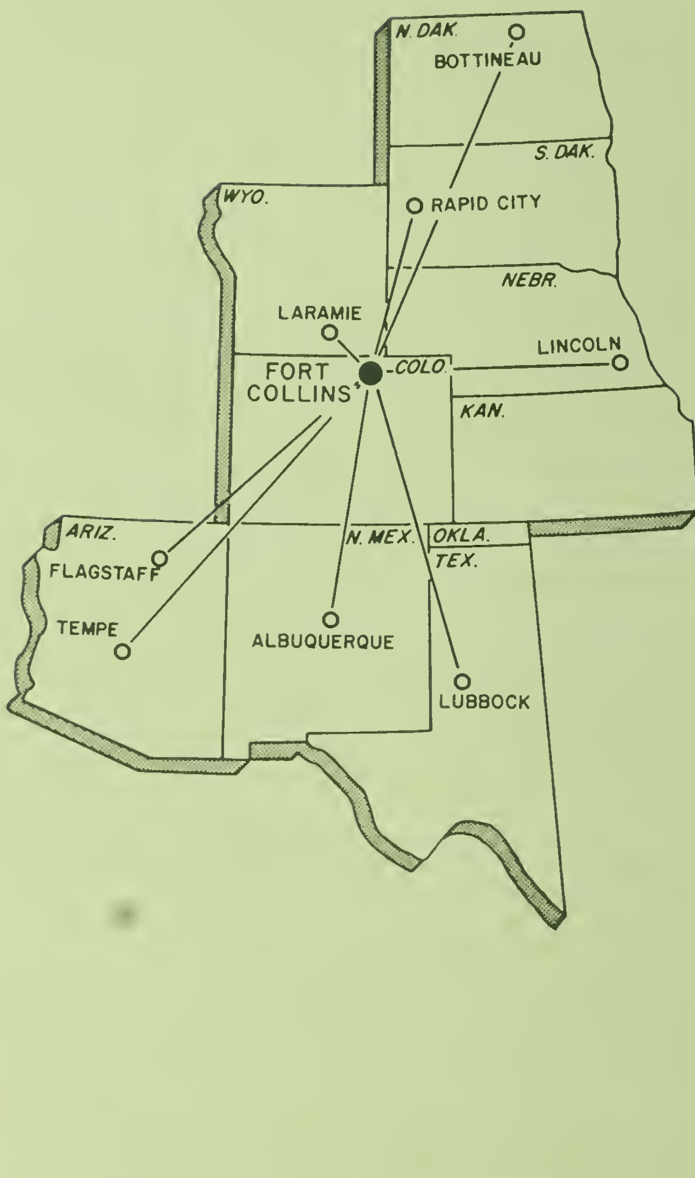

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N. MEX.
OKLA.
TEX.
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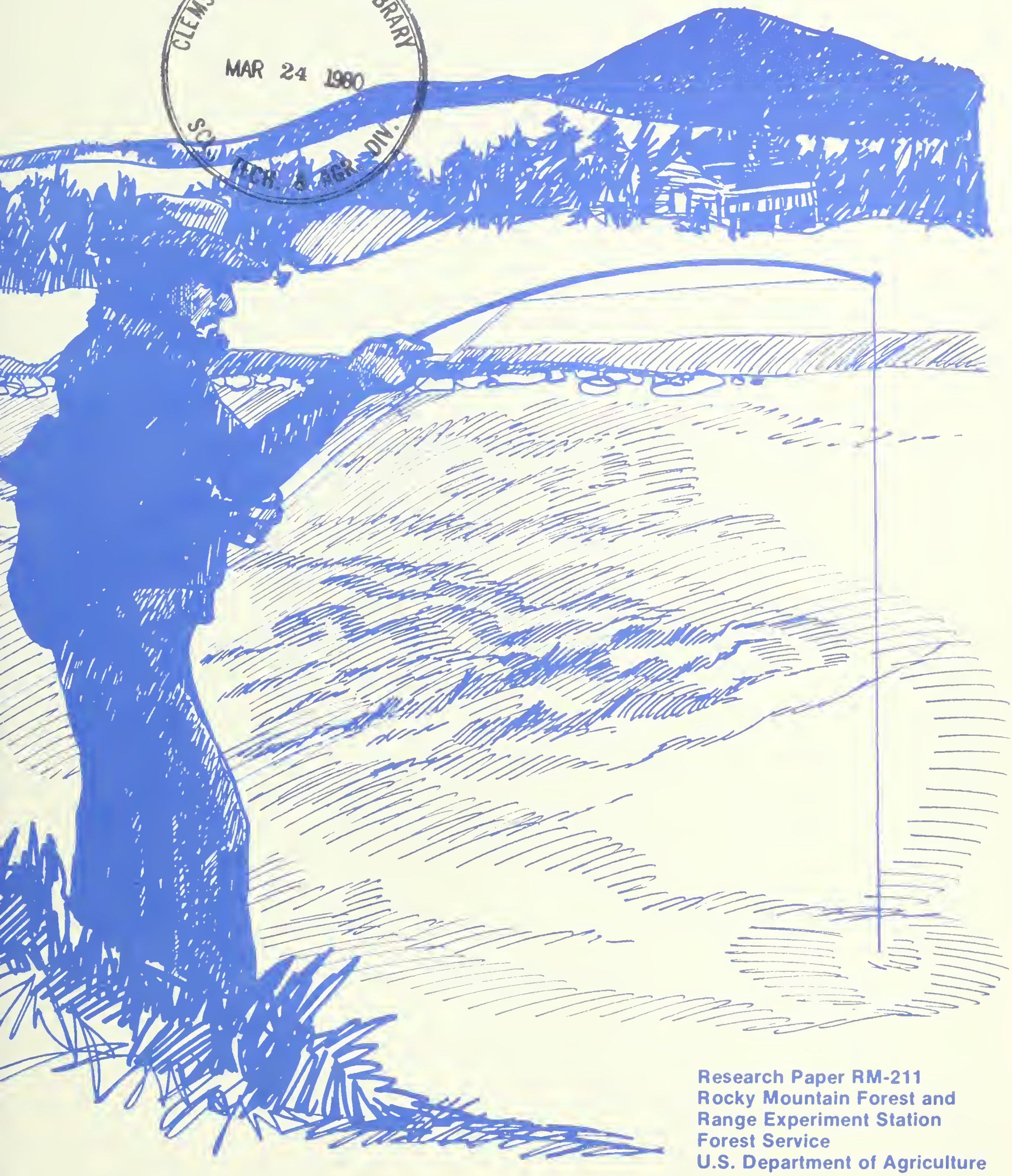
The Effect of Lake-based Recreation and Second Home Use on Surface Water Quality in the Manitou Experimental Forest

Stanley L. Ponce and Howard L. Gary



Research Paper RM-211
Rocky Mountain Forest and Range Experiment Station
Forest Service
U.S. Department of Agriculture

Abstract

Measurements during one summer indicated dispersed fishing, picnicking, and use of sealed-vault outdoor toilets did not significantly degrade water in Manitou Lake. Poor siting of four long-established second homes on private lands along a stream increased total coliform, fecal coliform, suspended solids, and orthophosphate concentrations.

Research Paper RM-211 December 1979

The Effect of Lake-based Recreation and Second Home Use on Surface Water Quality in the Manitou Experimental Forest

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Rocky Mountain Forest and Range Experiment Station[1]

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Contents

The Effect of Lake-based Recreation and Second Home Use on Surface Water Quality in the Manitou Experimental Forest

Stanley L. Ponce and Howard L. Gary

MANAGEMENT IMPLICATIONS

Mountain homes and associated road systems adjacent to a live stream in the Manitou Experimental Forest had significant impacts on water quality. The White Spruce Gulch study area showed little impact, partially because of the lack of homes in the study area, but more so because of the proper road design and placement. The results at Hotel Gulch, on the other hand, demonstrate the poor design of roads and waste disposal systems in a second home development can have a distinct impact on stream water quality, particularly during and immediately after summer rainfall events.

Land managers should pay particular attention to design and construction of second home developments. Road systems should follow topographic contours and have properly sized culverts laid along the channel grade at stream crossings. Vegetative buffer strips of adequate width should also be maintained and/or established between the road and stream channel. In addition, water bars should be placed on the road surface to direct overland flow to buffer strips. Drainage water should be diverted out of ditches at intervals short enough to prevent ditch erosion. Sewage disposal systems should be designed in relation to stream proximity and the assimilative capacity of the soil.

Good planning for future roads, home sites and protection of vegetative cover on undeveloped private land within the Manitou Experimental Forest will directly reduce surface runoff and sedimentation in live streams. Better types and placement of home waste treatment systems will also help maintain the present aquatic habitat.

INTRODUCTION

As a result of recent water quality legislation, resource managers have become increasingly concerned with the impact of land management activities on the quality of the water resource along the Front Range urban corridor in Colorado. Mountain home developments, picnic areas, and campgrounds are commonly oriented around streams and lakes, and may cause degradation of water quality. The specific objective of this study was to quantify the impact of lake-based recreation and an old second home development on surface water quality in the Manitou Experimental Forest.

PAST WORK

Outdoor Recreation

Campground recreation and day-use recreation along streams and lakes do not always have a detectable impact on water quality. The magnitude of the impact appears to be a function of the type of activities and intensity of uses.

Brickler and Utter (1975) found the most prominent source of water contamination in developed recreation areas in Arizona was sewage disposal facilities. Due to heavy use and overloading, such facilities may become sources of biological and nutrient contamination. This is important because the biological contamination can be a direct health risk to downstream users while the nutrient input may lead to eutrophication in adjacent mountain lakes or in downstream reservoirs.

Johnson and Middlebrooks (1975) reported picnicking and campground use resulted in degradation of stream quality in Utah's Wasatch Front. They found sharp increases of fecal coliform counts coincided with peak recreational use while concentration and mass flow of fecal coliforms dropped sharply at the end of the recreation season. This indicates a direct relationship between stream quality and user intensity.

Aukerman and Springer (1976), studying the Little South Fork of the Cache la Poudre River in the Central Rockies, found small increases in fecal coliform counts at areas accessible by paved roads. However, areas reached only by unpaved roads and footpaths showed no increase. Schillinger and Gordon (1976) reported similar results on the Hyalite drainage near Bozeman, Mont.

Brickler and Utter (1975) also presented general management guidelines to limit further deterioration of water quality in recreational lakes and streams in Arizona. They reported specific recreational areas and activities have individual problems, such as turbidity, nitrates, orthophosphates, and minor fecal contamination. These problems usually require management actions not universally applicable.

Recreation Home Development

Homes used for recreation or as primary residences are increasing rapidly on private lands in and near national forests. Construction, disposal of sewage, and increased recreation associated with home development may generate many types of water contaminants.

Sediment is the most prevalent water pollutant associated with recreational home development (U.S. Environmental Protection Agency 1973). Sediment comes from roads associated with development; road cuts and fills, stream crossings, road surfaces, and site clearing and grading for home construction are all potential sources of sediment (Howe 1972).

Sewage disposal systems including septic tank and leach fields are the primary source of biological contamination of waters draining mountain home developments (Howe 1972). Brickler and Utter (1975) reported bacterial contamination (fecal coliform) in groundwater resulting from a poorly designed leach field associated with a recreation area. Exceedingly high concentrations of coliform organisms have also been reported for mountain home developments in Colorado (Millon 1970,

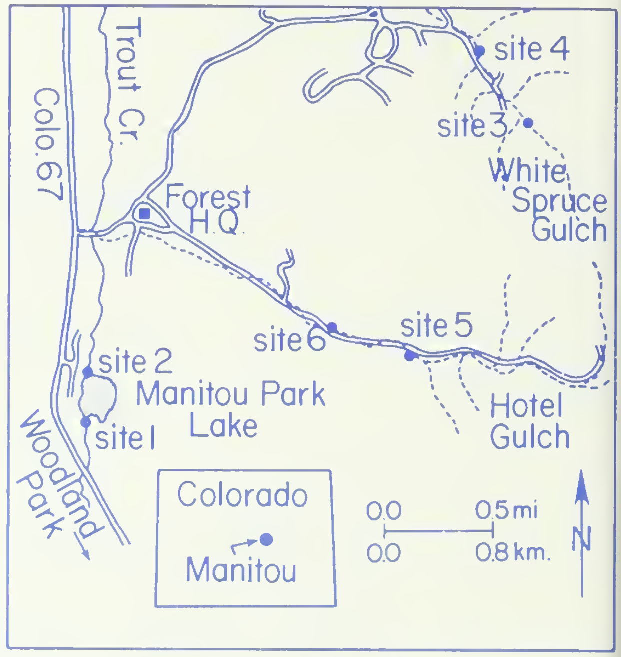

Figure 1.—Location of study sites within the Manitou Experimental Forest.

Burns et al. 1973). Wadleigh (1968) found that sewage effluent in a secluded valley of California was the main source of high nitrate concentration in groundwater.

The utility of soil for sewage treatment is dependent on many factors—including physical characteristics, such as soil texture, depth, slope, percolation rate, moisture content, and chemical and biological factors, such as pH and the presence of soil microbes (Orlob and Krone 1966, Romero 1970). However, when soil conditions are not limiting, septic tanks and leach field systems are an effective means of sewage treatment (Segall 1976).

STUDY AREA

Local Characteristics

The study area is about 45 km northwest of Colorado Springs, Colo., in the Manitou Experimental Forest on a section of Trout Creek, a major headwaters tributary of the South Fork of the South Platte River (fig. 1). This area is representative of much of the Front Range of the Colorado Rockies.

The vegetation consists principally of dense to open stands of ponderosa pine and native bunchgrasses on the drier sites and Douglas-fir on moist north aspects. Topographic features include ridges, narrow mountain valleys, and large broad parks. The valley and park soils have developed from alluvial material derived from Pikes Peak granite. These gravelly soils are highly permeable, unstable, and erode when protective plant cover is removed.

The climate is characterized by dry and cold winters and cool summers. Annual precipitation, largely rain, averages about 430 mm with about three-fourths of the total falling between April 1 and September 30. Streamflow in the study section of Trout Creek usually ranges from about 0.5 m^3 sec at the height of the spring runoff in May to less than 0.01 m^3/sec in October.[2]

The general study area was settled more than 100 years ago. Most of the easily accessible timber was logged before 1900, and the area was heavily grazed by cattle and horses until the early 1930's. In the late 1930's most of the land was transferred to the USDA Forest Service. The remaining area in private ownership has been used primarily for livestock grazing, but it is anticipated that much of this land will be developed for residential communities in the future.

Study Site Description

Manitou Lake

The effect of lake-based recreation was examined at Manitou Lake. This shallow manmade lake has about 5 ha of surface and has an earth fill dam with a concrete spillway (fig. 2). The steep slope of the dam face is well protected by rock riprap. Elevation is 2,358 m. Parking areas for vehicles are more than 60 m from the lake. There are three sets of outdoor toilets above the dam along the west bank about 75 m from the water's edge. All waste is contained in sealed vaults. The developed west shore is a heavily used picnic area, with all tables more than 25 m from the lake. Fishing is the major recreational activity. Swimming is prohibited but occurs on occasion. Recreationists have full access to the lake perimeter. Daily visitor use starting in May ranges from none during stormy weather to several hundred during peak use. Visitor use is heaviest on weekends and remains heavy until freezup in late fall.

Two sites were established to monitor the effect of recreation on the quality of the lake water. Site 1 was located immediately above the lake on Trout Creek, and site 2 was at the outlet on the spillway (fig. 2).

[2]*Unpublished data on file. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. 80526.*

Figure 2.—Manitou Lake recreational area.

Home Development

The collective effect of four second homes established 20 to 30 years ago on surface water quality was examined on an intermittent tributary to Trout Creek. Study sites were established immediately above and below a 0.6-km reach of privately owned land in Hotel Gulch (fig. 1). Site 5, above the housing, was at 2,532 m elevation; and site 6, below the housing, was at 2,462 m. The homes were in a narrow east-west oriented canyon with steep, well shaded side slopes. Tree cover is mainly old-growth Douglas-fir and aspen. The stream was perennial throughout the study, but flows are generally intermittent during July and August.

The only access through the area is an old unimproved bulldozed road 3 to 3.5 m wide. The road ranges from about 0 to 3 m above the stream and is generally less than 5 m from the stream. The road crosses the stream twice (over culverts) about halfway through the study reach. Three homes were on the south side of the creek and one on the north side. All homes were less than 15 m from the stream. Two of the homes had septic tanks and leach fields. The septic tank and leach field for one home were less than 8 m from the stream and less than 1 m above the usual stream level. Two homes had outdoor toilets. The pits, less than 15 m from the stream, were not lined or sealed and were in a rundown condition. Each of the rustic second homes were continuously occupied by two or more people during the period of study (fig. 3).

As one check on effects of home development, a section of unimpacted stream on White Spruce Gulch (private land platted for large-lot development) was also sampled to ascertain changes that may occur without development (fig. 1). Vegetation in the canyon and near the stream was similar to that in Hotel Gulch. Elevation at site 3 was 2,520 m and at the lower (site 4) 2,455 m. The horizontal distance between sites was also 0.6 km. The only development within this canyon was a 3- to 4-m-wide, good quality, gravel access road generally 10 to 15 m from the stream and one spur road to gain access to westerly facing lots located above the stream channel (fig. 4). Gravel roads like the one mentioned above may erode during intense rainstorms. The road crossed the stream three times over culverts near the center of the study reach, and once directly through the stream.

METHODS

Field Measurements

A record of daily precipitation was obtained from a recording gage at the headquarters of the Manitou Experimental Forest. Instantaneous discharge (Q) was determined using area-velocity when flow volume permitted. A pygmy-type current meter was used to measure water velocity; however, when flows on Hotel and White Spruce Gulches were very low, discharge was measured in control sections below rock-constructed waterfalls using a liter-graduated cylinder and stopwatch. Water temperature (TEMP) was measured using a laboratory-grade mercury thermometer.

Grab samples of lake or stream water were collected in sterile polyethylene bottles. The stream samples were taken in midstream and integrated over the entire depth when flow permitted. During the very low flows on Hotel and White Spruce Gulches, samples were taken from the artificial waterfalls described earlier. Water samples were immediately placed in an ice chest and refrigerated after transporting to the laboratory at the Manitou Experimental Forest headquarters. All analyses were preformed as soon as possible after collection, usually within 24 hours.

Sampling Frequency

A scheme for routine sample collection was developed to monitor two distinct periods of use: weekdays and weekends. Samples were collected every Thursday and Sunday from June 17 through October 3, 1976, at each of the six sites in order to test user intensity. At the beginning of the study, a diurnal test over a 24-hour period indicated very little change in the water quality, and it was concluded composite sampling was not necessary. As a result, single grab samples were taken at nearly the same time at each site during the routine collection. The samples were analyzed for suspended solids (SS), TEMP, orthophosphate (PO_4), total coliform (TC), and fecal coliform (FC).

Figure 3.—Rustic second home in Hotel Gulch.

Figure 4.—Graded road with berms and ditches protect the stream channel in White Spruce Gulch.

The most intensive use of Manitou Lake occurred during the July 4 holiday. This holiday period was monitored utilizing a week-long study from July 1 through 7, 1976. Grab samples were taken twice daily, in the morning at 9 a.m. and in the evening at 8 p.m. The samples were analyzed for SS, TC, and FC.

It was suspected runoff resulting from summer rainstorms would act as a major mechanism transporting pollution to the streams. Two events were sampled on Hotel Gulch only. Samples were collected as frequently as possible during the entire storm hydrograph and analyzed for SS, TC, and FC.

Laboratory Measurements

SS concentrations were determined using the nonfilterable residue procedure outlined by the American Public Health Association, Inc. (1975). High concentration of SS in stream water may kill fish and other aquatic life by causing abrasion injuries, and clogged gills and respiratory passages. Indirectly, SS may also carry and trap bacteria and decomposing organic wastes on stream bottoms which may result in oxygen depletion.

PO_4 concentration, the only phosphate form determined directly, was measured by the ascorbic acid method (American Public Health Association, Inc. 1975). Surface waters containing more than 200 $\mu g/l$ of phosphates generally indicate pollution from agricultural fertilizer runoff, water treatment plants, or leaching from septic tanks (McKee and Wolf 1963).

The presence of TC and FC was determined by the membrane filter technique (American Public Health Association, Inc. 1975). These bacteria, always present in intestinal tracts of warm-blooded animals, are eliminated in large numbers in fecal waste. They are not usually pathogenic themselves and do not generally multiply outside the intestines, but are often found in the company of intestinal pathogens affecting man and other mammals. Their presence usually indicates that intestinal waste products have reached a water source.

Water samples for bacteriological analyses were collected in sterile bottles, filtered, and prepared within 6 hours of colletion. Three levels of sample concentration were examined for each sample, 100, 10, and 1 ml.

Statistical Analyses

Two basic statistical analyses were performed. First, a measure of central tendency was made with the data collected routinely on Thursday and Sundays. The mean was calculated for SS, TEMP, and PO_4, while the median and range of counts per 100 ml were determined for TC and FC. Second, the data were tested for significance by the "t" test for paired differences. Significance referred to throughout this paper was the 5% level of probability ($p = 0.05$). Paired differences were computed for Thursday versus Sunday at each sampling site, morning versus evening during the week-long study at Manitou Lake, and upstream versus downstream at each study section over the entire study period (only Thursday and Sunday data used in this analysis), the Manitou Lake week-long study, and the storm runoff on Hotel Gulch.

RESULTS AND DISCUSSION

Manitou Lake

Although recreation user intensity varied, water quality remained virtually unchanged from Thursday to Sunday in any given week. Counts of people using the area revealed an average of 84 on Thursdays and 225 on Sundays (fig. 5). No significant difference was found for any of the parameters sampled when Thursdays (low visitor days) were compared with Sundays (high visitor days). These results suggest user intensity (within the limits examined) had little effect on water quality in Manitou Lake. These results were in contrast to those noted earlier for Utah's more heavily used Wasatch Front (Johnson and Middlebrooks 1975).

A summary of results of routine sampling for the inlet and outlet sample points is given in table 1, and figure 6 illustrates time trends of selected parameters. SS concentration for the two sites averaged about 25 mg/l. SS concentrations were highly variable in June and July, but there was no apparent correlation between discharge and SS concentration at either site (fig. 6). For the local area,

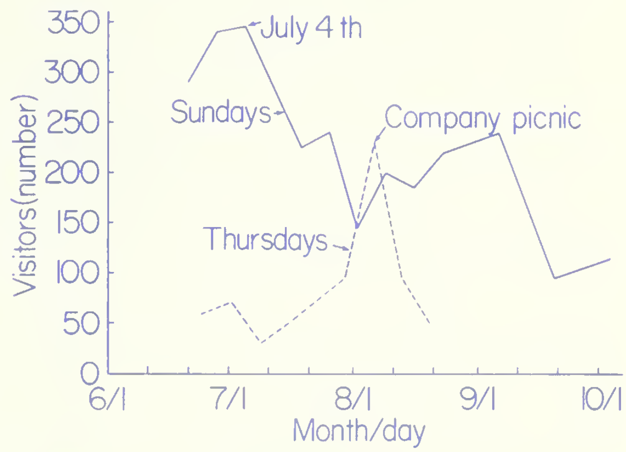

Figure 5.—Number of visitors at noon for selected Thursdays and Sundays at Manitou Lake, summer of 1976.

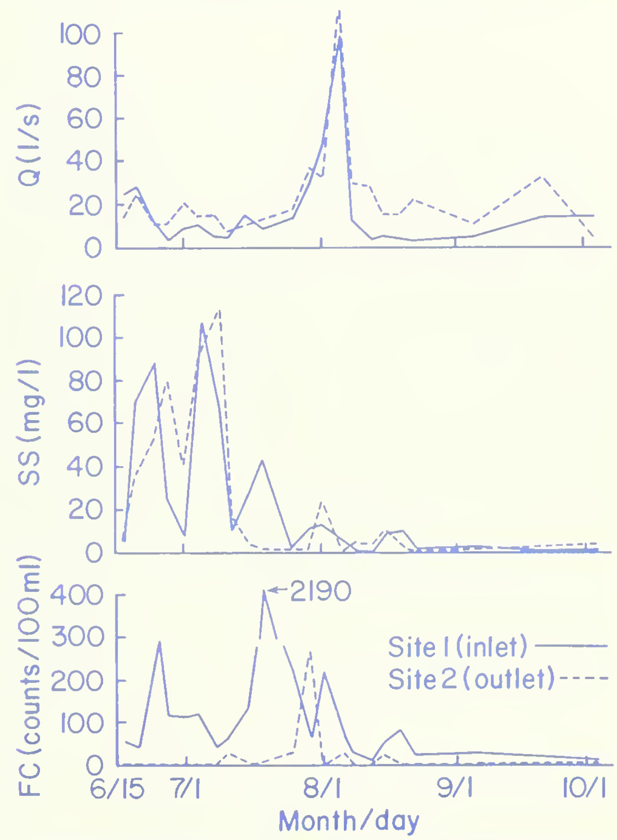

Figure 6.—Streamflow (Q), suspended solids (SS), and fecal coliform (FC) at Manitou Lake.

Table 1. Summary of routine sampling at Manitou Lake from June 17 to October 3, 1976

Site (location)	SS	TEMP	PO_4		TC	FC
	mg/l	*°C*	*µg/l*		*Counts per 100 ml*	
1 (Inlet)	Mean 24.8	17	87	Median	66	64
				range	0-2050	11-2179
2 (Outlet)	Mean 24 5	17	42	Median	13	1
				range	0-250	0-270

Table 2 Summary of daily counts of total and fecal coliform (TC and FC) bacteria at Manitou Lake from July 1 to 7, 1976

Date	Site	Morning sample TC	FC	Visitors	Evening sample TC	FC
		Counts per 100 ml		*Number at 3 p.m.*	*Counts per 100 ml*	
July 1	1	270	103	69	180	92
	2	42	1		28	1
July 2	1	75	29	30	280	220
	2	20	1		3	1
July 3	1	106	98	136	72	162
	2	4	0		23	2
July 4	1	92	120	345	24	44
	2	1	0		0	0
July 5	1	230	92	225	83	40
	2	9	0		56	7
July 6	1	258	192	29	461	88
	2	9	5		15	4
July 7	1	132	20	22	136	48
	2	14	1		39	0

annual acumulations of SS, composed mainly of organic and mineral material, are characteristically flushed out during the spring and early summer. Recreational activities at Manitou Lake apparently had no practical effect on SS concentrations.

Recreation activities around the lake and use of sealed-vault outdoor toilets also had little impact on the microbe levels in the lake. Median concentrations of FC dropped from 64 counts per 100 ml at the inlet to 1 count per 100 ml at the outlet. In the week-long study for July 1 to 7, 1976, TC and FC counts at the inlet were all significantly higher than TC and FC counts at the outlet (table 2). Effluent concentrations of FC at the outlet were continually near zero irrespective of user intensity or time of day. Visitor use above the lake ranged from about 350 people at noon on July 4 to less than 25 on July 7.

The nutrient and temperature conditions of the lake were conducive to aquatic plant growth. Average TEMP and PO_4 concentration were 17° C and 64 µg/l, respectively. Although water temperature and nutrient concentration may have caused development of algal growths observed in shallower portions of the lake, the data do not suggest the recreational use of the lake affects these two constituents appreciably. There is little difference in the average TEMP at the inlet and at the outlet (table 1), apparently because water entering the lake has been heated to its capacity. In addition, average PO_4 concentration in the effluent is less than half that in the influent. The PO_4 causing algal growth was probably derived outside the study reach and not the result of recreation use at the lake.

Mountain Home Development

White Spruce Gulch

None of the parameters monitored on this undeveloped area were significantly different in the upstream and downstream sites (table 3). Concentrations of SS were relatively low and averaged about 22 and 24 mg/l at the upstream and downstream sites, respectively. SS concentrations were highest in June in response to higher streamflow (fig. 7). High intensity summer rainstorms increased streamflow during August but did not increase SS and apparently indicated a threshold value of discharge had to be surpassed before SS were transported. The low SS concentrations during the summer also indicated few if any sediments came from the access road in White Spruce Gulch.

Hotel Gulch

Results of a paired comparison test indicated a significant difference between the upstream and downstream counts of TC and FC (table 3).

Similarly, the average concentration of SS was about 16 mg/l at the upstream site and about 22 mg/l at the downstream site (table 3). From mid-June to early July, SS were relatively high and similar trends were exhibited at both sites (fig. 8). Concentrations of SS at both sites dropped to relatively low values before the start of summer rains. After the rains began, increased sediment loading in the stream below the housing area was readily apparent, while streamflow volumes were about the same at each site.

TEMP averaged nearly 2° C higher in the downstream direction in Hotel Gulch (fig. 8), apparently in response to variable shading over the stream.

Mean PO_4 concentrations for the routine sampling were 33 µg/l at the upstream site and 43 µg/l at the downstream site (table 3, fig. 9). These concentrations were similar to those reported draining through granites by Hem (1970).

In general, the PO_4 concentration tended to respond inversely to discharge, indicating a fairly constant mass of PO_4 was delivered to the stream and probably derived from natural sources, such as rocks and soil, rather than from sewage (fig. 9). However, slightly higher levels of PO_4 downstream do not preclude a partial input from sewage.

FC concentrations were significantly higher downstream from the development (fig. 10). The median concentration was 20 counts per 100 ml at the upper site and 40 counts per 100 ml at the downstream site. This trend was different than observed for the White Spruce Gulch stream section where there is no home development. This apparently indicates contamination of stream water in Hotel Gulch, perhaps from sewage disposal. This observation was further supported by a high temporal relationship between storm runoff in midsummer and FC concentration.

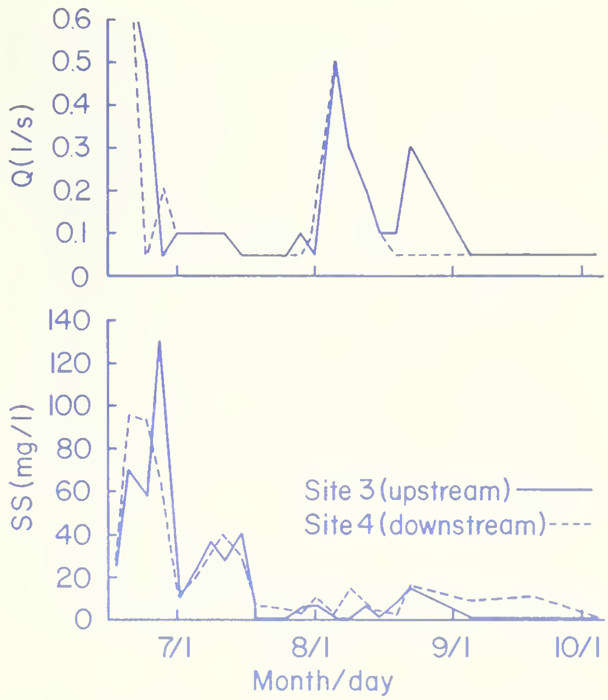

Figure 7.—Streamflow (Q) and suspended solids (SS) along an undeveloped stream section in White Spruce Gulch.

During the study, runoff from two storms was monitored at Hotel Gulch. Paired comparison tests for each storm showed significant differences in SS, TC, and FC at the upstream and downstream sites. Results of the July 18 storm are illustrated in figure 11. This storm produced 10 mm of rain in a 1-hour period. Streamflow increased substantially through the study reach. The contrast between the sharp peak observed at the downstream site and the gradual rise in discharge upstream indicates surface runoff directly into the stream.

Table 3. Summary of routine sampling for White Spruce and Hotel Gulches, June 17 through October 3, 1976

Site (location)	SS	TEMP	PO_4		TC	FC
	mg/l	*°C*	*µg/l*		*Counts per 100 ml*	
	White Spruce Gulch (undeveloped)					
3 (upstream)	Mean 21.9	6.3	32	Median	7	0
				range	0-260	8
4 (downstream)	Mean 23.5	8.0	40	Median	6	0
				range	0-68	0-72
	Hotel Gulch (developed)					
5 (upstream)	Mean 15.5	8.1	33	Median	20	0
				range	0-134	0-3
6 (downstream)	Mean 22.3	10.0	43	Median	40	3
				range	0-114	0-92

SS concentration increased with discharge in the downstream direction. SS at the upper sampling site did not exceed 102 mg/l and, in general, remained below 20 mg/l. At the downstream site, SS peaked at 2,500 mg/l. It was apparent from field observations that sediment was derived primarily from the road adjacent to the stream, and to a lesser extent, from the home sites. The stream channel apparently contributed a minor amount of sediment, as evidenced by the response of the upstream site.

A substantial increase also occurred in FC concentration at the downstream site during the storm. The concentration upstream remained near zero, while it exceeded 7,000 counts per 100 ml downstream. The high surge in FC was probably caused by flushing a detention storage carrying surface-derived FC, perhaps from the outdoor toilets.

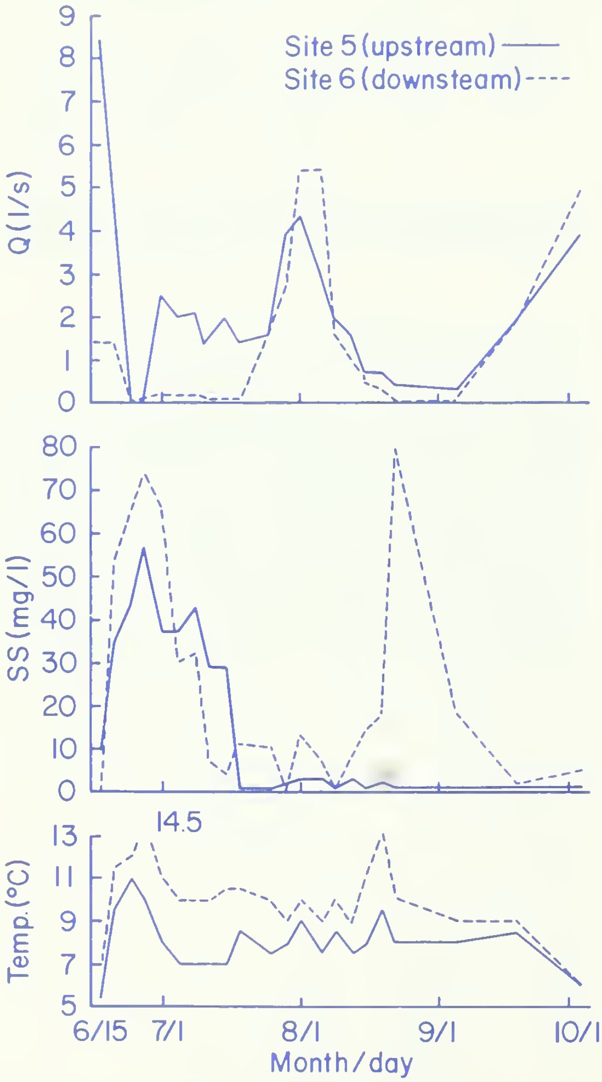

Figure 8.—Streamflow (Q), suspended solids (SS), and temperature (TEMP) along a developed stream section in Hotel Gulch.

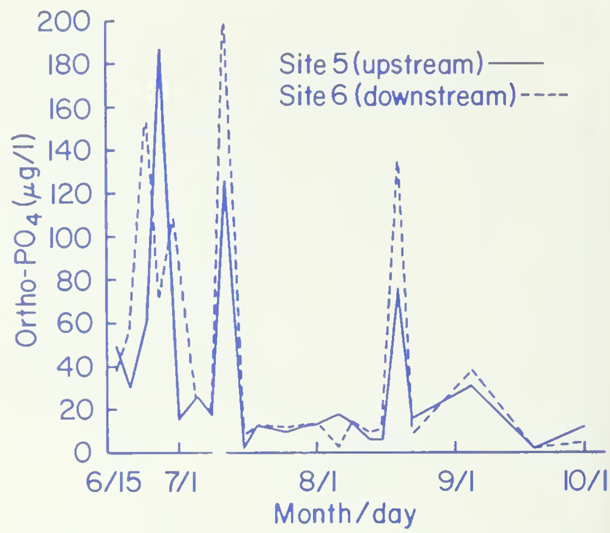

Figure 9.—Orthophosphate (PO_4) trends in Hotel Gulch.

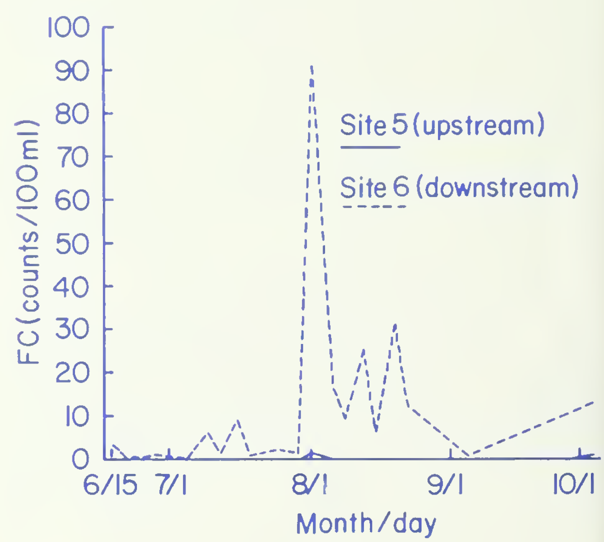

Figure 10.—Fecal coliform (FC) trends in Hotel Gulch.

Results of the July 21 storm are illustrated in figure 12. This small storm produced 5.1 mm of rain in less than 1 hour. Significant increases in the downstream direction were again observed for SS and FC. Peak runoff was nearly equal to that of the July 18 storm flow, while SS and FC concentrations were much lower. The reduction in SS and FC concentrations was apparently the result of the "flushing" action of the storm runoff occurring 3 days earlier. However, it should be noted that even though the pollutant concentration was lower, the home development was the apparent major source of the stream water contamination.

CONCLUSIONS

Recreational use at Manitou Lake did not significantly degrade water quality for the one season of study, based on the water constituents examined. In fact, water quality improved as the water passed through the lake. FC and SS concentrations were all reduced substantially, while the other constituents sampled remained relatively unchanged.

Several differences in water quality directly related to land use were noted between developed and undeveloped study areas on Hotel Gulch and White Spruce Gulch. SS concentration was slightly greater at the developed area. This was apparently caused by increased sedimentation from road cut material cast near the stream channel and close siting of homes near the stream channel.

TC and FC densities were the most sensitive indicators to characterize land use differences. These bacteriological parameters increased significantly as water moved through the inhabited Hotel Gulch study area, while little change was noted in the undeveloped White Spruce Gulch study area.

Home development had the greatest impact on stream water quality during and immediately following rains. The hydrograph at the downstream site in Hotel Gulch illustrated a much more rapid response to precipitation than the upstream station. SS rose from near zero to several thousand mg/l while similar results were observed for FC. The majority of runoff and sediment was derived from the road and surface flow from bare and disturbed areas around the home sites. Increased FC probably resulted from increased surface runoff around the homes and, perhaps, contamination by sewage.

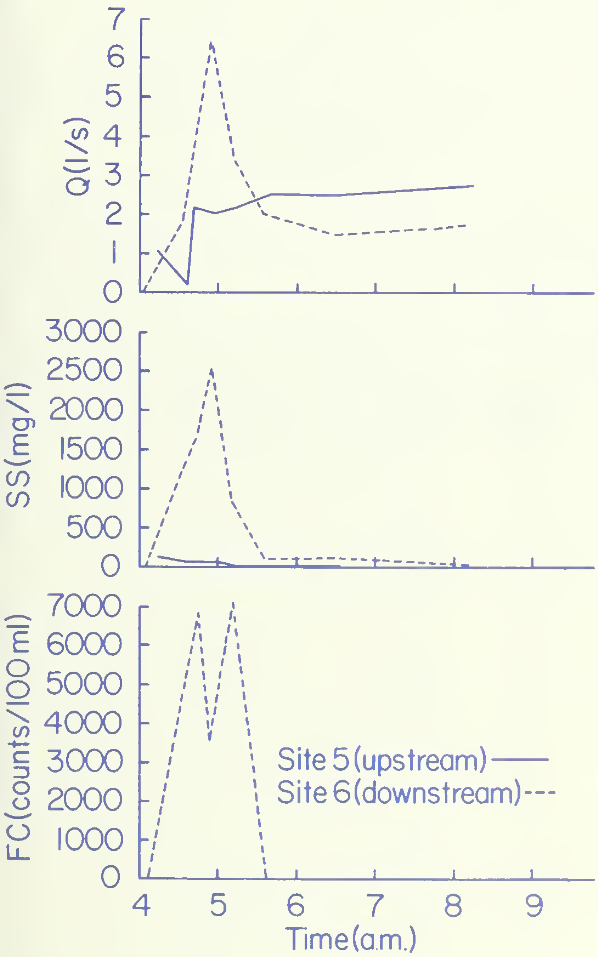

Figure 11.—Streamflow (Q), suspended solids (SS), and fecal coliform (FC) on July 18, 1976, in Hotel Gulch.

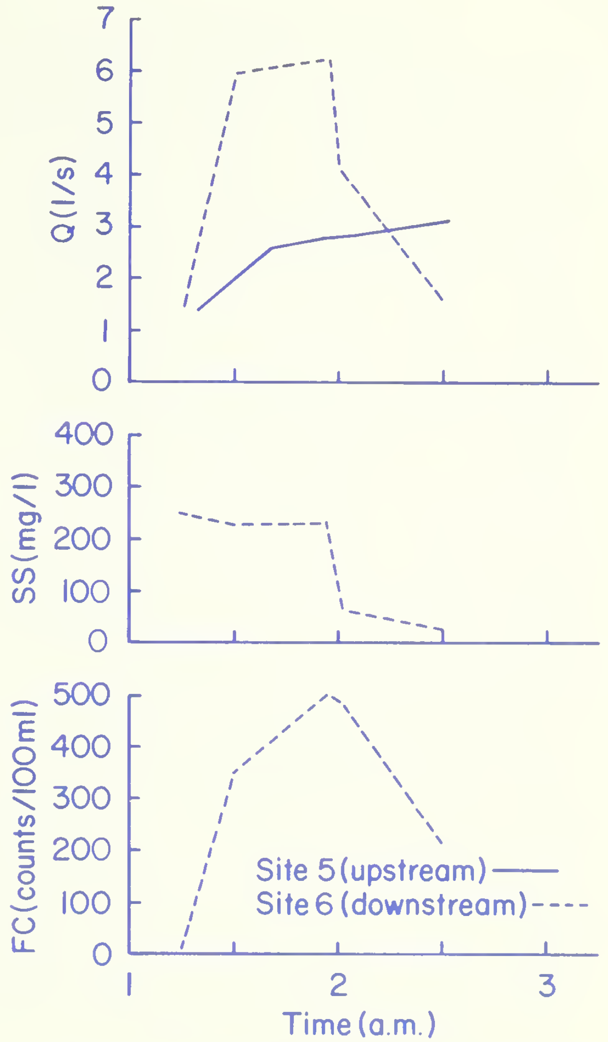

Figure 12.—Streamflow (Q), suspended solids (SS), an fecal coliform (FC) on July 21, 1976, in Hotel Gulch.

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Measurements during one summer indicated dispersed fishing, picnicking, and use of sealed vault outdoor toilets did not significantly degrade water in Manitou Lake. Poor siting of four long-established second homes on private lands along a stream increased total coliform concentrations, fecal coliform concentrations, suspended solids, and orthophosphate.

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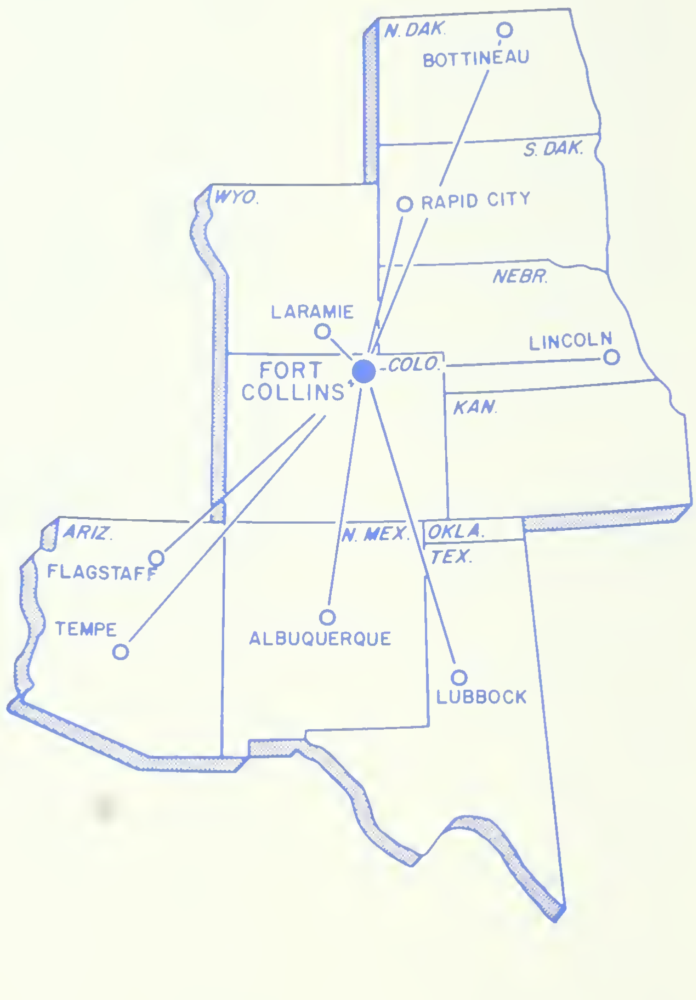
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Effects of Harvesting Ponderosa Pine on Nongame Bird Populations

Robert C. Szaro and Russell P. Balda

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Rocky Mountain Forest and
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U.S. Department of Agriculture

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Effects of Harvesting Ponderosa Pine on Nongame Bird Populations

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and

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Abstract

Bird species diversity and species richness in the ponderosa pine forest were not significantly affected by forest cutting and logging except on the clearcut plot. Bird population densities were significantly increased on the silviculturally cut and irregular strip shelterwood plots and were significantly decreased on the severely thinned and clearcut plots. Guidelines are recommended that will allow substantial logging of the ponderosa pine forest while still maintaining bird density, diversity, and species richness.

[1]*Central headquarters maintained at Fort Collins in cooperation with Colorado State University. Szaro is at the Station's Research Work Unit at Tempe in cooperation with Arizona State University. Study was conducted under graduate program at Northern Arizona University.*

Effects of Harvesting Ponderosa Pine on Nongame Bird Populations

Robert C. Szaro and Russell P. Balda

Management Implications

The forest manager can remove between one-sixth and two-thirds of the available foliage of the ponderosa pine forest either in strips (and probably in blocks) or by thinning without detrimentally affecting the breeding bird community in terms of species richness, density, and diversity. Increased densities on silviculturally cut and irregular strip shelterwood plots are probably at least partially due to openings (MacArthur et al. 1962; Marshall 1957, 1963). However, forest treatments must consider that the quality of the bird community on cut and control areas are not equal. Species found on the control plot, such as the hermit thrush, red-faced warbler, western flycatcher, and pygmy nuthatch, are replaced on the cut areas by species such as the western wood pewee, yellow-rumped warbler, and rock wren.

When forests are managed for tree and/or water yield, some specific guidelines can be followed to minimize the impact of habitat modification on bird populations. To simply state that foliage volume can be reduced by one-sixth to two-thirds is of little real significance to forest managers. Foliage volume is important to the birds because it is related to the resource base but is difficult and time consuming to measure. Therefore, to maintain and/or increase (by up to 35%) ponderosa pine forest bird populations, the following guidelines are recommended:

1. The total basal area of a given stand can be reduced by 15% to 50%. However, large-scale removal should be in strips or blocks. In a uniform thinning operation, consider removing only 30% of the total basal area.
2. Remove no more than 45% of those trees with a d.b.h. of 9 inches or greater. Leave a minimum of 32 trees per acre.
3. Remove no more than 75% of those trees with a d.b.h. between 6 and 9 inches. Leave a minimum of 17 trees per acre.
4. Remove 80% of the trees with a d.b.h. between 3 and 6 inches leaving approximately 25 trees per acre.
5. Gambel oak should not be removed at all. If absolutely necessary, remove no more than 25% of the oaks.
6. Several overmature trees per acre should be left to allow for adequate snag recruitment.
7. Snags should be left as nesting and roosting sites for cavity nesters. Balda (1975) suggests 2.6 snags per acre.

These guidelines are based on a comparison between the control plot and the silviculturally cut and the irregular strip shelterwood plots.

Introduction

Avian ecologists have long been interested in relating breeding bird populations to the vegetation of an area (Beecher 1942, Johnston and Odum 1956, Bond 1957). As the structure of a habitat becomes more complex, the number of different bird species increases (Karr 1968, MacArthur and MacArthur 1961, MacArthur et al. 1966, Recher 1969). The population density of blackburnian warblers[2] and myrtle warblers appears to be closely correlated with foliage volume (MacArthur 1958). Moreover, foliage volume may be an important factor limiting the densities of parula warblers and nuthatches (Balda 1969, Morse 1967). Data by Balda (1969) strongly suggest that removing tall ponderosa pines (40 to 70 feet) may have a negative effect on the density of Grace's warblers; whereas the removal of the understory may reduce the populations of the gray-headed junco and the chipping sparrow.

Bird population densities in a particular habitat are believed to be regulated by many factors. Any alteration of that habitat may affect the suitability of the habitat for a given species' niche requirements. This study examined effects of timber management practices on bird populations and ways these practices can be used to manage nongame bird populations.

[2]Common and scientific names of all birds and trees referred to in this paper are listed in the appendix.

Study Areas

Five study plots were chosen in relatively homogeneous stands of ponderosa pine with a buffer around the periphery of at least 330 feet. Study plots contained about the same proportions of different size classes of trees and density of Gambel oak. All study areas were set up as 35-acre plots except for the study area on the clearcut watershed, which encompassed 100 acres.

The five study areas are in the Coconino National Forest, Coconino County, Arizona. All the areas are located within a 13-mile radius on the Beaver Creek Watershed. The areas included a clearcut, a severely thinned, an irregular strip shelterwood, a silviculturally cut (individual tree selection), and a control plot. All study sites were cut before the study began except for the silviculturally cut area, which was cut during the spring of 1974.

The ponderosa pine vegetation type, which was found on all study areas before treatment, is found primarily in areas of brolliar, siesta, and sponsellar soils (Williams and Anderson 1967).

Control Plot

The control is located on watershed 13 approximately 41 miles southeast of Flagstaff at an elevation of 7,200 feet. The study area is on a southwest-facing slope of about 17°, in the west-central portion of the 368-acre watershed.

Watershed 13 was left untreated as the control area. Ponderosa pine was the dominant tree species with an importance value of 253 (table 1). There were approximately 262 trees per acre with a canopy volume of 276,800 cubic feet per acre and a total basal area of 116.3 square feet per acre. Of the trees of the plot, 78% had a d.b.h. of 9 inches or smaller (table 2). In fact, the control plot had 3.7 times as many trees with a d.b.h. between 3 and 6 inches than any other study plot (table 2).

Silviculturally Cut Plot

The silviculturally cut plot is located on watershed 8, approximately 39 miles southeast of Flagstaff at an elevation of 7,400 feet. The study area is on a west-facing slope of about 13°, in the southwest corner of the 1,800-acre watershed.

The prescription called for stands made up of trees smaller than 10 inches d.b.h. to be thinned to a growing stock level of 60 square feet per acre of basal area.[3] Stands consisting of trees 12 inches d.b.h. and larger were thinned to an actual 70 square feet per acre of basal area. Trees were cut to upgrade the stand rather than to obtain uniform spacing. In most cases, Gambel oak were left intact.

The treatment was completed in early spring 1974; ponderosa pine was the major dominant tree species with an importance value of 263.4 (table 1). There were approximately 96 trees per acre with a canopy volume of 243,500 cubic feet per acre. This amounted to a reduction of 28.9% in the available foliage. The total basal area for all tree species was 101.5 square feet per acre.

Irregular Strip Shelterwood Plot

The irregular strip shelterwood cut plot is located on watershed 14, approximately 42 miles southeast of Flagstaff, at an elevation of 7,050 feet. The study area is on a south-facing slope of about 9°, in the southeast corner of the 546-acre watershed.

The objective of the treatment was to increase water yield while at the same time providing good timber production and pleasing esthetics (Brown et al. 1974). Clearcut strips were designed primarily to increase streamflow. The alternative "leave" strips were thinned to improve production.

The pattern was one of alternate cut and leave strips. The cut and leave strips averaged 60 and 120 feet in width, respectively. Irregular-shaped spacers of uncut trees, 50 to 70 feet long, at intervals of about 400 feet, were left in the cut strips to break up the visual continuity. Most of the Gambel oak were left in the cut strips; where there was enough oak to break up the continuity of the strips it was not necessary to use spacers. Width of the clearcut area within any strip varied as much as 50% (i.e., 120 ± 60 feet) to provide an esthetically pleasing, irregular pattern of elongated openings.

The treatment was completed in spring 1970. Ponderosa pine was the dominant tree species with an importance value of 228.2 (table 1). There were approximately 74 trees per acre with a canopy volume of 92,700 cubic feet per acre and a total basal area of 54 square feet per acre.

Severely Thinned Plot

The severely thinned plot is located on watershed 17, approximately 27 miles south of Flagstaff at an elevation of 6,860 feet. The study area is on

[3]*Personal communication with Fred Larson, Research Forester, USDA Forest Service, Flagstaff, Ariz.*

Table 1.—Composition of trees on all forested study areas

Species	Relative density	Relative dominance	Relative frequency	Importance value	Absolute density	Total foliage volume
	(percent)	*(percent)*	*(percent)*	*(index)*	*(trees per acre)*	*(ft³/acre)*
Control						
Ponderosa pine	90.1	85.7	77.0	252.8	236	234,900
Gambel oak	8.4	8.3	19.3	36.0	22	28,700
Alligator juniper	1.5	6.0	3.7	11.2	4	13,200
Silviculturally cut						
Ponderosa pine	91.5	92.5	79.4	263.4	88	202,500
Gambel oak	8.5	7.5	20.6	36.6	8	41,000
Irregular strip shelterwood						
Ponderosa pine	79.1	82.0	67.1	228.2	59	62,000
Gambel oak	20.4	15.7	31.5	67.6	14	30,300
Alligator juniper	0.5	2.3	1.4	4.2	1	400
Severely thinned						
Ponderosa	86.8	91.9	74.3	253.0	24	48,500
Gambel oak	13.2	8.1	25.7	47.0	4	8,600

Table 2.—Tree size distribution on all forested study areas (trees per acre)

Area	3-6 inches d.b.h.	Percent control	6-9 inches d.b.h.	Percent control	Over 9 inches d.b.h.	Percent control	Absolute density	Percent control
Control	135.5	----	68.1	----	58.4	----	262	----
Silviculturally cut	36.7	27.1	15.5	22.8	43.8	75.0	96	36.6
Irregular strip shelterwood	24.9	18.4	17.2	25.3	31.9	54.6	74	28.2
Severely thinned	6.2	4.6	9.0	13.2	12.8	21.9	28	10.7

a southwest-facing slope of about 8°, in the southwest corner of the 121-acre watershed.

Treatment was intended to provide a reasonable opportunity for increased water yield while leaving a lightly stocked timber stand that could be subjected to even-aged management (Brown et al. 1974). Slash was piled in strategically arranged windrows. Windrows were piled as high and narrow as possible to maximize snow trapping and retention. Windrows were arranged with 30-foot breaks at intervals of 200 feet or less to reduce possible fire spread.

Treatment was completed in spring 1969. Ponderosa pine was the dominant tree species with an importance value of 253 (table 1). There were approximately 28 trees per acre with a canopy volume of 57,100 cubic feet per acre and a total basal area of 22.2 square feet per acre.

Clearcut Study Plot

The clearcut plot is located on watershed 12, approximately 43 miles southeast of Flagstaff at an elevation of 7,040 feet. The study area is on a southwest-facing slope of about 10°, in the southeast corner of the 200-acre watershed.

The treatment was designed to test the effects of clearcutting all the woody vegetation on the watershed and windrowing the resultant slash (Brown et al. 1974). All wood products that could be sold were removed from the watershed. The remaining slash and debris were machine windrowed in such a way as to trap and retain snow, reduce evapotranspiration losses, and increase the drainage efficiency of the watershed. In areas of heavy slash, the windrows were at least 5 feet high and were spaced about 100 feet apart. In areas of lighter slash, the windrows were spaced further apart to achieve the minimum height. Windrows were placed in either an east-west or northeast-southwest direction.

The treatment was completed in spring 1967. Since that time, there has been considerable shrubby growth by Gambel oak next to the slash windrows.

Methods and Materials

Tree measurements were made on all plots except the clearcut site. The plotless point-quarter method (Cottam and Curtis 1956) was used to sample trees with a d.b.h. of 3 inches or larger. A grid composed of 104 points (416 trees) was sampled on each plot. These data were then analyzed using the standard formulas of Cottam and Curtis (1956) to obtain the following: absolute density, relative dominance, relative frequency, relative density, and importance value. The following additional data were also recorded for the trees sampled at each point: total tree height, height from the ground to the lowest live limb, and outer crown diameter at the lowest live limb. Tree crowns were classified as conical, cylindrical, or hemispherical. Tree crown data were then analyzed and expressed in terms of foliage (or crown) volume.

Breeding bird counts were made during the 1974 and 1975 breeding seasons using the spot-map method described by Kendeigh (1944). Ten censuses were taken each year on each study site. Population densities were averaged for the 2-year period to eliminate effects of climatic fluctuations.

Species diversity (H′) (Shannon and Weaver 1948) was calculated on the mean densities for all plots by the following formula:

$$H' = -\Sigma P_i \ln (P_i)$$

where P_i is the proportion of a given bird species present. Evenness (E) was calculated by the following:

$$E = H'/\ln S$$

where S is the number of species present (richness).

Bird Community Composition

The effects of habitat alteration on species composition and densities have been examined in areas where the habitat was altered by logging (Hagar 1960; Kilgore 1971; Lack 1933, 1939; Lack and Lack 1951), burning (Blackford 1955, Bock and Lynch 1970, Marshall 1957) and other means (Karr 1968, Yeager 1955). The effects of the various treatments on the breeding bird communities of the clearcut, severely thinned, irregular strip shelterwood, and silviculturally cut plots were pronounced (table 3). The openings made by cutting led to an increase of those species which appear to require a more open habitat (rock wren, robin, western wood pewee, and yellow-rumped warbler) and a decrease or elimination of those species which appear to require dense foliage (western flycatcher, red-faced warbler, hermit thrush, black-headed grosbeak, and pygmy nuthatch). Cutting the irregular strip shelterwood and silviculturally cut sites increased population density and slightly changed species composition when compared to the control site.

These results tend to contradict the idea that the greatest bird species diversity and population densities are in the climax forest (Johnston and Odum 1956, Karr 1968, Kendeigh 1948, Shugart and James 1973). Studies have shown that population densities were highest in intermediate stands (Bond 1957, Kendeigh 1946). Karr (1968) noted a decline in species richness and density in the last forest stage in Illinois. The impact of fire on vegetation and, in turn, on breeding bird populations was studied in chaparral (Lawrence 1966), in pine-oak woodland (Marshall 1963), and in ponderosa pine (Lowe et al. 1978). The more open habitat produced by burning in both vegetative types led to an increase in numbers of species and density with some changes in species composition. A significant increase in bird species richness and abundance followed logging in the Douglas-fir region of northwestern California (Hagar 1960) and in a giant sequoia forest of northern California (Kilgore 1971). Similarly, the cutting and/or logging of the habitat in the ponderosa pine forest increased bird population densities and altered species composition.

Bird pairs on all the treated plots except the clearcut site were more highly packed (the average amount of foliage volume per average pair of birds was smaller) than bird pairs on the control plot. Pair packing on the severely thinned plot was 67,800 cubic feet per pair, whereas on the irregular strip shelterwood plot there was 64,200 cubic feet of foliage per pair. In contrast, on the control site, there was 251,400 cubic feet of foliage per pair, and on the silviculturally cut site, there was 140,300 cubic feet of foliage per pair. On the severely thinned plot, bird pair packing was higher than on the control site because of the great reduction in foliage which was not accompanied by a proportional decrease in population density. In fact, on the irregular strip shelterwood plot, not only was the amount of available foliage reduced by two-thirds, but the densities increased as well, resulting in much higher pair packing. Birds on both these heavily treated watersheds might come into greater potential competition with each other.

Bird pairs on both the severely thinned and the irregular strip shelterwood plots were equally packed, suggesting that approximately 65,000 cubic feet of foliage is the minimum required by a given pair. If the bird community on the control

Table 3.—Breeding bird composition of the study areas (2 year average pairs per 40 ha)

Species	Control	Silviculturally cut	Irregular strip	Severely thinned	Clearcut
Pickers and gleaners					
Mountain chickadee (CD)	5.3	5.3	4.5	0.8	----
Pygmy nuthatch (CD)	14.3	16.5	6.0	1.9	----
House wren (CD)	----	----	3.0	----	----
Solitary vireo (FN)	3.0	6.0	9.0	6.0	----
Yellow-rumped warbler (FN)	1.5	12.0	3.0	1.5	----
Grace's warbler (FN)	9.0	19.1	14.3	6.8	----
Red-faced warbler (GN)	3.0	----	----	----	----
Western tanager (FN)	1.5	5.6	3.0	----	----
Hepatic tanager (FN)	----	----	1.5	----	----
Guild Density	37.6	64.5	44.3	17.0	----
Ground feeders					
Robin (FN)	----	3.0	5.3	3.8	0.5
Rufous-sided towhee (FN)	----	----	----	----	6.9
Chipping sparrow (FN)	2.3	6.0	9.0	4.5	----
Mourning dove (FN)	3.0	1.5	----	5.3	----
Rock wren (GN)	----	----	7.2	4.5	5.0
Hermit thrush (GN)	1.9	0.4	----	----	----
Gray-headed junco (GN)	15.0	18.8	11.3	6.4	1.8
Guild Density	22.2	29.7	32.8	24.5	14.2
Hammerers and tearers					
Common flicker (CD)	3.0	3.0	3.4	3.0	0.8
Hairy woodpecker (CD)	3.0	3.0	4.5	2.3	----
Acorn woodpecker (CD)	----	----	----	3.0	----
White-breasted nuthatch (CD)	6.8	11.3	10.5	7.5	----
Steller's jay (FN)	7.5	4.5	5.3	5.3	----
Black-headed grosbeak (FN)	3.3	3.0	1.5	----	----
Guild Density	23.6	24.8	25.2	21.1	0.8
Aerial feeders					
Western flycatcher (CD)	4.9	4.2	----	----	----
Western wood pewee (FN)	----	2.3	9.0	3.0	----
Say's phoebe (FN)	----	----	1.5	----	----
Violet-green swallow (CD)	8:3	8.3	3.0	----	----
Western bluebird (CD)	4.5	7.9	13.5	5.8	----
Mountain bluebird (FN)	----	----	----	----	0.5
Broad-tailed hummingbird (FN)	6.0	4.1	12.0	9.8	----
Common nighthawk (GN)	3.0	1.5	3.0	3.0	----
Guild Density	26.7	28.3	42.0	21.6	0.5
Nesting guilds					
Cavity and depression (CD)	50.1	59.5	48.4	24.3	1.3
Foliage nesters (FN)	37.3	67.1	74.4	46.0	12.4
Ground nesters (GN)	22.7	20.7	21.5	13.9	1.8
Total density	110.1	147.3	144.3	84.2	15.5
Diversity (H′)	2.83	2.80	2.94	2.81	1.35
Evenness	0.93	0.91	0.94	0.96	0.69
Richness	21	22	23	19	7

plot was as highly packed as that on the severely thinned plot, it should support approximately 425 pairs per 100 acres. Since foliage volume does not appear to be the limiting factor, then factors such as territoriality, food supply, and lack of openings or other habitat configurations may limit bird populations.

The foraging and nesting guilds were variously affected by forest cutting and logging (table 3). The pickers and gleaners and the ground feeders increased in population density on the silviculturally cut and irregular strip shelterwood plots. The aerial feeders increased by 57% on the irregular strip shelterwood plot in response to the open strip areas, whereas the hammerers and tearers remained relatively stable on all the forested watersheds. All the foraging guilds, except for the ground feeders, were virtually eliminated from the clearcut plot. The cavity and depression nesters and ground nesters greatly decreased in population density on the severely thinned plot, whereas the foliage nesters greatly increased in population density on the silviculturally cut and irregular strip shelterwood plots. Interestingly, the majority of the ground feeders on the clearcut plot were also foliage nesters. These birds used the Gambel oak saplings that were growing throughout the area for nesting substrate. The cavity nesters which also use cavities for roosting comprised between 60% and 94% of the wintering bird community (Szaro 1976).

Eleven species (solitary vireo, pygmy nuthatch, Grace's warbler, white-breasted nuthatch, common flicker, hairy woodpecker, steller's jay, gray-headed junco, chipping sparrow, broad-tailed hummingbird, and western bluebird) were present on all the forested plots during the study. The common nighthawk was observed on all areas in 1975 but was not found on the silviculturally cut plot in 1974. Several species increased their density in their typical habitat (the foliage) on the treated plots. Of the species found on all the forested plots, eight (all but the common flicker, hairy woodpecker, and pygmy nuthatch) had their highest population densities on treated plots indicating density increases in response to openness. In contrast, population densities of five species (red-faced warbler, pygmy nuthatch, western flycatcher, violet-green swallow, and black-headed grosbeak) were significantly reduced with heavy alteration of the habitat. The rock wren, robin, and western wood pewee bred only on treated plots, whereas the acorn woodpecker was found exclusively on the severely thinned plot. These species probably required the increased openness of the habitat. The common flicker, hairy woodpecker, and steller's jay maintained relatively stable densities on both the control and treated plots.

Bird species diversity and species richness in the ponderosa pine forest were not significantly affected (based on an importance criterion of at least a 15% difference) by treatment except on the clearcut plot. Bird population densities were significantly increased by forest cutting on the silviculturally cut and irregular strip shelterwood plots and were significantly decreased on the severely thinned and clearcut plots. For a more detailed description of treatment and climatic effects see Szaro (1976).

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Appendix

Bird Common and Scientific Names

Common name	Scientific name
Mourning dove	*Zenaida macroura*
Common nighthawk	*Chordeiles minor*
Broad-tailed hummingbird	*Selasphorus platycercus*
Common flicker	*Colaptes auratus cafer*
Acorn woodpecker	*Melanerpes formicivorous*
Hairy woodpecker	*Picoides villosus*
Say's phoebe	*Sayornis saya*
Western flycatcher	*Empidonax difficilis*
Western wood pewee	*Contopus sordidulus*
Violet-green swallow	*Tachycineta thalassina*
Steller's jay	*Cyanocitta stelleri*
Mountain chickadee	*Parus gambeli*
White-breasted nuthatch	*Sitta carolinensis*
Pygmy nuthatch	*Sitta pygmaea*
House wren	*Troglodytes aedon*
Rock wren	*Salpinctes obsoletus*
American robin	*Turdus migratorius*
Hermit thrush	*Catharus guttatus*
Western bluebird	*Sialia mexicana*
Mountain bluebird	*Sialia currucoides*
Solitary vireo	*Vireo solitarius*
Yellow-rumped warbler	*Dendroica coronata auduboni*
Grace's warbler	*Dendroica graciae*
Red-faced warbler	*Cardellina rubrifrons*
Western tanager	*Piranga ludoviciana*
Hepatic tanager	*Piranga flava*
Black-headed grosbeak	*Pheucticus melanocephalus*
Gray-headed junco	*Junco caniceps*
Rufous-sided towhee	*Pipilo erythrophthalmus*
Chipping sparrow	*Spizella passerina*

Tree Common and Scientific Names

Common name	Scientific name
Ponderosa pine	*Pinus ponderosa*
Alligator juniper	*Juniperus deppeana*
Gambel oak	*Quercus gambellii*

Szaro, Robert C., and Russell P. Balda. 1979. Effects of harvesting ponderosa pine on nongame bird populations. USDA For. Serv. Res. Pap. RM-212, 8 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Bird species diversity and species richness in the ponderosa pine forest were not significantly affected by forest cutting and logging except on the clearcut plot. Bird population densities were significantly increased on the silviculturally cut and irregular strip shelterwood plots and were significantly decreased on the severely thinned and clearcut plots. Guidelines are recommended that will allow substantial logging of the ponderosa pine forest while still maintaining bird density, diversity, and species richness.

Keywords: *Pinus ponderosa*, timber harvesting, nongame birds, wildlife management.

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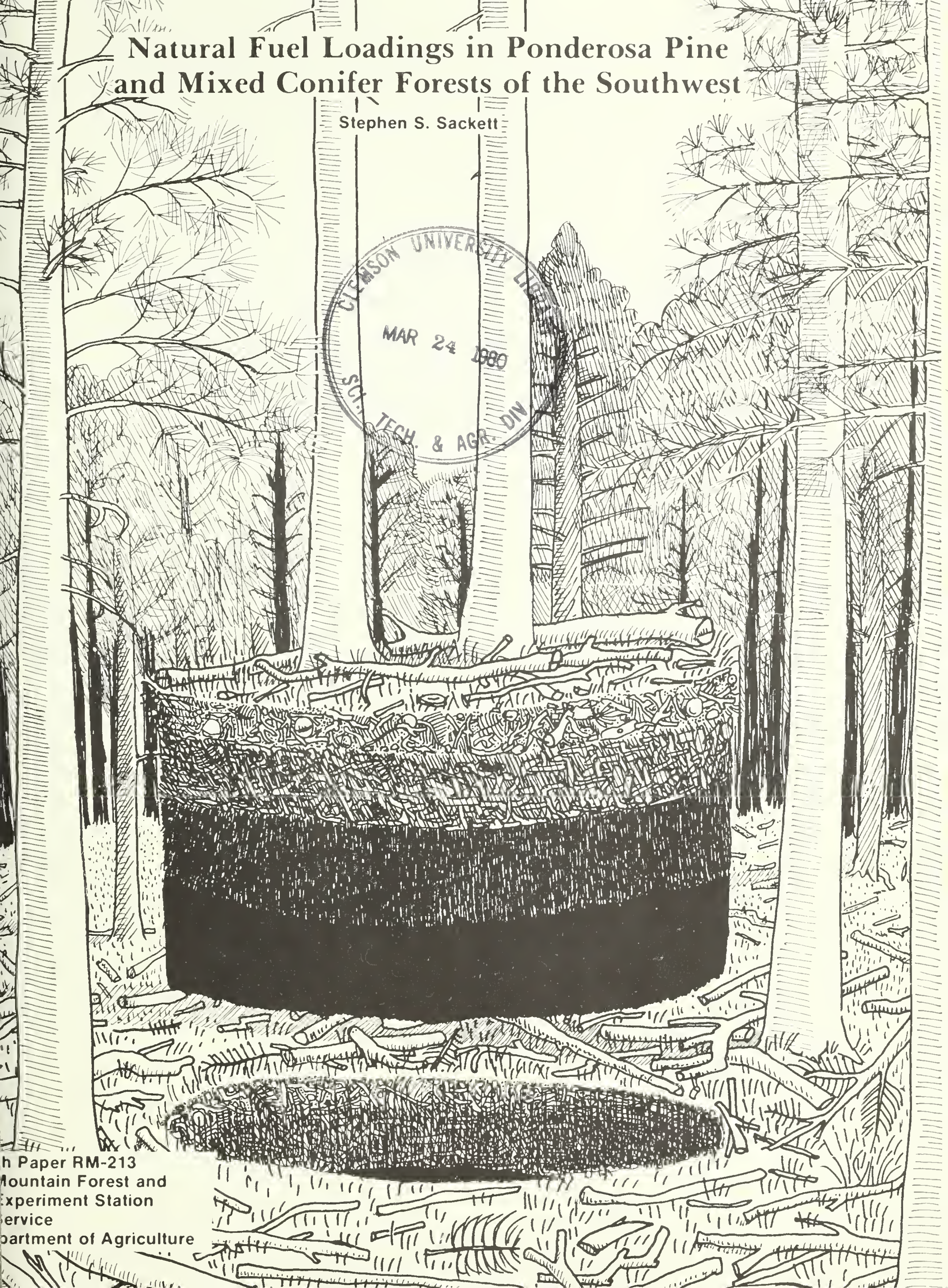
Natural Fuel Loadings in Ponderosa Pine and Mixed Conifer Forests of the Southwest

Stephen S. Sackett



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Abstract

Natural dead fuel loading in 62 undisturbed southwestern ponderosa pine stands averaged 21.9 tons per acre, 12.7 tons per acre ≤1-inch diameter. Sixteen mixed conifer stands averaged 44.1 tons per acre of dead fuel. Heavy humus loads contributed to loading of 22.2 tons per acre of fuel ≤1-inch diameter.

Research Paper RM-213 December 1979

Natural Fuel Loadings in Ponderosa Pine and Mixed Conifer Forests of the Southwest

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Contents

Natural Fuel Loadings in Ponderosa Pine and Mixed Conifer Forests of the Southwest

Stephen S. Sackett

Management Implications

No reliable method could be found to predict natural dead fuel loadings in ponderosa pine (common and scientific names in app. 1) and mixed conifer forests of the Southwest using basal area and/or a number of other independent stand variables. Variation within and between stands is too great to make fuel loading estimations practical. However, the study reported provides a better understanding of the existing wildland fuel situation.

Some wildland managers are concerned primarily with activity-generated fuel (slash), but natural fuel can be a problem in itself. Natural fuel loads can cause extreme fire behavior conditions during dry, windy weather experienced almost every fire season in the Southwest. Fires traveling through fine surface fuels common in southwestern ponderosa pine forests can produce fireline intensities and flame lengths great enough to seriously damage productive overstories. Flame lengths of the magnitude potentially available make crowning probable in typical southwestern ponderosa stands having large proportions of continuous, vertical ladder fuels in the form of stagnated (doghair) thickets. Two-thirds of the large fuel is rotten, punky, woody material adding to extreme fire behavior in the form of spotting and torching.

Although natural fuel loads in mixed conifer were found to be twice the weight of ponderosa pine, the seriousness of the condition is greatly reduced because mixed conifer grows in areas where critical fire weather is infrequent. One source of heavier loading is in the duff that can cause tedious mopup problems after a wildfire. Another is the large woody fuels that add to spotting and torching. Rapid surface fire spread in mixed conifer is not a serious threat because of the short, compact needles.

Even though an effective natural fuel estimator is not yet available for Southwest forest conditions, this paper points out the need for practicing fuel management in natural timber stands as well as in stands where activity-generated fuels are being created. In fact, fuel reduction in advance of fuel-generating activities will reduce the seriousness of the slash problems. Both fine surface fuels and large woody fuels create unique fire problems given a fire start. Both need to be dealt with in managing fuels. The fine surface fuels are managed to reduce rates of fire spread; resistance to control is modified by treating the large fuels.

Introduction

Accurate estimates of natural fuel loading are needed in a variety of situations, such as predicting fire behavior and damage; preattack planning; developing fuel management plans; assessing fire potential in and around residential developments in forests; and as an aid to silviculturists, landscape architects, wildlife biologists, and land use planners.

Such information is needed in Arizona, New Mexico, and Colorado for ponderosa pine (10.3 million acres according to Schubert 1974) and mixed conifer (2.5 million acres according to Jones 1974) forests, many in need of fuels management to eliminate excessive fuel loadings.

Literature

Byram (1959) developed a fire intensity formula involving the relationship between available fuel loading, heat content of the fuel, and rate of spread. The formula is expressed as:

$$I = Hwr$$

where

I = fire intensity (Btu/ft/s of fireline)
H = heat content of the fuel involved (Btu/lb)
w = weight of available fuel (lb/ft^2)
r = rate of spread (ft/s)

A number of fire effects can be related to fire intensity, including crown scorch and/or consumption of standing timber. In loblolly pine, for instance, fireline intensities greater than 1,000 Btu/ft/s can easily kill crop trees (Sackett 1972). Van Wagner (1973) did a similar study in Canada and established a relationship between fire intensity and scorch height in red, white, and jack pine stands.

Fuel loading estimates have been obtained in a number of ways. Slash loading can be predicted from information obtained in the timber sale survey (Brown et al. 1977, Wade 1969, Wendel 1960). Downed woody material can be inventoried using the planar intersect method to determine loading (Brown 1974). Forest floor weights, however, have been studied only to a limited extent in Arizona and with conditional success because of inherent variability. Ffolliott et al. (1968, 1976, 1977) and Aldon (1968) studied forest floor weights in conjunction with water retention on some Arizona watersheds. These works included prediction equations relating forest floor weight to stand basal area (Ffolliott et al. 1968, 1976, 1977) and age (Aldon 1968) but from very limited data. Brown (1970), while studying ponderosa pine fuels in Montana, found an average of 2,890 pounds per acre of litter (L layer) and as much as 23,400 pounds per acre of total forest floor material. Dieterich (1963) related basal area to fuel weight in comparatively homogeneous red pine plantations with relatively good success. Work by Brender et al. (1976) related fuel weight to age of stand and basal area in loblolly pine plantations. Additional work by McNab and Edwards (1976) predicts fuel loading of slash and longleaf pine by age of rough (time since last burn). From previous studies, basal area seems to be the best single predictor (Brender et al. 1976, Kiil 1968, Dieterich 1963).

Previous research indicates that large variations in fuel weight may be expected within any stand due to differences in stand density, age, site, species, previous activities, etc. Then too, "Southwest ponderosa pine occurs mainly as irregular, uneven-aged stands consisting of small even-aged groups." (Schubert 1974). This study sampled different combinations of "small even-aged groups" in an effort to determine fuel loading on a broad base—one on which management decisions must be made. That condition adds yet another source of variation.

This report confirms the inherent variability, with conclusions being based on a program of intensive sampling in a large number of ponderosa pine and mixed conifer stands in Arizona, New Mexico, and southern Colorado. Those working with treatment and manipulation of natural fuels should be aware of this variability.

Study Objectives

A study was begun in 1975 to determine fuel loadings in ponderosa pine and mixed conifer forests of the southwestern United States and to develop prediction equations for the estimate of those fuels.

Ponderosa pine and mixed conifer stands were selected in cooperation with various timber and fire management personnel for fuel loading studies on various public lands throughout Arizona, New Mexico, and southern Colorado. Mature stands selected represented the conditions on a particular forest or area. Further, the stands had not been disturbed by fire, disease, or insects, or any man-caused activity (e.g., logging or thinning) for at least 20 years. Stands undergoing or proposed for preattack planning were given priority for inventory. Sixty-two ponderosa pine stands and 16 mixed conifer stands were selected.

Sampling Procedure

Once an area was selected, a 3-acre plot was established. Disturbances, topography, and other problems made it necessary to confine the stand sample size to 3 acres. Ninety sample points were established on a 9 by 10 grid systematically arranged over the plot. One square foot was cut in the forest floor down to mineral soil at each point; the sample was then extracted, bagged, and held for analysis. The forest floor consists of the litter (L) layer, recently cast organic material; fermentation (F) layer, material starting to discolor and break down because of weather and microbial action; and the humified (H) layer, where decomposition has advanced. It is the L layer that Brown and Davis (1973) describe as "the loose surface litter on the forest floor, normally consisting of fallen leaves or needles, twigs, bark, cones and small branches that have not yet decayed sufficiently to lose their identity." This surface fuel provides the highly combustible material for flaming combustion and extreme fire behavior during times of high fire danger. The F and H layers make up the combustible ground fuel that lies beneath the loose surface fuel; ground fuel generally burns as glowing combustion. At nine of the sample points, taken on a diagonal across the grid, the L, F, and H layers were collected separately. Woody material ≤ 1 inch in diameter was collected separately also. On 18 of the grid points, heavier woody material was inventoried on 50-foot transects in random directions (Brown 1974). Tree diameters (d.b.h.) were measured on five circular sub-plots of equal area (20% of plot area). Basal area was calculated for each plot from "all trees" and from trees ≥5 inches d.b.h. Site index (Minor 1964) was determined from trees having good form and active growth.

Fuel samples were weighed after being oven-dried at 85° to 95° C until weight loss ceased. Rocks and other inorganic material were eliminated from the samples by a combination water bath and muffle furnace combustion process. Woody materials collected were separated into 0- to 1/4-inch- and 1/4- to 1-inch-diameter classes. "Other" material consists of components such as cones, bark, etc., and pieces of woody and needle material, too small to effectively separate.

Results

Contrary to previous findings by Ffolliott et al. (1968, 1975, 1977) this study did not yield reliable statistical relationships for predicting dead fuel loadings in ponderosa pine and mixed conifer from either basal area or duff depth. Differences between the findings of Ffolliott et al. and this study may be attributable to variations in stand structures, sampling intensity, or in processing the sampled material for weight determination. The results of the study further indicate that a wide range of fuel loading may be expected within and between stands of both ponerosa pine and mixed conifer. For example, the coefficient of variation (the standard deviation divided by the mean) ranged from 46% to 131% in the 62 ponderosa pine stands sampled.

Ponderosa Pine

Basal area in ponderosa pine stands investigated ranged from 55 to 201 square feet per acre. Ponderosa pine stands sometimes included small numbers of juniper, aspen, and oak. Tree size composition (even-aged groups) varied tremendously within each uneven-aged stand studied. Site index (100-year base) varied from 48 to 108.

Needles in the surface fuels (table 1) averaged 1.0 tons per acre and ranged from 0.3 to 2.8 tons per acre. Woody material was not picked up by layer, but a companion study[2] indicates that, on the average, 42%

[2]*Prescribed Burning Interval Study, Study Plan 75.1.5 on file at Forestry Sciences Laboratory, Arizona State University, Tempe, Ariz. 85281.*

Table 1.—Southwestern ponderosa pine dead fuel loadings (basis: 62 stands)

Fuel component	Mean	Standard deviation	Proportion of 0- to 1-inch-diameter dead fuel	Proportion of all dead fuel
	Tons per acre		*Percent*	
L layer (surface fuel) needle material	1.0	0.5	8	5
F layer (ground fuel) needle material	3.8	1.3	30	17
H layer (ground fuel) humus (needle origin)	6.1	2.5	48	28
0- to 1/4-inch-diameter woody material	0.2	.1	2	1
1/4- to 1-inch-diameter woody material	1.0	.5	8	4
Other material	.6	.5	4	3
Total dead fuel 0- to 1-inch diameter	12.7	3.0	100	58

Fuel component	Mean	Standard deviation	Portion of >1-inch-diameter dead fuel	Proportion of all dead fuel
	Tons per acre		*Percent*	
Fuel > 1-inch diameter				
1- to 3-inch material	1.4	0.7	15	6
>3-inch rotten material	5.0	4.3	54	23
>3-inch sound material	2.8	4.4	31	13
Total dead fuel >1-inch diameter	9.2	6.1	100	42
All dead fuel	21.9	7.6		100

of the total woody material ≤ 1-inch diameter is found with the surface fuels—39% of the 0- to 1/4-inch material and 44% of 1/4- to 1-inch material. That adds an estimated 0.1 tons of 0- to 1/4-inch material and 0.4 tons of 1/4- to 1-inch material to the needle material, an average of 1.5 tons per acre of surface fuels ≤ 1-inch diameter.

F layer needle material ranged from 0.6 to 6.1 tons per acre with an average of 3.8 tons per acre. Humus layer material, produced primarily from decay of needles, averaged 6.1 tons per acre. A range of humus weights from a low of 1.4 tons per acre to 12.5 tons per acre was found in the 62 study locations. Combining the F and H layer produces a ground fuel loading (needle material) of 9.9 tons per acre. Add to that the woody material ≤ 1-inch diameter, and the figure increases to 10.6 tons per acre.

The 0.6 tons per acre of "other material" found in the study was distributed through the fuel layers. Combining all material ≤ 1-inch diameter lying on the ground, we find an average fuel load of 12.7 tons per acre. Needles obviously made up the biggest portion of fine fuels; about 86% of all material ≤ 1-inch diameter or about 10 tons per acre in mature natural ponderosa pine (data summary in app. 2).

Larger material in the form of fallen snags, limbs, branches, and broken tops add appreciably to the total fuel load. These woody fuels were not sampled, but were estimated on each plot using the planar intersect method (data summary in app. 3). Weight of material 1 to 3 inches in diameter ranged from 0.4 to 3.5 tons per acre. The average was 1.4 tons per acre. Woody material greater than 3 inches in diameter averaged 7.8 tons per acre. The range of weights, however, extended from no large material on one site to 28.8 tons per acre on another. Rotten woody material > 3 inches in diameter accounted for the greatest woody fuel loading (5.0 tons per acre). Sound material of the same size class was somewhat more than half that amount (2.8 tons per acre). Total dead fuels amounted to almost 22 tons per acre of combustible material.

Mixed Conifer

Southwest mixed conifer stands contain varying proportions of Douglas-fir, white fir, southwestern white pine, corkbark fir, ponderosa pine, blue and Engelmann spruce, and aspen. There was a diversity of species composition in the 16 stands selected for study.

Total dead fuel ≤ 1-inch diameter averaged more than 22 tons per acre. Needle material accounted for 78% (17.3 tons per acre), woody material 16.4% (3.6 tons per acre), and other material 5.6% (1.3 tons per acre).

Surface fuel (L layer) in the mixed conifer stands studied was 3.5 tons per acre. Of this, the fine fuels (all except 1/4- to 1-inch woody) amounted to 2.4 tons per acre. Upper level ground fuels (F layer) had a needle fuel loading component much the same as ponderosa pine—3.9 tons per acre. Needle-derived material in the humus (H) layer accounts for 55% of all material ≤ 1 inch (12.3 tons per acre). A summary of the weights are in table 2, complete figures in appendix 4. Material greater than 3 inches diameter averaged 18.6 tons per acre with some stands exceeding 45 tons per acre. Rotten material totaled almost 2 tons per acre more than sound material (data summary in app. 5).

Discussion

Ponderosa Pine

Fuel loadings in "natural," undisturbed ponderosa pine stands are quite heavy. Small particle fuels account for as much of the total loadings as do the large fuels. Although they are not heavy loads, the fact that most of the larger material is rotten may be important. Not only is the rotten material more easily consumed under dry conditions, but it also produces numerous fire brands and provides a more receptive place for fire brands to land and ignite than does sound material.

Mixed Conifer

Fuel loadings in "natural" undisturbed mixed conifer stands are heavy also. Weight of needle material in the L and F layers is comparable to ponderosa pine. However mixed conifer humus is more than twice the weight of that found in ponderosa pine; all size classes of woody material are more than double, also.

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Table 2.—Southwestern mixed conifer dead fuel loadings (basis: 16 stands)

Fuel component	Mean	Standard deviation	Proportion of layer	Proportion of 0- to 1-inch-diameter dead fuel	Proportion of all dead fuel
	----Tons per acre----		-------------Percent-------------		
L layer (surface fuel)					
Needle material	1.1	0.5	30	5	2
0- to 1/4-inch woody material	0.7	.3	21	3	2
1/4- to 1-inch woody material	1.3	.7	36	6	3
Other material	.4	.3	13	2	1
Total	3.5	1.1	100	16	8
F layer (ground fuel)					
Needle material	3.9	1.6	79	17	8
0- to 1/4-inch woody material	0.3	0.1	7	1	1
1/4- to 1-inch woody material	.4	.2	7	2	1
Other material	.4	.2	7	2	1
Total	5.0	1.8	100	22	11
H layer (ground fuel)					
Humus (needle origin)	12.3	4.7	90	56	28
0- to 1/4-inch woody material	0.4	0.4	3	2	1
1/4- to 1-inch woody material	.6	.5	4	2	1
Other material	.4	.5	3	2	1
Total	13.7	5.6	100	62	31
Total dead fuel					
0- to 1-inch diameter	22.2	6.2			

Fuel component	Mean	Standard deviation	Proportion of >1-inch-diameter dead fuel	Proportion of all dead fuel
	----Tons per acre----		--------Percent--------	
Fuel > 1-inch diameter				
1- to 3-inch material	3.3	1.3	15	8
> 3-inch rotten material	10.3	7.8	47	23
> 3-inch sound material	8.3	7.2	38	19
Total dead fuel >1-inch-diameter	21.9	13.7	100	50
All dead fuel	44.1	18.0		100

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Appendix I

Common and Scientific Names of Trees

Aspen	*Populus* spp.
Blue spruce	*Picea pungens* Engelm.
Corkbark fir	*Abies arizonica* (Merriam) Lemm.
Douglas-fir, Rocky Mountain	*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco
Eastern white pine	*Pinus strobus* L.
Engelmann spruce	*Picea engelmannii* Parry
Jack pine	*Pinus banksiana* Lamb.
Juniper	*Juniperus* spp.
Loblolly pine	*Pinus taeda* L.
Longleaf pine	*Pinus palustris* Mill.
Oak	*Quercus* spp.
Ponderosa pine	*Pinus ponderosa* Laws.
Quaking aspen	*Populus tremuloides* Michx.
Red pine	*Pinus resinosa* Ait.
Slash pine	*Pinus caribaea* Morelet
Southwestern white pine	*Pinus strobiformis* Engelm.
White fir	*Abies concolor* (Gord. & Glend.) Hildebr.

Appendix 2

Dead fuel loading (tons per acre) in southwestern ponderosa pine stands (≤ 1-inch-diameter material)

	Needle material				Woody material		Dead fuel
	L layer	F layer	H layer	Other material[1]	0 to 1/4 inch	1/4 to 1 inch	0- to 1-inch diameter
Kaibab NF							
Jacob Lake	1.8	4.5	8.8	1.4	0.4	0.2	17.1
Lambs Lake	0.8	6.1	5.2	0.5	.2	1.0	13.8
Lupine	.8	1.3	8.9	.9	.2	1.4	13.5
Three Lakes	.9	2.3	11.9	1.4	.1	1.1	17.7
Grand Canyon National Park							
Big Taper	.4	6.0	4.5	1.1	.1	1.2	13.3
Cape Royal	1.0	4.7	9.8	.8	.3	1.4	18.0
Naji Point	1.6	3.7	12.5	.7	.2	1.7	20.4
Walhalla	.6	6.7	8.7	1.3	.2	.8	18.3
Coconino NF							
Clints Well	.9	3.3	11.7	.6	.2	1.0	17.7
Fort Valley	1.1	4.7	7.9	1.4	.2	.1	15.4
G.A. Pearson Natural Area	.8	2.2	9.5	.3	.2	1.0	14.0
Long Valley	1.5	3.1	5.8	.4	.4	.5	11.7
Tonto NF							
Ellison Creek	—	—	—	—	—	—	4.8
Tonto Village	—	—	—	—	—	—	8.2
Apache-Sitgreaves NF							
Agate	.9	2.3	7.7	.2	.1	.3	11.5
Bear Rock	—	—	—	—	—	—	12.7
Blue Range Primative Area	1.0	2.6	4.1	.4	.3	1.9	10.3
Bull Flat	.9	2.5	2.4	.5	.3	1.8	8.4
Castle Creek, South	1.4	3.2	5.4	0.3	0.4	1.6	12.3
Fawn	0.8	4.1	7.7	.3	.1	.7	13.7
Hawk-Owl	1.2	3.0	9.0	1.0	.3	1.0	15.5
Holcomb Sale	.6	3.0	4.1	.4	.2	1.5	9.8
Horsefly	1.5	4.5	7.5	.5	.2	1.0	15.2
Larson Ridge	.8	3.1	2.6	.3	.6	2.2	9.6
Mamie Creek	.9	4.4	4.5	.1	.1	.5	10.5
Red Hill Trail	.7	1.8	4.9	.1	.1	.7	8.3
Watts Sale	1.6	4.4	5.2	.3	.1	.7	12.3
Wildcat Road	.5	1.8	3.0	1.1	.2	2.1	8.7
San Carlos Apache Indian Reservation							
Bronco Junction	—	—	—	—	—	—	12.3
Turkey Tank	—	—	—	—	—	—	14.9
Wallow	1.4	4.8	9.0	.4	.1	.4	16.1
Fort Apache Indian Reservation							
Bonito Creek	2.8	4.9	6.6	.3	.1	.5	15.2
Lofer Ridge	1.2	5.8	6.0	.6	.3	1.0	14.9
Gila NF							
High Clark Springs	.7	1.9	9.2	.5	.1	.6	13.0
Meadow Creek	1.0	3.8	4.5	.1	.3	.4	10.1
Meason Park	—	—	—	—	—	—	9.7
Multiple Use Demo. Area	.7	5.1	4.1	.2	.2	.6	10.9
Pine Flat	.9	3.2	5.9	.1	.1	.2	10.4
School Marm	.7	3.6	6.5	.6	.1	1.2	12.7
Sheep Corral Canyon	.8	5.8	4.6	.3	.1	.5	12.1
Sheep Springs	.8	5.3	2.1	.1	.3	.8	9.4
State Line	1.9	2.9	1.4	1.8	.7	2.7	11.4
Trap Springs	.8	3.8	5.9	.2	.2	.9	11.8
Navajo Indian Reservation							
Wheatfields	.6	4.1	3.3	.7	.1	.6	9.4
Cibola NF							
Boon Place	.8	4.3	3.4	.1	.3	.7	9.6
Fubar	.6	.6	5.4	.1	.2	.4	7.3
Upper Section	.5	4.1	3.6	.4	.1	.7	9.4

Appendix 2 — Continued

	Needle material			Other material[1]	Woody material		Dead fuel 0 to 1-inch diameter
	L layer	F layer	H layer		0 to ¼ inch	¼ to 1 inch	
Santa Fe NF							
Cat Mesa	1.5	4.4	6.6	.5	.2	.9	14.1
Firewood	1.0	3.3	7.9	.6	.3	1.1	14.2
Mesa Junction	.6	2.5	5.0	2.4	.1	.6	11.2
Carson NF							
El Valle	1.5	2.9	6.1	.4	.3	1.1	12.3
Kiowa Mountain	.8	5.7	8.3	1.0	.1	.6	16.5
Ojitos	.7	3.8	7.4	.1	,1	,8	12.9
Rio Trampas	.7	5.6	3.3	.5	.1	1.2	11.4
Bandelier National Monument							
Escobas Mesa	1.6	3.1	5.2	.5	.5	.7	11.6
Lincoln NF							
Daisy	1.4	4.5	6.5	.9	.5	1.3	15.1
Hughes Canyon	1.3	3.5	5.8	.7	.5	.8	12.6
San Juan NF							
First Fork	1.0	4.0	5.8	1.3	.6	1.7	14.4
Little Devil Creek	.3	2.3	5.0	.6	.4	1.2	9.8
Mud Spring	.5	3.2	5.7	.4	.3	.5	10.6
Piedra Trail	.4	3.3	6.0	.4	.3	.6	11.0
Rocky Draw	.7	6.1	5.0	.4	.5	1.2	13.9
Study average (N=56/62)	1.0	3.8	6.1	.6	.2	1.0	12.5

[1]Other material: includes cones, bark, miscellaneous plant parts, and any other material too small to separate effectively.

Appendix 3
Dead fuel loading (tons per acre) in southwestern ponderosa pine stands (>1-inch-diameter material)

	1 to 3 inches	Over 3-inch sound	Over 3-inch rotten	Total over 3 inches	Total 1 to over 3 inches	Total[1] dead fuel
Kaibab NF						
Jacob Lake	2.0	2.8	3.7	6.5	8.5	25.6
Lambs Lake	2.0	0..8	3.8	4.6	6.6	20.5
Lupine	2.3	2.8	5.3	8.1	10.4	23.9
Three Lakes	2.0	4.2	2.7	6.9	8.9	26.6
Grand Canyon National Park						
Big Taper	0.8	3.1	0.6	3.7	4.5	17.9
Cape Royal	.9	5.2	1.1	6.3	7.2	25.1
Naji Point	1.8	2.6	4.5	7.1	8.9	29.3
Walhalla	.5	1.3	.0	1.3	1.8	20.2
Coconino NF						
Clints Well	1.4	10.4	18.4	28.8	30.2	47.9
Fort Valley	.8	.9	11.8	12.7	13.5	28.9
G. A. Pearson Natural Area	.4	7.9	5.4	13.3	13.7	27.7
Long Valley	1.2	3.1	17.4	20.5	21.7	33.4
Tonto NF						
Ellison Creek	1.0	.7	1.9	2.6	3.6	8.4
Tonto Village	.5	.2	1.1	1.3	1.8	10.0
Apache-Sitgreaves NF						
Agate	1.7	.6	4.2	4.8	6.5	18.0
Bear Rock	2.7	2.6	6.6	9.2	11.9	24.6
Blue Range Primitive Area	1.1	6.1	4.2	10.3	11.4	21.7
Bull Flat	1.4	3.3	4.6	7.9	9.3	17.8
Castle Creek, South	1.9	2.8	14.9	17.7	19.6	31.9
Fawn	2.7	1.4	3.6	5.0	7.7	21.4
Hawk-Owl	1.9	2.5	9.3	11.8	13.7	29.1
Holcomb Sale	1.1	1.6	9.1	10.7	11.8	21.6

Appendix 3.—Continued

	1 to 3 inches	Over 3-inch sound	Over 3-inch rotten	Total over 3 inches	Total to over 3 inches	Total dead fuel
Horsefly	2.0	13.1	3.4	16.5	18.5	33.8
Larson Ridge	2.5	3.8	9.4	13.2	15.7	25.2
Mamie Creek	0.9	1.6	3.4	5.0	5.9	16.4
Red Hill Trail	.8	0.4	7.2	7.6	8.4	16.7
Watts Sale	.6	.7	1.5	2.2	2.8	15.1
Wildcat Road	1.3	.2	12.6	12.8	14.1	22.8
San Carlos Apache Indian Reservation						
Bronco Junction	1.1	.2	1.8	2.0	3.1	15.4
Turkey Tank	1.5	4.4	7.2	11.6	13.1	28.0
Wallow	1.4	1.2	6.5	7.7	9.1	25.2
Fort Apache Indian Reservation						
Bonito Creek	2.0	8.6	4.5	13.1	15.1	30.3
Lofer Ridge	3.5	17.4	4.9	22.3	25.8	40.7
Gila NF						
High Clark Springs	1.3	.6	10.7	11.3	12.6	25.6
Meadow Creek	.7	.0	.0	.0	0.7	10.8
Meason Park	.7	2.2	2.1	4.3	5.0	14.7
Multiple Use Demonstration Area	2.5	1.1	1.6	2.7	5.2	16.1
Pine Flat	.7	.1	.9	1.0	1.7	12.1
School Marm	2.5	1.1	8.4	9.5	12.0	24.6
Sheep Corral Canyon	1.0	3.6	13.9	17.5	18.5	30.6
Sheep Springs	.8	1.1	.0	1.1	1.9	11.2
State Line	1.3	.1	4.9	5.0	6.3	17.8
Trap Springs	2.3	.0	6.8	6.8	9.1	20.8
Navajo Indian Reservation						
Wheatfields	.4	.4	4.1	4.5	4.9	14.3
Cibola NF						
Boon Place	.6	1.1	9.6	10.7	11.3	20.9
Fubar	.8	2.4	3.0	5.4	6.2	13.4
Upper Section	.4	.6	8.0	8.6	9.0	18.4
Santa Fe NF						
Cat Mesa	1.3	6.2	8.1	14.3	15.6	29.6
Firewood	.7	13.0	2.6	15.6	16.3	30.5
Mesa Junction	1.8	2.1	7.9	10.0	11.8	23.1
Carson NF						
El Valle	.4	.0	.5	.5	.9	13.1
Kiowa Mountain	.8	4.7	2.1	6.8	7.6	24.1
Ojitos	.9	.9	3.1	4.0	4.9	17.8
Rio Trampas	1.4	.4	1.8	2.2	3.6	15.0
Bandelier National Monument						
Escobas Mesa	.6	1.7	.7	2.4	3.0	14.5
Lincoln NF						
Daisy	2.1	2.4	3.0	5.4	7.5	22.5
Hughes Canyon	1.4	2.6	2.7	5.3	6.7	19.3
San Juan NF						
First Fork	1.3	3.0	2.9	5.9	7.2	21.6
Little Devil Creek	2.0	.6	1.8	2.4	4.4	14.1
Mud Spring	2.0	1.3	1.6	2.9	4.9	15.4
Piedra Trail	.6	1.5	1.9	3.4	4.0	15.0
Rocky Draw	.7	1.8	.9	2.7	3.4	17.3
Study average	1.4	2.8	5.0	7.9	9.2	21.7

[1]Total dead fuel is summation of total 1- to 3-inch material and dead fuel (0- to 1-inch diameter), appendix 2.

Appendix 4

Dead fuel loading (tons per acre) in southwestern mixed conifer stands
(≤ 1-inch diameter material)

	Needle material			Other material[1]	Woody material		Dead fuel 0- to 1-inch diameter
	L layer	F layer	H layer		0 to 1/4 inch	1/4 to 1 inch	
Apache-Sitgreaves NF							
Butterfly Spring	1.3	3.1	17.1	1.6	1.7	4.7	29.5
Canker	1.3	5.7	11.2	0.6	1.6	1.8	22.2
Double Cienega	0.6	2.9	16.0	2.9	1.9	4.1	28.4
Dump	2.0	4.0	12.2	1.0	1.8	1.9	22.9
Fire Scar	1.5	3.1	12.2	.6	1.1	2.3	20.8
Hannigan	1.0	2.1	19.9	1.2	2.8	3.8	30.8
HQ Cienega	1.2	4.5	12.3	.3	1.1	1.9	21.3
Terry Flats	.6	4.5	17.8	1.1	2.3	2.7	29.0
Willow Creek	1.0	7.0	17.1	2.1	1.4	2.1	30.7
Bandelier National Monument							
Frijoles	1.1	3.3	9.8	1.5	1.0	2.0	18.7
Carson NF							
Cunningham Sale	.8	2.0	15.3	2.1	0.8	1.7	22.7
Maquinita Sale	.8	7.1	10.1	.9	.8	1.2	20.9
Palo Pass	.4	2.9	9.3	1.1	1.1	1.6	16.4
Lincoln NF							
Cloudcroft	1.0	3.3	4.3	.8	1.3	0.9	11.6
Silver Saddle	.5	2.0	9.2	1.1	1.1	1.3	15.2
Santa Fe NF							
Calaveras	1.9	4.8	3.7	.9	1.3	1.0	13.6
Study average (N=16)	1.1	3.9	12.3	1.3	1.4	2.2	22.2

[1]Other material: includes cones, bark, miscellaneous plant parts, and any other material too small to separate effectively.

Appendix 5

Dead fuel loading (tons per acre) in southwestern mixed conifer stands
(> 1-inch-diameter material)

	1 to 3 inches	Over 3 inches sound	Over 3 inches rotten	Total over 3 inches	Total 1 to over 3 inches	Total[1] dead fuel
Apache-Sitgreaves NF						
Butterfly Spring	4.1	23.4	22.9	46.3	50.4	79.8
Canker	1.9	2.5	12.3	14.8	16.7	38.8
Double Cienega	4.8	8.7	10.9	19.6	24.4	52.8
Dump	4.8	9.7	5.0	14.7	19.5	42.4
Fire Scar	5.0	2.9	2.5	5.4	10.4	31.2
Hannigan	3.9	11.5	13.7	25.2	29.1	59.9
HQ Cienega	1.5	6.2	8.5	14.7	16.2	37.5
Terry Flats	3.9	23.6	30.9	54.5	58.4	87.5
Willow Creek	2.5	2.2	13.6	15.8	18.3	48.9
Bandelier National Monument						
Frijoles	2.4	1.6	9.6	11.2	13.6	32.3
Carson NF						
Cunningham Sale	3.6	5.2	7.1	12.3	15.9	38.6
Maquinita Sale	2.3	4.0	3.3	7.3	9.6	30.5
Palo Pass	5.0	3.1	7.6	10.7	15.7	32.1
Lincoln NF						
Cloudcroft	2.1	5.4	12.5	17.9	20.0	31.6
Silver Saddle	1.5	17.8	1.6	19.4	20.9	36.1
Santa Fe NF						
Calaveras	3.1	5.7	2.6	8.3	11.4	25.0
Study average	3.3	8.3	10.3	18.6	21.9	44.1

[1]Total dead fuel is summation of total 1- to 3-inch material and dead fuel (0- to 1-inch diameter), appendix 2.

Sackett, Stephen S. 1979. Natural fuel loadings in ponderosa pine and mixed conifer forests of the Southwest. USDA For. Serv. Res. Pap. RM-213, 10 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Natural dead fuel loading in 62 undisturbed southwestern ponderosa pine stands averaged 21.9 tons per acre, 12.7 tons per acre $\leq$1-inch diameter. Sixteen mixed conifer stands averaged 44.1 tons per acre of dead fuel. Heavy humus loads contributed to loading of 22.2 tons per acre of fuel $\leq$1-inch diameter.

Keywords: Fuel loading, *Pinus ponderosa*, natural fuels, litter, woody fuels, duff, fuel management

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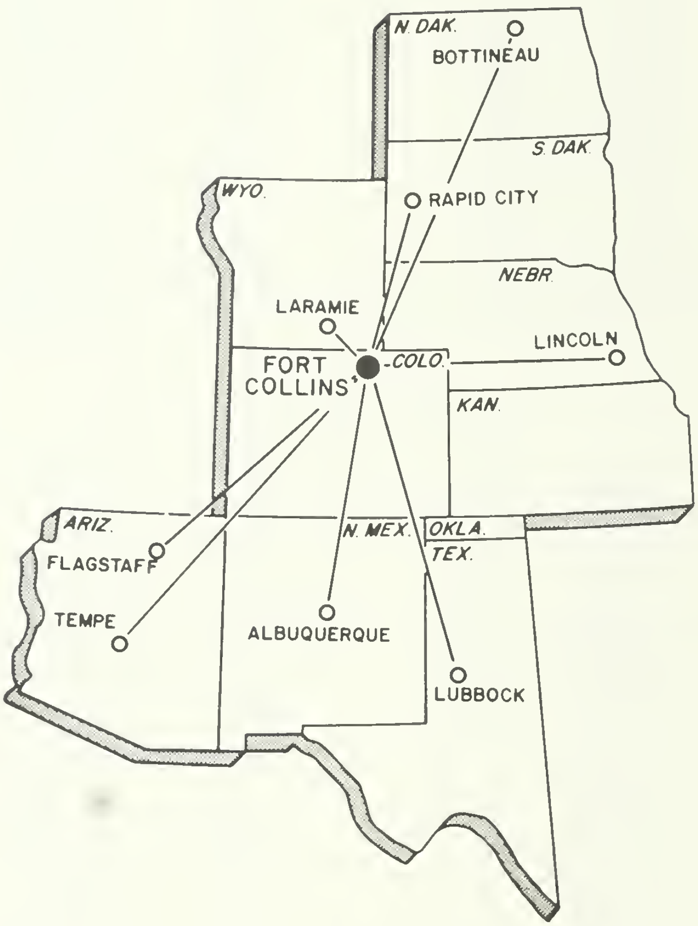
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N. MEX.
OKLA.
TEX.
FLAGSTAFF
TEMPE
ALBUQUERQUE
LUBBOCK

Rodent Population Densities and Food Habits in Arizona Ponderosa Pine Forests

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Rodent Population Densities and Food Habits in Arizona Ponderosa Pine Forests[1]

John G. Goodwin, Jr., Research Associate
and
C. Roger Hungerford, Professor of Biological Sciences
University of Arizona

Abstract

Habitat preference, effect of timber harvesting on population densities, and food habits were determined for small rodents inhabiting ponderosa pine in north-central Arizona. *Peromyscus maniculatus* was the major species, with a density of 1 to 11 per acre. Forbs were the primary summer food item for all rodent species. Seeds and flowers comprised 75% of the vegetative diet and leaves or stems 25%. Approximately 85% of the total diet was vegetation,and 15% was insects.

[1]Research reported here was funded by the Rocky Mountain Forest and Range Experiment Station, RWU-RM-1654. Station's headquarters is at Fort Collins, in cooperation with Colorado State University. Supervision was provided by David R. Patton, Principal Wildlife Biologist, at the Station's Research Work Unit at Tempe, in cooperation with Arizona State University.

Rodent Population Densities and Food Habits in Arizona Ponderosa Pine Forests

John G. Goodwin, Jr. and C. Roger Hungerford

Management Implications

Rodent population density and biomass are generally low in untreated ponderosa pine[2] forests. Thinning of pine with its resulting slash increases density and biomass 200-1,000%. The deer mouse is the most typical of the pine type. Its population density is directly related to the amount of slash and large logs on the ground. Logging operations normally increase the number of downed logs, improving the habitat for deer mice.

Brush mice and woodrats are normally found in high densities along rocky slopes but seldom inhabit pure pine stands. Windrowing slash can create "fingers" of habitat for these species and allow them to invade the pine stands. Mexican woodrats appear to be better adapted to different habitats than white-throated woodrats.

The cliff chipmunk is found along rock cliffs and in thinned pine stands. Density increases as the forest is thinned, but this species does not inhabit clearcuts. Altitudinal zonation limits cliff chipmunks to below 7,300 feet elevation. Gray-collared chipmunks prefer mature forests above 7,300 feet. Along that boundary, interspecific competition favors the cliff chipmunk in open stands and the gray-collared chipmunk in more dense forests. The golden-mantled ground squirrel prefers areas above 7,300 feet elevation but inhabits both open and dense pine stands.

Pocket gophers inhabit both treated and untreated forests but prefer areas with deep topsoils. However, this species was not found in high densities on any of the study areas.

Thinning ponderosa pine forests would favor cliff chipmunks over gray-collared chipmunks where both species are present. Clearcutting would eliminate both species and the golden-mantled ground squirrel. However, the degree of thinning, when all slash is removed, would have little effect on other species. If cull logs and large diameter limbs are left scattered after thinning, deer mouse densities will increase in proportion to the increase in cover. When slash is piled or windrowed, brush mice and Mexican woodrats will move into the pine type, and deer mouse population density will increase slightly. Therefore, the treatment of slash, rather than the actual pine thinning, is the primary factor determining rodent density and species diversity.

Forbs were the primary food item for all rodent species during the summer. Seeds and flowers were preferred to other parts of the plant. Ponderosa pine seeds and seedlings did not contribute significantly to the summer rodent diet on the Beaver Creek Watershed.

Introduction

Rodents are an important part of the ponderosa pine ecosystem since they feed extensively on various plant species, and in turn, are fed upon by many terrestrial and avian predators. High rodent population densities can significantly affect plant survival or reproduction (Schmidt and Shearer 1971, Dingle 1956). A sudden drop in their population can stress predatory species forcing them to seek alternate food sources. Therefore, any treatments affecting rodent populations may also influence other plants or animals.

[2]Scientific names of plants and animals referred to in this paper are listed in the appendix.

Study Areas

The Beaver Creek Watershed is located on the Coconino National Forest approximately 30 miles south of Flagstaff, Ariz.

Vegetation types found on the Beaver Creek Watershed include ponderosa pine, alligator juniper, Utah juniper, and semidesert. However, this study was limited to the pine type generally found above 6,500 feet elevation.

The forest is primarily composed of ponderosa pine but contains some Gambel oak and alligator juniper (Brown et al. 1974). The basal area per acre of a typical stand includes 92 square feet of pine, 18 square feet of Gambel oak, and 5 square feet of alligator juniper (Brown et al. 1974). The size mixed classes are dominated by 2- to 10-inch or 26-inch-plus trees, with a shortage of trees in the 14- to 24-inch class (Brown et al. 1974).

The soils are primarily clay or silty clay less than 2 feet deep and derived from basalt parent material (H. E. Brown 1971). Average precipitation varies within the watershed from about 22 to 28 inches per year (Price 1967). Topography within the pine type is dominated by a southwest aspect with a 5° to 15° slope dropping from about 7,600 to 6,500 feet. Several steep mountains rising to nearly 8,000 feet and several rocky canyons provide some variations in slope and aspect.

Understory vegetation beneath the undisturbed ponderosa pine is generally open, with about 124 pounds per acre of grasses and 58 pounds per acre of forbs and half-shrubs. Dominant grasses include bottlebrush squirreltail, mutton bluegrass, blue grama, and black dropseed. Important forbs include western ragweed, spreading fleabane, trailing fleabane, and showy aster (Brown et al. 1974).

This study was conducted on 6 of the 18 experimental watersheds: watersheds 8, 10, 11, 13, 14, and 17. Watershed 13 was untreated and served as the control area for comparison with the treated watersheds. Watersheds 11, 14, and 17 were treated between 1958 and 1971, and watersheds 8 and 10 were cut in 1974 while this study was in progress. Watershed descriptions and treatments are presented in table 1.

Rodent population densities were determined by intensive live trapping on a 4.17-acre site on each watershed studied. Each site was chosen to typify the habitat found on that watershed.

The site on watershed 13 contained a wide mixture of pine age classes ranging from overmature trees more than 24 inches in diameter to thickets of reproduction less than 2 inches in diameter. The ground was covered by pine needles, small twigs, and fallen trees. Grass and forb growth was very sparse. The southern edge of the site bordered on one of the two rocky canyons found on the watershed.

The site on watershed 14 was dominated by thinned pine and oak but included portions of two strip cuts. Some slash had been piled and burned, but much of the cut reproduction (less than 2 inches in diameter) remained on the ground along with many downed logs 8 inches or more in diameter. The ground litter had also been disturbed by the logging operation, exposing some rock and bare soil. At the time of this study, grass and forb growth was good on this disturbed soil.

The site on watershed 17 had been severely thinned, leaving only even-aged pine 14-24 inches in diameter and some Gambel oak. The slash had been windrowed and covered approximately 15% of the area. The rows were spaced about 50 feet apart. Ground disturbance during logging stimulated understory vegetation growth, especially common mullein and other invading species.

Watershed 11 was clearcut, and all slash was removed or burned. A stand of intermediate wheatgrass, blue grama, bottlebrush squirreltail, and other grasses provided food and ground cover for rodents. This site contained 35% surface rock. Many large rocks had been exposed and dislodged during logging, creating good rodent habitat. Smaller rock was probably brought to the surface by frost heaving.

The site on watershed 8 was heavily forested with pine. Many trees were in the medium size classes, which are not common on the Beaver Creek Watershed. Thick litter and numerous fallen logs covered the ground. Grass and forb growth was good in the more open areas but poor in the dense pine stands.

The trap site on watershed 10 included about two-thirds pine and one-third juniper, the approximate ratio of these types on this watershed. The pine was generally young with few trees more than 12 inches in diameter. The ground under the pines was covered by a shallow litter layer with very few fallen logs or rock. The juniper was generally in rocky ground with little topsoil. A rocky slope bordered the northern edge of the trap site. Understory vegetation was sparse.

Methods and Materials

Live Trapping

A live trap grid developed by Cockrum and Vaughan (1971) and used on their Sonoran Desert validation studies in southern Arizona was chosen for this study. The square grid contained 196 live traps in 14 rows of 14 traps each spaced 33 feet apart. Trap spacing was based on the radius of the home range of the brush mouse, the least mobile species probably present on the watershed. Spacing between traps was set at 33 feet to expose animals to at least four traps and, therefore, provide data to determine their home range.

From two to four potential trap sites for each watershed were chosen from a topographic map and then inspected on the ground. To minimize intersite variability, all sites were chosen on south to west facing aspects with less than 10% slope. Manpower and time limitations prevented study of more than one site per watershed; therefore the site most representative of the overall watershed habitat was selected for trapping.

Table 1.—Descriptions and treatments of the watersheds used for the rodent study

Watershed number	Acres[1]	Elevation[1] (feet)	Trees per acre[2]	Basal area per acre[2]	Treatment
13	910	7,200	898	98	This is an untreated watershed covered with mixed ponderosa pine. Two rocky canyons extend into the watershed and contain a mixture of pine and juniper.
14	1,349	7,300	[3]726	54	A strip, shelterwood cut was done in 1970-71. One-third of the watershed was cleared in irregular, 30-90 feet wide strips, and two-thirds were thinned to 80 square feet basal area per acre. Slash from the leave strips was partially piled and burned. The pine was cut so as to leave mostly 14- to 24-inch trees. Small Gambel oak was left in the strip cuts.
17	299	7,040	[3]1,082	30	In 1969 the pine was heavily thinned leaving 30 square feet basal area per acre of 14- to 24-inch trees. All juniper and large Gambel oak were removed. The slash and windrowed perpendicular to the drainage pattern.
11	188	6,610	0	0	This watershed was cleared and planted in grass in 1958. Heavy stands of vegetation, primarily intermediate wheatgrass (*Agropyron intermedium*), blue grama (*Bouteloua gracilis*), and bottlebrush squirreltail (*Sitanion hystrix*) built up from 1958-66. From 1967-71 spring and fall grazing removed one-half of the perennial grass growth.
8	1,802	7,360	[3]473	[3]98	This watershed was untreated during 1972-73 research. In spring 1974, the area was thinned with a shelterwood-seed tree cut.
10	571	6,880	[3]635	[3]75	This watershed was uncut pine and juniper during the 1972-73 research. In 1974, one-third of the area was cut in small clearings (less than 10 acres) and the slash was piled. The remaining timber was thinned.

[1]Price (1967)
[2]Ffolliott (1974)
[3]Pretreatment data

Rodents were captured in 4- by 4- by 10-inch screen and metal live traps. A mixture of peanut butter and rolled oats was used as bait. Traps were checked at dawn and dusk and rebaited every 3 days or as needed. Captured animals were marked by toe clipping, weighed, sexed, and released.

During summer and fall of 1972, trapping was conducted on the untreated control, silviculturally improved, big game habitat improvement, and clearcut and range reseeded watersheds (table 2). Each grid was run for a 10-day interval followed by periodic 2-day checks. This resulted in the watersheds receiving from 14 to 19 days of trapping. In summer 1973, the control, irregular strip shelterwood, and severely thinned (treated 1969) watersheds each received 18 consecutive days of live trapping. This live trapping provided data on species, density, and distribution in the different habitats on each watershed. However, a severe winter between these summers significantly reduced the rodent populations. Since more of certain species were killed than others, rodent population densities could not be compared among watersheds not trapped each year.

During summer 1974, each of the watersheds except the big game habitat improvement was trapped for 5 consecutive days (table 2). Therefore, rodent population densities were compared between watersheds based primarily on the 1974 data. The big game habitat watershed was being logged in 1974 and the fallen trees and piled slash prevented trapping. Densities for this area were based on the species density ratio between this watershed and the control for 1972. For example, the brush mouse population density on the control in 1974 dropped to 66% of the 1972 level (from 29 to 19). Therefore, the 1974 population density of this species on the big game habitat watershed was calculated as 66% of its 1972 density.

In 1975, the silviculturally improved, big game habitat, and control watersheds were trapped for 5-day periods in summer and fall to determine rodent population densities after timber harvesting.

Density estimates were made by dividing the actual number of a species caught by the percentage of the trap grid in which it was found. For example, brush mice were caught on the control live trap grid (4.17 acres), but since the species was found in only 23% of this acreage, its density was estimated by dividing 19 by 0.96 acres rather than by the entire 4.17 acres. The actual number of animals caught was used to determine density rather than a calculated total population because small sample sizes with few recaptures generally prevented precise population estimates.

Table 2. Dates of live trapping for each watershed

Watershed	1972	1973	1974
13-Control watershed	June 18-27 July 24-26 Aug. 2-3 Aug. 30-31	June 21- July 8	May 29- June 2
11-Clearcut and range reseeded	July 23- Aug. 2 Sep. 21-28		June 3-7
10-Big game habitat improvement	July 8-17 Aug. 5-6 Oct. 22-23		
8-Silviculturally improved	July 6-15 Aug. 10-11 Aug. 30-31		June 4-8
14-Irregular strip shelterwood		June 21- July 8	May 29- June 2
17-Severely thinned		July 24- Aug. 10	June 8-12

The changes in rodent populations caused by the watershed treatments were evaluated in terms of both density and biomass. Weights for each species on each watershed were averaged, and the averages for species common to several watersheds were compared. Since averages did not differ significantly between watersheds, all weights for each species were pooled to provide an average for total biomass calculations.

Observations of areas sought by deer mice when released from live traps showed they consistently used stumps and downed logs for escape cover. Therefore a correlation was run between deer mice and downed logs more than 6 inches in diameter available for cover. Windrowed slash was not included in the square footage measurement because it consisted primarily of smaller diameter material.

Snap Trapping

Snap trapping was used to obtain specimens for stomach analysis and to provide additional data on species distribution. Museum specials and rat traps were distributed at 10-yard intervals along existing timber inventory transects. These parallel transect lines were spaced 12 to 20 chains apart throughout the watersheds. Trapping was conducted in August and September 1972 and June through August 1973. Fall and winter trapping was unsuccessful because rain and snow triggered or covered the traps. From 50 to 200 traps were set each night. Trapping continued until approximately 20 of the most common species were captured on each watershed.

Gopher Census

Pocket gophers were censused by mound counts using a modification of Howard's (1961) method during August 14-17, 1973. Mound groups were counted in a 13.2-foot-wide strip along the existing timber inventory transects. When a fresh mound was found, no additional mounds were counted for 5 yards. This method assumed a mound group covering a maximum area of 25 square yards and one animal per mound group. Therefore, a direct estimate of the gopher population could be made.

Vegetation Analysis

The different components of the ground cover on the watersheds were measured using a modification of Daubenmire's (1959) method during summer 1972. Ground cover was classed as percent grass, forb, litter, bare soil, and rock to show any significant differences between the watersheds. The percent grass and forb cover also indicated the relative abundance of food available to rodents. An 8- by 20-inch area was measured at each of the 145 to 195 inventory points already established on the existing timber inventory lines on the watersheds. Percent cover for grass and forbs was based on stem area at ground level.

Stomach Analysis

Food preferences during summer were determined by microscopic analysis of their stomach contents based on the method described by Storr (1961) and Anthony (1972). Most plant species have a characteristic epidermal cuticle design by which they can be identified. Most cuticles are not affected by the digestive process and, therefore, provide an accurate means of identifying plant species either in the stomach or in feces.

A reference collection of known cuticle samples was needed for this technique. Common plant species on the Beaver Creek watersheds were collected and dried during summer field work and later made into reference slides. Three slides were made for each species: one of flower or seed material, one from leaves and stem, and one from the root system.

Stomachs of rodents collected by snap trapping were preserved in 10% formalin until ready for processing. The stomach contents were then boiled in 5 to 10 ml of concentrated nitric acid until the plant cuticles separated. These cuticle fragments were then compared with the known cuticle samples.

Habitat Preferences

Ten species of rodents were captured on the Beaver Creek watersheds during trapping in 1972-74. These included the deer mouse, brush mouse, white-throated woodrat, Mexican woodrat, cliff chipmunk, gray-collared chipmunk, golden-mantled ground squirrel, rock squirrel, and the Mexican vole.

The rock squirrel was too large to be consistently caught in either the live or snap traps and, therefore, will not be discussed as part of this study. Also, no further discussion will be made of the Mexican vole because of its apparent rarity on the study areas.

Deer Mouse

The deer mouse was the most characteristic species of the ponderosa pine ecosystem. This species was captured on all six watersheds and was present in every habitat type, although often in low densities. The deer mouse was the principal species found in pure stands of pine, mixed pine-juniper, and in open grassland. This was consistent with the habitat described for deer mice in other studies (Geluso 1971, Jameson 1951 and 1952, Gashwiler 1959 and 1970, Tevis 1956).

A near perfect correlation was found between the population density of deer mice on the grids and the square feet of stumps and downed logs available for hiding and nesting places (fig. 1). The mice consistently hid in the larger logs or stumps. The fallen logs created still air spaces which served as good nesting sites. Nests were also found inside bark which had separated from stumps and logs. Mice were rarely seen entering holes in the ground, and very few dens of this type were found during the study.

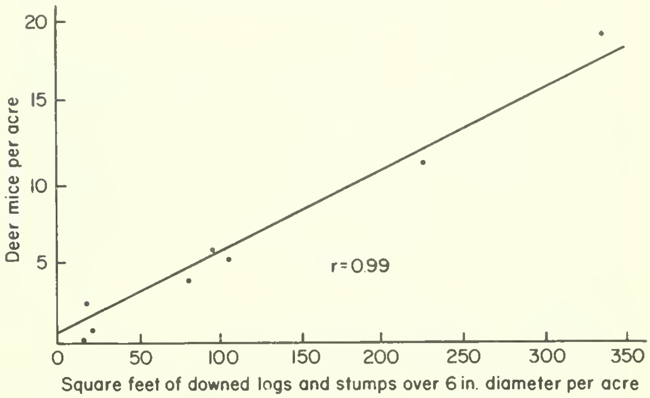

Figure 1.—Response of deer mouse density to increased ground debris in the pine habitat.

The population density of deer mice increased from two mice per acre in areas where debris measured less than 25 square feet per acre to 19 mice per acre when the debris increased to 335 square feet per acre.

Correlation between deer mouse population density and trees per acre, basal area per acre, site index, and percent grass, forbs, litter, rock, and bare soil on each trap site were not significant.

Brush Mouse and Woodrat

The habitat preferred by brush mice, white-throated woodrats, and Mexican woodrats was almost identical. All three species were found in very high density along rock ledges and slides. Studies by Brown (1969), Jameson (1951 and

1952), and Geluso (1971) agree that these species prefer habitat with rock cliffs and brush-rock slopes.

Along these rocky slopes, brush mouse population density ranged from 20 per acre in mild years to 6 per acre after a harsh winter. Woodrat populations varied from 2 to 10 per acre. Eighty-five percent of the recaptures for these species were within 60 feet of the rock ledges, and no recaptures in open ponderosa pine stands were more than 210 feet from rocky cover.

Windrowed slash serves as an additional habitat type used by these species. However, the rodents were seldom captured far from the slash, and none of the marked animals were captured in an adjacent windrow only 100-130 feet away. Brush mouse and woodrat population densities in the slash varied from 4 to 12 per acre and 2 to 11 per acre, respectively.

These species were quite rare in the pure stands of pine and in the mixed pine-juniper areas. Their population densities were slightly higher (one per acre) in the open grassland, possibly because of the rocks and rock crevices found on the ground surface.

Both species of woodrat were consistently caught on the rocky slopes, but only the Mexican woodrat was captured in the windrowed slash. Also, the few individuals found in the pure pine were all Mexican woodrats. Therefore, it appears that the Mexican woodrat may be more adaptable to different habitats than the white-throated woodrat.

Southern Pocket Gopher

Pocket gopher mounds were found on all six watersheds and in most habitat types, but this species was only common on the silviculturally improved watershed. There the gophers found deep soil with abundant grasses and forbs for food. A significant correlation ($r = 0.67$, d.f. 4, $p < 0.10$) was found between number of gophers and percent surface rock, which served as an indicator of top soil depth. Davis et al. (1938) and Miller (1948) found that gophers favored deep soils.

Measurable gopher populations were only found on three watersheds. The pretreated silviculturally improved watershed had a density of 0.22 gophers per acre, and the irregular strip shelterwood and severely thinned watersheds had populations of 0.04 to 0.05 gophers per acre. Studies have found that the size of gopher territories varies considerably with habitat type and population density (Hansen and Remmenga 1961) and that densities may reach 8 to 10 gophers per acre (Ingles et al. 1949). Since gopher population densities on Beaver Creek did not exceed 0.22 per acre, and generally were much less, this species appeared to be relatively unimportant in this ecosystem.

Chipmunk

Since trap success for both species of chipmunks was less than 1% on all areas, habitats used and density estimates were based on observations made during the study.

The cliff chipmunk was consistently observed and occasionally captured in the area where the pine had thinned, but was seldom seen in the untreated pine stands. The gray-collared chipmunk was only seen or captured in dense stands of fairly mature pine and usually at the higher elevations.

Studies by J. H. Brown (1971), Heller (1971), and Sheppard (1971) showed that interspecific competition and altitudinal zonation played key roles in determining chipmunk distribution and population density. Brown (1971:305) stated:

> "*E. dorsalis*, the more aggressive and more terrestrial species, chases *umbrinus* from those areas where the trees are so widely spaced that *umbrinus* must flee on the ground. The competitive advantage immediately shifts to the more social and arboreal *umbrinus* when the trees are sufficiently large and dense that their branches interlock. In these habitats *umbrinus* readily escapes *dorsalis* by fleeing through the trees over routes that the more aggressive species cannot follow. In such situations the aggressive nature of *dorsalis* actually becomes competitively disadvantageous because the more social *umbrinus* is so numerous that *dorsalis* wastes a great deal of time and energy on fruitless chases."

This statement seems to describe observations of cliff and gray-collared chipmunks in the mature forest on the silviculturally improved watershed. Observations of aggression between the two species showed that the cliff chipmunk was dominant and that the gray-collared chipmunk sought protection in the trees when confronted.

The gray-collared chipmunk was only found in the most mature of the forests studied, and also lived at the highest average elevation (7,360 feet). On a nearby watershed (average elevation 7,300 feet), where the pine had been thinned, many cliff chipmunks were found, but the gray-collared chipmunk was not present. However, the gray-collared chipmunk was seen in other nearby stands which contained a wide mixture of pine age classes but always at high elevations. Lowe

(1975) found that gray-collared chipmunks were abundant in the mature forests west of Flagstaff at elevations between 7,400 and 8,000 feet, but that their density decreased as the forest canopy was opened. He found no cliff chipmunks on any of his study sites.

Therefore, it appears that altitudinal zonation separates these species at about 7,300 feet. Along this boundary, the cliff chipmunk dominates the more open forest stands, while the gray-collared is more abundant in the more dense forests.

Population densities of cliff chipmunks varied widely from about 1 per 20 acres in dense pine stands to about 1 per 2 acres in thinned pine stands and along the rock ledges inhabited by woodrats and brush mice.

Gray-collared chipmunk population densities were calculated at 2 per acre in May and 5 per acre in August by another study in Coconino County (Clothier 1969). Observations on Beaver Creek supported these estimates.

Golden-mantled Ground Squirrel

The golden-mantled ground squirrel was abundant in the same habitat where the gray-collared chipmunk was found. The dense, mature forest on the silviculturally improved watershed appeared to be the preferred habitat, but this species was also seen in more open stands but only at high elevations. Lowe et al.[3] found that ground squirrels were abundant in both dense and open forests above 7,400 feet elevation. Therefore, altitudinal zonation appears to limit the distribution of ground squirrels on the Beaver Creek watersheds. Density was estimated at 1 per 4 acres in the denser forests and 1 per 20 acres in more open stands.

Timber Harvesting Effects on Rodent Populations

Three basic habitat types were present in the uncut forest: pure pine, mixed pine-juniper, and rock slopes. Since the treatments involved manipulation of tree density and slash removal, only the first two habitat types were affected. The rock slopes contained high rodent populations, but pretreatment and post-treatment densities were comparable.

The results of each treatment were evaluated on the basis of changes in rodent population density, total biomass, and species diversity comparing populations to the control watershed pine type during the study period. Population changes were assessed for each habitat type and then combined to provide an average density and biomass for the entire watershed.

[3]*Lowe, Philip O., Peter F. Ffolliott, Warren P. Clary, and E. L. Fitzhugh. 1975. Effect of a wildfire on rodent populations in Arizona ponderosa pine. Unpub. rep. Watershed Dep., Univ. Ariz.*

Control Watershed

The untreated control contained two habitat types. Approximately 85% of the watershed was covered by pine stands; the other 15% was rocky canyons.

The pine stands were very poor rodent habitat, because there were few downed trees or little debris to provide cover, and few grasses or forbs to provide food. Rodent population density was calculated at only 1.3 animals per acre, all deer mice. The watershed was too low for ground squirrels or gray-collared chipmunks, and the dense forest excluded cliff chipmunks. Rocky soil made most areas unfavorable for pocket gophers. Biomass for this habitat was 16.5 grams per acre. Figure 2 shows how these density and biomass estimates rank with the other watersheds.

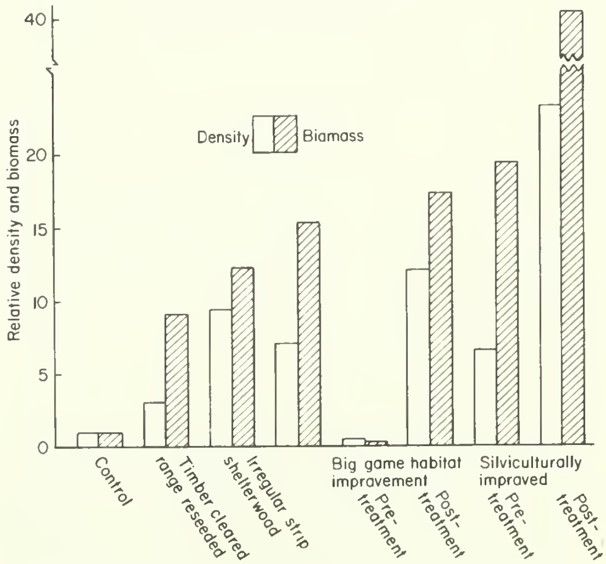

Figure 2.—Rodent density and biomass relative to the control watershed. Base levels on the control watershed were 1.25 animals per acre for density and 16.54 grams per acre for biomass.

The rock canyons proved to be excellent habitat for several species. There were 19.8 brush mice per acre, 2.1 woodrats per acre, 0.5 cliff chipmunks per acre, and 0.1 deer mice per acre for a total of 22.5 animals per acre. The brush mouse was most important in terms of both density and biomass but the woodrat added significantly to the total biomass. The average density for the entire watershed was 4.4 animals per acre and the biomass was 134.1 grams per acre.

Irregular Strip Shelterwood

This watershed bordered on the east edge of the control watershed and, prior to treatment, the areas were similar in tree size and density. About 95% of the watershed was covered by pine which was moderately thinned, and the other 5% consisted of scattered rock outcroppings.

Thinning the pine left many cull logs and large branches scattered on the area. Some of the slash was not piled, and much of that which was piled was not completely burned. The disturbed soil also stimulated forb growth. These conditions created excellent habitat for deer mice. This species had a population density of 11.0 per acre and a biomass of 163.5 grams per acre. These figures show a 782% increase compared to the deer mouse population on the control watershed. The pine also contained small populations of pocket gophers which were probably attracted by the abundant forbs, and Mexican woodrats which were drawn to the unburned slash. Thinning the pine raised the cliff chipmunk population density to the level close to that found in the open rocky canyons of the control watershed. Density in the thinned pine increased 830% to 11.6 animals per acre, and biomass increased 1,133% to 203.9 grams per acre.

The scattered rock outcroppings were not extensive enough to provide a significantly different habitat type, and most densities were the same as those found in the surrounding pine. The total population density of animals throughout the watershed was 11.7 animals per acre and total biomass was 215.5 grams per acre.

Severely Thinned

The pine on this watershed was severely thinned, and the slash was piled in parallel rows. About 80% of the area was covered by pine and the other 20% by windrowed slash. Pretreatment timber inventory indicated this watershed originally had a more dense forest than the control watershed.

The thinned pine, with a density of 5.3 animals per acre was good habitat for deer mice. Cliff chipmunk population density was 0.7 per acre, which was the highest for this species on any of the watersheds. A small population of pocket gophers also was present. These figures indicate a rodent population density 383% higher than that found on the control watershed. Biomass (104.6 grams per acre) increased 533% over that of the control.

The windrowed slash was good habitat for brush mice and Mexican woodrats with respective population densities of 12.1 and 2.4 animals per acre. Since these species were only incidental inhabitants of other thinned or unthinned pine stands, it appears that the slash created "fingers" of new habitat which allowed brush mice and Mexican woodrats to extend their range into the pine. Deer mouse and cliff chipmunk population densities in the windrowed slash were similar to those found in the pine.

Total rodent population density for the watershed was 8.9 animals per acre, and total biomass was 254.3 grams per acre. The most significant aspect of this treatment was the increased species diversity resulting from the windrowed slash. The brush mice and Mexican woodrats comprised 32% of the total rodent density and 49% of the biomass.

Clearcut and Range Reseeded

This conversion from pine to grassland represents the extreme in forest manipulation. About 95% of the habitat was grassland and 5% rock outcroppings.

Deer mouse population density measured 2.6 animals per acre—a 111% increase over the control. Few downed logs, which normally provide nest sites for deer mice, were available, but the machinery used in the logging operation had dislodged many large rocks near the ground surface, creating crevices which served as alternate nest areas.

Additionally, the loss of the tree roots, which stabilized the soil, allowed frost heaving to bring smaller subsurface rock to ground level. Consequently, in 1973, rock covered 35% of the ground surface. This provided habitat for low densities of brush mice and woodrats in the grassland (0.5 and 0.7 animals per acre, respectively). The population density of both species increased to 1.0 per acre in the rock outcroppings.

Rodent population density in the grassland was 192% greater than the control (3.7 animals per acre) and biomass increased 799% to 148.7 grams per acre. The slightly higher densities in the rock outcroppings resulted in a total density on the watershed of 3.9 animals per acre and a biomass of 159.2 grams per acre.

Big Game Habitat Improvement

Three habitat types were present on this watershed: pine covered 60% of the area; mixed pine and juniper covered 30%; and the remaining 10% was comprised of rock slopes.

Before treatment in 1974, the pine stands contained little cover for rodents and supported only about 0.1 animal per acre. The mixed pine-juniper type provided neither the downed logs to attract deer mice nor the surface rock to support brush mice, and, therefore, contained only 0.2 animal per acre (12% of the density in the control forest). Biomass was equally low, measuring 2.6 grams per acre.

The rock slopes averaged 10.8 brush mice per acre, 3.9 white-throated woodrats per acre, and low population densities of deer mice and cliff chipmunks. The brush mice were the most numerous species, but their biomass was only about one-half that of the woodrats.

The watershed averaged 1.6 animals per acre and supported a biomass of 84.3 grams per acre. Both the density and biomass found there were the lowest of all the watersheds.

This watershed was logged in 1974. The prescription calls for a thinning of the pine and creation of scattered openings up to 10 acres. The slash was piled in the clearings. The scattered logs left after treatments and the slash piles provided the necessary habitat for deer mice to increase to 600% of the density found on the control. The piled slash also allowed Mexican woodrats and brush mice to disperse into the pine habitat. In addition, the treatment caused an influx of pinyon mice, not previously found on this watershed. Their population density nearly equalled that of deer mice. The net effect of this treatment was a 4,800% increase in density and a 11,500% increase in biomass in the pine habitat. Rodent populations on the rock slopes did not change after treatment of the pine habitat.

Silviculturally Improved

This watershed had a more mature forest than that found on the control and was higher than the other study areas.

Before treatment in 1974, seven species were found in the pine stands. Two of these, gray-collared chipmunks and golden-mantled ground squirrels, were not present on any other watershed. The deer mouse was the most numerous species with a population density of 3.8 per acre. However, the gray-collared chipmunk was almost as prevalent with 3.0 per acre. The latter species contributed 184.7 grams per acre, which accounted for 58% of the pine type biomass of 320.6 grams per acre. Small populations of brush mice, Mexican woodrats, cliff chipmunks, ground squirrels, and pocket gophers increased the total rodent population density to 7.9 animals per acre (a 532% increase over the control). Excluding the two species not found in the pine on the control watershed because of altitudinal zonation, the density was still 286% above the control level. These figures indicated that more mature pine stands supported a greater population density and diversity of rodents.

The silviculturally improved watershed was logged in 1974. The prescription called for a moderate thinning of the forest and removal of the slash. However, when the study area was trapped in 1975, most of the slash still remained scattered on the ground. This slash created ideal habitat for deer mice which increased in population density to 650% of the pretreatment level. The population density of other species remained unchanged following treatment. Therefore, the net effect of the treatment was a 270% increase in population density (caused entirely by deer mice) and a 100% increase in total rodent biomass.

Food Habits

A review of the literature on food habits of rodents showed the great adaptability of the order *Rodentia*. Ample evidence demonstrates that a species may feed primarily on insects in one habitat while eating only vegetation in another location. This supports the generally accepted opinion that rodents are basically opportunistic, feeding on whatever is most abundant.

Jameson (1952) described the diet of deer mice as consisting mostly of forb and grass seeds in the summer and primarily tree seeds in the winter. Hamilton (1941) found eastern mice fed on insects, vegetation and fruits during the summer and insects and seeds in the winter. Tevis (1956) listed grasses and forbs as comprising 82% of the summer diet of ground squirrels with the other 18% being insects. He found that chipmunks were more insectivorous, eating 22% insects and 78% seeds and vegetation. Many studies showed pocket gophers to be very dependent on forbs (Miller 1964, Vaughan 1967, Ward and Keith 1962, and Tietjen et al. 1967) while other articles stated grasses and pine roots were the staple items (Dingle 1956, Meyers and Vaughan 1964). Differences in habitat and food availability probably account for these variations.

The food habits portion of this study was based on the assumption that the rodents would be opportunistic in their feeding habits. Forty-three of the most common grasses, forbs, trees, and shrubs were collected on the watersheds, and reference slides showing flowers and seeds, leaves and stems, and root samples were made for each plant.

A total of 185 animals were collected in approximately 5,000 trap nights. Chipmunks and ground squirrels were very difficult to trap; therefore, an additional 23 of these species were collected with a shotgun to improve the sample size.

Estimates of the vegetative ground cover on the watersheds showed 57% was grass and 43% was forbs. No estimates were made of seed material present in the ground litter or percentage of ground cover occupied by tree and shrub seedlings. Young's[4] initial studies of insect population density and biomass on the Beaver Creek watersheds showed that both values decreased as the intensity of treatment increased.

The average diet of the Beaver Creek rodents was very consistent for all species except pocket gophers. Insects comprised 15% by volume of the total diet and vegetation or unknowns 85% (fig. 3). The estimate for insects is probably low, because only the legs and exoskeleton were readily identified. Most of the soft parts of the insects were either destroyed by digestion or were not recognized during the analysis. Forbs comprised 58%, grasses 16%, and trees less than 1% of the total volume. Unknowns made up 11% of the diet. Analysis of deer mouse diet showed some variability in plant species eaten on treated versus untreated watersheds but the averages for percent grasses, forbs, and trees were not significantly different. Therefore it appears that the watershed treatments did not alter the rodents' diet. Analysis of the diet for other species between treated and untreated watersheds was not practical because of small sample sizes.

[4]*Young, R. M. 1973. Relative insect density and biomass. p. 17-20.* In *Beaver Creek evaluation project progress report. Unpubl. rep. U.S. Dep. Agric., For. Serv., Rocky Mt. For. and Range Exp. Stn., For. Sci. Lab., Flagstaff, Ariz.*

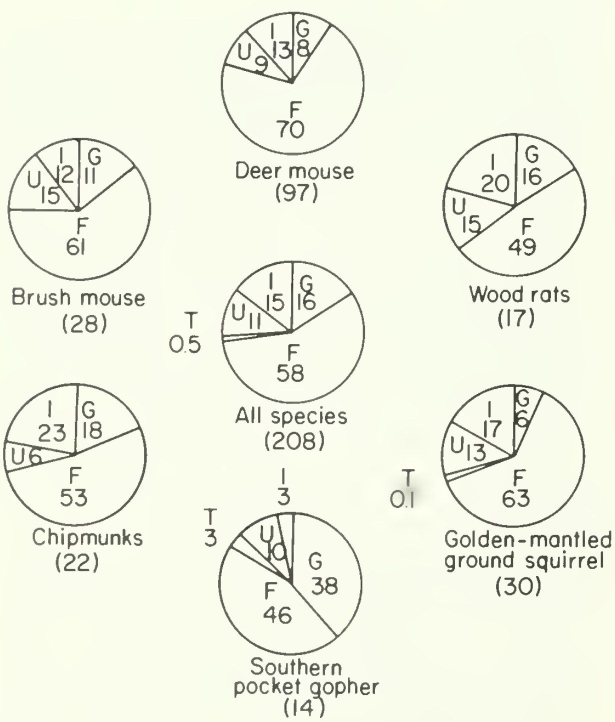

Figure 3.—Percentage of food types found in rodent stomachs collected during summers of 1972-73. Numbers in parentheses indicate sample size; letters stand for grass (G), forbs (F), tree (T), insects (I), and unknown (U). Numbers with letters indicate percent of total.

Although forbs made up 43% of the ground cover, they provided a significantly higher proportion of the average diet (x^2 = 4,269, 4 d.f., $p < 0.05$). Groundsel dominated the diet of all rodents, accounting for 25% of the vegetation eaten. Other important forbs were goldenrod, Arizona agoseris, spreading fleabane, goldenweed, and white sweetclover.

Since the average rodent had an average of 3.8 species in its stomach when captured, it appears that each animal was feeding heavily from a small number of plants. When stomachs were opened in the lab for treatment, the contents were usually layered into different colors and textures of material. Each layer was probably particles of a single plant species. Seed heads and flowers accounted for about 75% of the diet, with leaves and stems providing 25%. Only pocket gophers ate root material.

In summer, rodents ate relatively few ponderosa pine seeds and seedlings on Beaver Creek. Seedlings comprised only 3% of pocket gopher diet, and seeds were an incidental item in the diet of several species. Seeds which are normally dropped in the fall may be eaten during other seasons. Pocket gophers may depend more heavily on pine seedlings during fall and winter when forbs and grasses are less abundant, but because of the low population density of pocket gophers in the study area, there should be little damage to pine reproduction.

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Appendix

Plants

Alligator juniper	*Juniperus deppeana*
Blue grama	*Bouteloua gracilis*
Black dropseed	*Sporobolus interruptus*
Bottlebrush squirreltail	*Sitanion hystrix*
Flannel mullein	*Verbascum thapsus*
Gambel oak	*Quercus gambelii*
Intermediate wheatgrass	*Apropyron intermedium*
Muttongrass	*Poa fendleriana*
Ponderosa pine	*Pinus ponderosa*
Showy aster	*Aster commutatus*
Spreading fleabane	*Erigeron divergens*
Trailing fleabane	*Erigeron flagellaris*
Utah juniper	*Juniperus osteosperma*
Western ragweed	*Ambrosia psilostachya*

Animals

Gray-collared chipmunk	*Eutamias cinereicollis*
Cliff chipmunk	*Eutamias dorsalis*
Uinta chipmunk	*Eutamias umbrinus*
Mexican vole	*Microtus mexicanus*
White-throated woodrat	*Neotoma albigula*
Mexican woodrat	*Neotoma mexicana*
Brush mouse	*Peromyscus boylei*
Deer mouse	*Peromyscus maniculatus*
Pinyon mouse	*Peromyscus truei*
Golden-mantled ground squirrel	*Spermophilus lateralis*
Rock squirrel	*Spermophilus variegatus*
Southern pocket gopher	*Thomomys umbrinus*

Agriculture—CSU, Fort Collins

Goodwin, John G., Jr., and C. Roger Hungerford. 1979. Rodent population densities and food habits in arizona ponderosa pine forests. USDA For. Serv. Res. Pap. RM-214, 12 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Habitat preference, effect of timber harvesting on population densities, and food habits were determined for small rodents inhabiting ponderosa pine in north-central Arizona. *Peromyscus maniculatus* was the major species, with a density of 1 to 11 per acre. Forbs were the primary summer food item for all rodent species. Seeds and flowers comprised 75% of the vegetative diet and leaves or stems 25%. Approximately 85% of the total diet was vegetation and 15% was insects.

Keywords: rodents, timber harvesting, food habits, wildlife habitat.

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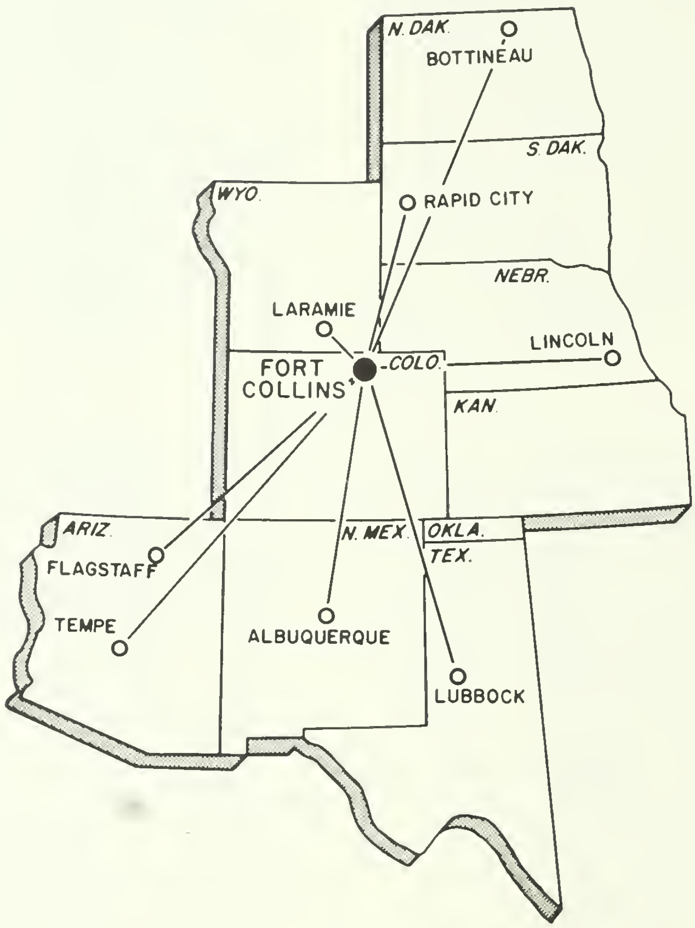

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Carnivora Food Habits and Habitat Use in Ponderosa Pine Forests

Frank J. Turkowski

Research Paper RM-215
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture

Abstract

Major food items of carnivores on the Beaver Creek Watershed (with percentage of scats in which each was found) were mammals 50%, birds 6%, reptiles 3%, arthropods 37%, and plants 60%. Although habitat manipulation influenced carnivore use of the treated watersheds, the modifications were not harmful to most carnivore species.

Plant a tree! Mark the 75th birthday of the Forest Service by giving a living gift to future generations.

JSDA Forest Service
Research Paper RM-215

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Carnivora Food Habits and Habitat Use in Ponderosa Pine Forests

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Contents

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Management Implications

Habitat manipulations alter the food supply of carnivores and thereby influence their populations. Earlier studies have documented that carnivores can be influenced by habitat conditions and prey abundance (Lauckhart 1956, McCord 1974, Rollings 1945, Wood 1952, Wood et al. 1958). Actions that increase grasses and forbs are beneficial to most prey populations, especially if downed trees and slash are left for cover (Chew et al. 1959; Cook 1959; Lawrence 1966; LoBue and Darnell 1959; McCulloch 1962, 1963, 1965, 1966; Reynolds 1964; Turkowski and Reynolds 1970; Turkowski and Watkins 1976). In such instances, predators would ultimately benefit, because their food sources are increased.

Altered habitat conditions also could directly benefit predators by providing more denning sites and cover for stalking prey, and by otherwise improving habitat conditions.

Generally, it appears that although habitat manipulations in ponderosa pine habitat influenced predator food habits and behavior on the Beaver Creek area, the changes are not harmful to most carnivore species, as seen by their use of the treated watersheds as much as the untreated stands of ponderosa pine.

Introduction

At least 12 species of Carnivora including coyotes, gray foxes, bobcats, skunks, raccoons, weasels, and badgers inhabit most ponderosa pine forest areas in the southwestern United States (Hall and Kelson 1959), yet little is known about the role of these predators in this ecosystem. (Scientific names of flora and fauna referred to in this paper are listed in the appendix.) Much of this habitat is being modified by watershed-management techniques; and, though primary consumers are known to be influenced by vegetation manipulation, there is limited knowledge of how these effects are manifested through food chains or food webs to the predators, especially in forest habitats.

Study Area

The Beaver Creek experimental watersheds are on the Coconino National Forest near Happy Jack, Ariz. (fig. 1). Elevations vary from 6,800 to 8,000 feet. Slopes are moderately steep and well drained. Soils are mostly silty clays and silty clay loams. January is the coldest month. The average temperature is 45° F. The average annual precipitation is 25 inches. Summer moisture averages 5 inches, mostly during July and August. Winter moisture is from snow.

Ponderosa pine is the dominant tree. Gambel oak, junipers, New Mexican locust, and aspen are also found in some areas.

Understory plants include Arizona fescue, blue grama, mountain muhly, Junegrass, geranium, peavine, and clover.

The Beaver Creek Project was established during the late 1950's to evaluate watershed treatments. The influences are evaluated by their effects upon water yield, sedimentation, flood control, timber production, forage, wildlife, and esthetics. Pilot treatments in ponderosa pine forests are being tested on watersheds of up to 2,036 acres. There is permanent water on most of the watersheds.

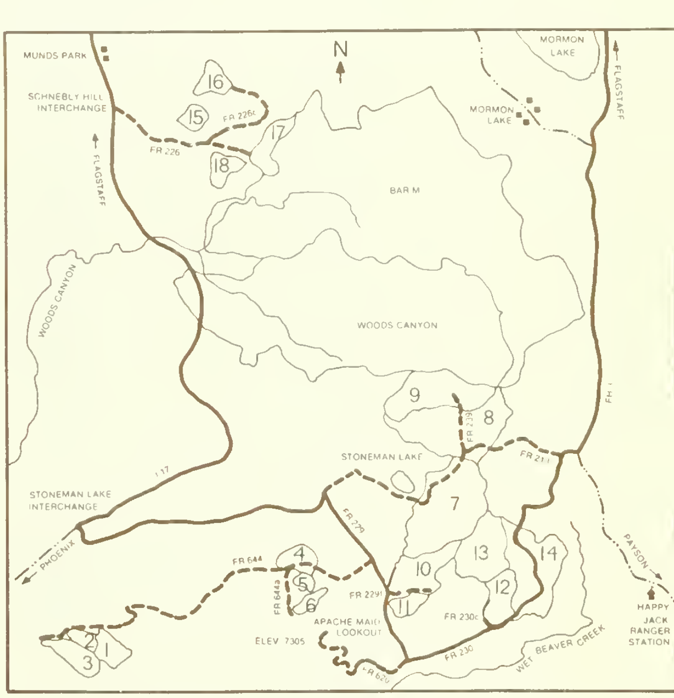

Figure 1.—The Beaver Creek experimental watersheds. Individual watersheds are outlined and numbered.

ecific land-management systems investigated in study were overstory clearcut and slash wind-ed (watershed (WS) 12); one-third overstory clear-vith remainder thinned to 80 square feet of basal per acre (WS 14); overstory thinned to 30 square of basal area per acre (WS 17); and overstory tively cut to a silvicultural standard (WS 8). Addi-l activities were assessed on an area with over- representing natural conditions (WS 13), and on rea with overstory to be cut for wildlife habitat ovement (WS 10) (fig. 1). Check areas adjacent to f the above plots were also assessed.

rnivores known to inhabit the study area were tes, gray foxes, bobcats, mountain lions, black s, striped skunks, badgers, long-tailed weasels, raccoons.

Methods

obtain information on food habits and species position, carnivore droppings were collected each h by driving or walking over a prescribed route of iles of unpaved roads. Each month from March to June 1974 was represented at least once by samples. The route included 12.5 miles in the five ed watersheds and one control watershed, and 8.5 s in untreated areas adjacent to the watersheds. A of 200 miles was driven over study areas during hs without snow, and 30 miles were driven during hs with snowfall. Scats were placed in small ic bags and labeled according to date, location, species. Identification of most scats was made by , size, and shape (Murie 1954) and by associated cs and other markings.

yotes, gray foxes, and bobcats contributed over of the total number of analyzed scats. Track ts also indicated that these species were the most dant carnivores. Scats of coyotes, gray foxes, ats, and mountain lions were easy to distinguish if cats kept their original shape. Many droppings of other predators, especially scats containing large entages of juniper berries or insect remains, were rphous and often indistinguishable. Additional ified scats or stomachs were taken from live-ped or road-killed small carnivores. This technique lied most of the striped skunk and raccoon ples. Scats included in the food habit analysis of all ivores were also obtained from near water tanks coincidental to work off the roads.

cal samples were stored and analyzed by the ods used by Gier (1957), Scott (1941, 1943), Wood 4), Murie (1946), and others for carnivore scat and entary tract analysis. Scats were washed, then ed in a large petri dish of water and floated apart. items were separated into groups of bones, teeth, es, feathers, hair, and invertebrate remains. hers, bones, and hair were dried to bring out col-and facilitate comparisons with study skins and ence skeletons. Data from each dropping were red on forms, then sorted for various analyses.

Fecal analysis has been determined to be a reliable method of determining carnivore food habits. For example, Wood (1954) reported that stomachs, intestines, and scats were similar in frequencies of food for several fur-bearers in Texas. Similar agreement was evident in gray fox habits as reported by Turkowski (1969).

Scat analyses provided general information on food habits of coyotes, bobcats, and smaller predators and allowed for comparisons of food between treated and nontreated areas by the frequency of occurrence of the prey species. Presence of the various food items was expressed in percentages of the total number of times each occurred in all the scats. Many foods were only identified into general categories. However, no item could have greater potential for scoring occurrences than another item with which it was contrasted in the same scat. This treatment included the undetermined items where foods could not be identified beyond a general grouping.

Results

General Diet of Carnivores

A total of 367 carnivore droppings were analyzed. The percent of scats containing food items in each of the major taxonomic categories is listed seasonally by species in table 1. Also presented is a summary of all the items within the major categories that were consumed by all the predators combined. An examination of this combined diet provides some knowledge of energy flow in ponderosa pine forests. Frequency of occurrence of major groups in the combined carnivore diet was: mammals 49.9, birds 6.3, reptiles 3.0, arthropods 37.3, and plants 60.5. In this total diet, arthropods were an important contribution, and many scats contained the remains of these invertebrates exclusively. Juniper berries were also consumed frequently and were found in 48.8% of all the scats, though some carnivore species relied on them more than this combined figure suggests.

Among the mammals used as foods, ungulates were frequent items for the study period. Deer were in 11.3% of the scats and elk were in 6.2%. Some of the deer and antelope, especially those eaten during the winter, were probably taken as carrion since some wounded animals were no doubt present after the hunting seasons. Cattle also contributed to the ungulate food category. The rodents most frequently in the carnivore diet were meadow mice and white-footed mice. Abert squirrels were found in 4.9% of the scats and rock squirrels were in 3.2% of the droppings. Reptiles were a minor percentage of the overall diet. The birds most frequently found were small perching species and the remains of a few turkeys. The reptiles found were lizards and snakes. Frog bones were detected in two scats, and fish scales were found in three droppings.

Table 1.—The frequency of occurrence (percent) of Carnivora scats by seasons from Beaver Creek ponderosa pine habitat containing representations in the major food categories

Carnivora	Season	Number of scats examined	Rabbits and hares	Rodents	Hoofed animals	Total mammal occurrence	Unidentified vertebrates	Birds	Reptiles	Fishes	Arthropods	Juniper berries	Other plants	Total plant occurrence
Coyote	Winter	11	0	9.1	54.5	63.6	0	0	0	0	9.1	54.5	0	54.5
	Spring	12	8.3	33.3	8.3	50.0	0	8.3	8.3	0	66.7	75.0	16.7	83.3
	Summer	15	0	40.0	53.3	80.0	0	1.0	6.7	0	60.0	53.3	33.3	73.3
	Fall	17	5.9	35.2	23.5	76.5	0	0	5.9	0	11.8	76.5	5.9	82.4
	Total	55	3.6	30.9	36.4	67.3	0	1.8	5.5	0	36.4	65.5	14.5	74.5
Gray Fox	Winter	19	0	15.8	10.5	26.3	0	0	0	0	10.5	89.5	5.3	89.5
	Spring	34	2.9	26.5	0	29.4	2.9	2.9	2.9	0	47.1	73.5	2.9	76.5
	Summer	24	4.2	33.3	16.7	50.0	4.2	20.8	4.2	0	87.5	12.5	25.0	37.5
	Fall	23	0	39.1	4.3	47.8	0	13.0	0	0	56.5	43.5	34.8	65.2
	Total	100	2.0	29.0	7.0	38.0	0	9.0	2.0	0	52.0	55.0	16.0	67.0
Bobcat	Spring	10	20.0	80.0	20.0	100.0	10.0	0	20.0	0	40.0	20.0	10.0	30.0
	Summer	35	22.9	65.7	34.3	94.3	2.9	11.4	2.9	0	25.7	5.7	5.7	11.4
	Fall	22	18.2	40.9	40.9	72.7	4.5	18.2	4.5	0	18.2	9.1	18.2	22.7
	Total	67	20.9	59.7	34.3	88.1	4.5	11.9	6.0	0	25.4	9.0	10.4	17.9
Other Carnivora and unidentified scats	Winter	17	0	11.8	29.4	41.2	0	5.9	0	0	11.8	82.4	5.9	82.4
	Spring	47	0	19.1	4.3	27.7	2.1	0	0	0	38.3	76.6	0	76.6
	Summer	23	4.3	13.0	8.7	39.1	4.3	8.7	4.3	8.7	60.9	21.7	21.7	43.5
	Fall	58	1.7	24.1	8.6	34.5	1.7	3.4	1.7	0	24.1	63.8	10.3	72.4
	Total	145	1.4	19.3	3.3	33.8	2.1	3.4	1.4	1.4	33.1	63.4	8.3	70.3
All Carnivora species combined	Winter	47	0	12.8	25.5	38.3	0	2.1	0	0	10.6	57.4	4.3	78.7
	Spring	103	3.9	29.1	4.9	37.9	2.9	1.9	3.9	0	49.5	69.9	3.9	72.8
	Summer	97	10.3	4.1	26.8	68.0	3.1	11.3	4.1	2.1	49.5	18.6	18.6	35.1
	Fall	120	5.0	31.7	15.8	50.0	1.7	7.5	2.5	0	27.5	51.7	15.8	63.3
	Total	367	5.4	31.1	16.9	49.9	2.2	6.3	3.0	0.5	37.5	48.8	11.7	60.5

onal Diet of Carnivores

amination of the food items consumed by all ators by seasons indicated how changing habitat itions related to use of prey animal and plant gy sources. The percentage of mammals in the predator diet was greatest from June to August east from December to May. This correlated with availability as evidenced by the trapping success mall mammals during these periods (Goodwin). Also, many small rodents hibernated or were ive from October through March, which partly unts for their absence in the diet at this time.

nts, mostly juniper berries, were found in from all seasons. These berries were abundant ost watersheds during fall, winter, and spring, their availability was reflected in the diet from ember through May. Birds were most prevalent in iet in summer and fall. Reptiles were least abun- in scats during winter, when reptiles were hiber- g, and were found most frequently during spring summer. Arthropods were consumed most often ghout spring and summer and were found in % of both the spring and summer scats. An in- se in the variety of food categories used within all najor groups in the early fall is probably due to ased energy requirements as young predators are ning adult size, as well as to the availability of the .

nong mammalian foods, rodents were the most fre- t in Beaver Creek carnivore scats. The Abert rel was the most frequent sciurid. Rock squirrels consumed in large numbers. Golden-mantled nd squirrels were also important foods when not in nation. The presence of this ground squirrel and a nunk in the winter diet suggests that these rodents sometimes be taken when hibernating.

eadow mice and white-footed mice were the main malian foods of forest carnivores. They were fre- t in the diet throughout the spring, summer, and Woodrats were in 4.0% of the droppings ighout warmer months, but none were found in er scats. There were fewer rabbits and hares in diet than expected (5.4%). There were also fewer its and hares in carnivore diets on the study area in most locations. The increased incidence of mule in Beaver Creek carnivore diets in summer ths was apparently due to increased fawn con- otion, as evidenced by the many hoofs contained in scats.

ptiles apparently were not taken in relation to availability. Fence lizards were the most frequent le in the diet and were found mostly in the spring fall. Lizards were found three times as often as es were. Another prey source which apparently not used to its fullest was the leopard frog, which abundant in many of the stock-watering tanks on Beaver Creek area. Fish remains were found in spring scats.

thropods were found in the diet during 11 months were taken most frequently in the spring and the summer. That there were arthropods in 10.6% of the winter scats again indicates some carnivores apparently dig beneath the snow to obtain food.

Grasshoppers and crickets were frequent food items. Many scats contained the remains of at least ten grasshoppers. Beetles were also frequent. Many beetles, such as darkling beetles, are large; and, since they were taken frequently, they were probably an important source of energy. Grasses were eaten throughout the year. Their consumption may function in scouring parasites from the alimentary tracts of predators.

As indicated by the average number of food types per scat for each season, dietary variability reflected the abundance of the kinds of foods available in the habitat. Beaver Creek carnivores ate the fewest kinds of items during winter months. For the canines (coyotes and gray foxes), dietary variability was lowest in winter, increased progressively through spring, and then was greatest during the June-August period. September-November scats indicated a decrease in the number of taxa taken by these canines. Coyote variability ranged from an average of 1.7 to 2.7 food types per scat. The number of gray fox food types varied from 1.3 per scat during winter to 3.5 during the summer months. The greatest number of food types per coyote scat was five from a summer sample, as it was for gray foxes. The number of taxa consumed by bobcats was similar during the spring, summer, and fall seasons, averaging from 2.1 to 2.3 per scat with a summer dropping and a fall sample each containing representatives of six taxa.

Coyote Food Habits

A total of 55 coyote scats were analyzed. Considering major food categories for the entire study period, there were mammals in 67.3% of the droppings. Meadow mice were the most frequent rodents, though squirrels were also important. Deer and elk also were frequent in the diet, being found in 16.4% and 9.1% of the scats, respectively. Birds, mostly Passeriformes, were in 1.8% of the scats. Plants and arthropods were in 74.5% and 36.4% of the scats, respectively. Plants were mostly juniper berries and grasses. Lizards were the only reptiles in the diet, and were in 5.5% of the droppings.

Analyses of seasonal food item frequencies (3-month periods) indicated that during the winter coyote diets consisted mainly of juniper berries and mammals, mostly deer and elk. Deer were present in 27.2% of the winter scats, elk in 18.1%. Meadow mice and white-footed mice were the only rodents found during the December-February period. The presence of a lizard in one winter sample, and of arthropod remains in 9.0% of the winter scats, indicates that coyotes may dig beneath and snow and into the ground (or perhaps in rotting logs) to obtain foods. The December-February period had the least variation in kinds of food categories consumed by coyotes.

March-May diets were generally similar to those of winter months, but warmer weather apparently increased the availability of some foods. Insect consumption increased during this season as did the frequency of reptile foods. Arthropods were in 66.7% of the coyote scats. Juniper berries were found in 75.0% of the droppings. Other items found equally in spring coyote scats were cottontails, squirrels, white-footed mice, antelope, and birds (8.3%). There were decreases in frequency of deer and elk. A scarcity of rodents was also evident in coyote diets at this time.

Coyote food habits were the most varied in the summer, including 17 taxonomic categories. Again, arthropods were an important item, being found in 60.0% of the scats. The summer reproductive seasons of small mammalian species increased their availability as prey items; white-footed mice, meadow mice, and woodrats made up a large portion of the summer diet. Rabbits, ground squirrels, and tree squirrels in the diet also increased over the previous season. Juniper berries continued to be available, but consumption declined and these were represented in 53.3% of the summer scats.

September-November scat contents were less varied. Field observations indicated that juniper berries were at their peak availability at this time. They were represented in 76.5% of coyote fall scats. Collectively, mammals were a large portion of the diet during this period. Deer fawns were still available and contributed to 23.5% of the fall scats. Lowering temperatures during this season probably caused the reduction in the number of arthropods consumed by coyotes.

Gray Fox Food Habits

One hundred gray fox scats were analyzed. Plants were found in 67.0% of the scats, mammals in 38.0%, bird remains in 9.0%, reptiles in 2.0%, and arthropods 52.0%. Juniper berries were important to the overall diet, with 55.0% of the fox scats for the entire study period containing these fruits. Rodents were an important mammal contribution to fox diets, with squirrels and deer mice the most significantly abundant species within this group.

Seasonal analyses indicated juniper berries in 89.5% of the December-February fox scats. Deer and antelope were each contained in 10.5% of the winter scats. Presumably most of these were carrion. Since most fawns are well grown by winter, it is unlikely a fox weighing 12 pounds or less could successfully prey upon a juvenile or adult animal. A few ground squirrels were taken during the winter months. Apparently many of these prey animals were in hibernation. Meadow mice were the only other rodents in gray fox diets during the winter.

March-May gray fox scats had a juniper berry frequency of 73.5%. Arthropods were in 47.1% of the spring scats. Mammalian foods also were more abundant than in the previous season; 20.5% of the scats contained remains of white-footed mice. Consumption of cottontails was also greater during this season than in winter. Woodrats were in a few of the summer scats also.

Gray fox diets continued to increase in variability during summer months. Insect consumption increased to an 87.5% frequency, while juniper berry frequency decreased to less than 13%. Rabbits were an important food. The summer diet contained a variety of rodents, including golden-mantled ground squirrels, chipmunks, white-footed mice, woodrats, and meadow mice. Birds also contributed to the diet; 20.8% of the summer scats contained feathers. The tree climbing abilities of gray foxes probably alowed them to take young birds from the nest, as evidenced by the pin feathers detected in some scats.

Fall gray fox diets were similar to summer diets in the number of taxa represented. Arthropods decreased in September-November to a frequency of 56.5. Conversely, juniper berry consumption increased, reaching a frequency of 43.5. White-footed mice and meadow mice each were in 13% of the fall scats. The use of these rodents by foxes was probably a reflection of their increased abundance as a result of the summer reproductive season.

Bobcat Food Habits

A total of 67 bobcat scats were examined in the study period. Mammals were found in 88.1% of all these scats, birds in 11.9%, reptiles in 6.0%, arthropods in 25.4%, and plants in 17.9% of the samples. The more carnivorous diet characteristic of most felines was reflected in the foods of Beaver Creek bobcats. Rodents as a group probably were the major part of the bobcat diet; rodent species were represented in scats throughout the study period. Deer, insects, meadow mice, and cottontails were important foods. Unlike the canines, bobcats consumed few juniper berries.

Apparently few bobcats use the Beaver Creek ponderosa pine habitats during winter, as evidenced by low track counts in the snow and by the absence of winter bobcat scats. Spring food habits of bobcats reflected the return of deer to ponderosa habitats from lower elevations. Meadow mouse remains were found in 30.0% of the droppings during this period. Tree squirrels and ground squirrels were taken, and arthropods contributed to 40.0% of the March-May scats. Rabbits and woodrats were also important foods. Thirteen taxonomic categories were represented in bobcat spring diets.

Twenty categories were represented in bobcat diets during the summer. Arthropods were in 25.7% of the scats, deer remains in 31.4%, and elk in 5.7%. Rabbits were also an important item, with jackrabbits and cottontails combined being found in over one-fifth of the scats. Rock squirrels were in 14.2% of the droppings. Over 11% of the samples contained Abert squirrels. Similar frequencies of birds were evident.

Bobcat fall diets were similar to those of summer. Deer at a 45.5% frequency continued to be an important food. Cottontails, birds, and arthropods were all

o. Declines in woodrat and meadow mouse popu-s were reflected in fall bobcat diets when com- to the items consumed in summer.

of Other Carnivores

e small sample and uneven seasonal distribution ack bear, mountain lion, striped skunk, and on scats placed limitations on interpretations of od habits of these species.

y two scats from black bears were found in rosa habitat; one contained juniper berries, the unidentified small fruits. Scats of small carnivore es were obtained mostly from live-trapped ls. Ten raccoon scats from the Beaver Creek indicated an 80% frequency of juniper berries, of grasses. Arthropods were evident in 30% of the Lizard remains were in one raccoon dropping, ish scales occurred in two scats.

single mountain lion dropping contained mule Abert and red squirrel remains, and a few er berries. Striped skunks contributed six scats, of them containing insects. A white-footed mouse uniper berries each were in one of these skunk .

f Beaver Creek Areas by Carnivores

e of the ponderosa pine watershed areas by carni-species was estimated by application of several ods: for spring, summer, and fall seasons, the er of scats that accumulated per mile of road in area was determined (scats per mile); during r, the number of identified sets of tracks in snow counted to give tracks per mile detected by the ver; the diets of carnivore species were examined ach area, and the number of food items consumed compared to the general availability of the food on each area.

t collections on watershed roads during each h from May through October resulted from about miles driven on the treated watersheds and over miles driven on adjacent untreated areas. There an average of 9.1 carnivore scats per mile on the ed watersheds and 8.7 scats per mile on the un-ed check areas. Comparison of overall predator ith prey availability indicated that WS 10 and the ol watershed had the greatest overall predator Squirrels, cottontails, and turkeys were important ivore foods during winter months, as were juniper es.

e preference for watershed areas shown by large ivores during warmer months was also examined taining selection indices. These were determined viding the average percent of tracks encountered mile traveled by the number of watershed miles led. Use of the areas by coyotes was related to base abundance, which was estimated by trap- and field observations. They used the untreated adjacent to WS 10 most often during the warmer hs, as indicated by the number of scats per mile of road. This watershed and the surrounding area had the greatest number of juniper trees and also rated highest in cottontail abundance. WS 12 and adjacent areas also rated high in coyote preference as well as in arthropod, cottontail, and deer abundance during the summer.

Gray foxes preferred WS 10 and the surrounding area during early summer, perhaps because juniper berries were abundant there at this time. They also preferred WS 12 where slash was windrowed. This area scored high in rodent numbers. There were many white-footed mice in the early summer fox diet. The control watershed was preferred in late summer probably because of the abundance of rodents and arthropods. The area adjacent to WS 17 also was used frequently by gray foxes. Trees on this watershed were heavily thinned with the slash piles left. The area had an abundance of grasshoppers and high populations of rodents in late summer.

In early summer bobcats preferred the control watershed (which was a high deer and elk density watershed), and they also indicated some preference for the adjacent WS 14. During late summer, WS 12 was most important to bobcats.

Winter Use of Watersheds by Carnivora

Predator use of Beaver Creek ponderosa pine habitats and the availability of prey were determined by walking or driving transects over the watershed areas soon after snowfall and recording the numbers of sets of tracks observed per mile. Track counts were made during December and January, and a total of 16.4 linear miles was traveled on the study areas.

Prey species were most available on WS 10, WS 12, and WS 13 during the winter. Most of the tracks observed in snow on all watersheds were small rodents, turkeys, and squirrels. Except for a single elk track on WS 12, ungulate tracks were not observed on any watersheds during the winter.

The abundance of tracks on each watershed indicated coyotes and gray foxes used the Beaver Creek ponderosa pine habitats more than most carnivores during the winter. The control watershed had the highest coyote use, and WS 10 and WS 12 were also important to these species. Gray foxes preferred WS 10 and WS 17. The greatest abundance of small rodents was on WS 17. The abundance of rodents in and adjacent to slash piles on these areas was probably a factor in attracting these predators. The abundance of juniper berries on WS 10 was also probably an important factor in influencing gray fox and coyote use of that area. The greatest density of carnivore tracks per mile was recorded for gray foxes on WS 10. Concentrations of up to 20 tracks per linear mile of transect were found on this area. Coyotes were second in the total density of tracks recorded on an area (10 per mile) which occurred on the adjacent area.

The only bobcat tracks detected on winter transects were on the control watershed. This activity, recorded in January, appeared to be the tracks of a single bobıt. Bobcat tracks (all probably from one animal) were ιso observed on WS 8 during December. Apparently ›bcats migrate to lower elevations during winter onths. Lack of winter bobcat scats detected in ›nderosa pine habitat added further evidence to this ıpposition.

Discussion

Analyses of scats from ponderosa pine habitat ıdicated the general, seasonal, and specific feeding atterns of carnivores. Predator food consumption is ıe result of interactions between many complex ıvironmental conditions and is not always easily ex- ıained. However, it appears that as in most parts of ıeir ranges, carnivores in the ponderosa pine type are pportunistic feeders, using foods that are locally or asonally available. This relationship to food vailability was reflected in the seasonal changes of ıe use of each major food group. The importance of ıy food item at a particular time is probably also ffected by its abundance in the habitat in relation to l other food items. Behavioral changes caused by eproductive seasons, responses to climatic conditions ıd other factors determine the vulnerability of prey ›ecies. Mammals were most frequent in the diet from lay through October, when their activity and eproduction levels were high. These vertebrates were ›nsumed less from December through March, when ıeir numbers and activity levels were reduced or the ıimals were in hibernation.

The increased consumption of deer by coyotes and ›bcats during the fawning season in July may be ecause fawns were easily attainable. Concealment is ıeir primary defense method during the first few eeks after birth. When fawns were larger and less ısceptible to predation, juniper berries were ripe, ıd most predators shifted to eating them and the vailable insects. Cold weather in mid-October iminated insects as a major energy source and again robably caused increased pressure on predators to ›tain other foods. Even with deer, rodent, and insect ›pulations declining at this time, the canines were ›parently able to adapt and use juniper berries as a buffer food" until more easily obtained foods were gain available.

As is the case in most carnivores, diets were most aried when energy demands increased during the enning season in spring and early summer. Availabil- y could have been the only reason birds were taken ıore frequently from March to June, but they did not ppear as important when the carnivores were not earing young. Other foods were taken in higher fre- uencies when carnivores were raising young and ere otherwise taken in lower frequencies. As ex- ected, reptiles and arthropods were most abundant ı the summer diet and were rarely taken during the older months when they were dormant.

Studies on captive animals indicate that diets of the ıore versatile predators, such as coyotes and gray foxes, reflect environmental conditions and prey availability more than food preferences. Gray foxes apparently were highly adaptable to winter conditions in the ponderosa pine habitat as they had the most varied diet among the Beaver Creek carnivores during this season. This probably explains why they were apparently the most abundant carnivore in the ponderosa pine habitats in winter. Their ability to subsist on a winter diet consisting of a large portion of juniper berries is apparently a key to this adaptability. Bobcats were more carnivorous and relied mostly on mammalian foods and apparently sought to avoid unfavorable habitats as indicated by their inactivity in ponderosa pine habitats during winter.

In addition to reducing prey availability, heavy snowfall apparently restricts bobcat movements. The combined results of heavy snow may have caused bobcats to retreat from higher ponderosa pine areas. McCord (1974) concluded that deep snow restricted bobcat movements. He noted that bobcats walked normally in snow less than 6 inches deep; but when they entered a drift above that depth, they retreated and circled it or bounded through it. Marston (1942) found that movement of bobcats was restricted in snows above about 7 inches deep. Nellis and Keith (1968) and Haglund (1966) also suggested that snow consistency was an important factor in the ability of bobcats to capture prey. During winter most Beaver Creek predators used plowed roads for travel when they were available but would occasionally take tangential courses to visit brush piles or small tree stands, apparently to investigate them for the presence of prey. Winter use of roads probably conserves energy by reducing the effort of walking in deeper snow. Of course, availability of food was probably also an important factor in habitat selection during winter. Raccoons and badgers were relatively inactive during winter months, as indicated by the scarcity of their tracks and droppings. A single set of fresh tracks of each of these species was observed in snow on a warm and sunny afternoon.

In addition to sharing certain qualities such as opportunism, Beaver Creek carnivores also showed features which were characteristic of each of their species throughout their ranges. For example, some niche specialization was evidenced by the bobcats on the study area. The bobcats relied heavily on white-footed mice and meadow mice as a major food source, as this species does in many other habitats. In addition to food habits, behavioral patterns (indicated by tracking Beaver Creek predators in snow) were also species specific. Methods of marking scent posts, digging, and other behavioral traits followed rigid patterns characteristic of each species.

It was not determined how many deer and elk taken by Beaver Creek carnivores were carrion. However, in winter, carrion could have made large contributions to the fecal samples examined, as evidenced by an elk calf carcass that was used by gray foxes for several months after it was placed in a dump ground. On one portion of the study area, WS 12, deer and elk made up rge portion of the bobcat diet. McCord (1974) found the high frequency of deer in scat samples of sachusetts bobcats was the result of predation and scavenging on carcasses, and Marston (1942) also d bobcats killed most deer they consumed. ever, other authors reported deer eaten by bob- usually were carrion (Hamilton and Hunter 1939, ngs 1945, Pollack, 1951, Erickson 1955).

it were determined that the large number of fawns n by bobcats on WS 12 were taken by predation, ppears that predator control could be effective is watershed for increasing deer fawn and elk calf ival. The deer and elk probably were attracted to cover, and perhaps the food available on wind- ed slash in WS 12. Thus, in an area known to be a itional fawning or calving ground, a selective con- program for predators would probably enhance ival and thus increase ungulate populations in the ounding suitable habitats.

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Appendix

Flora List

Arizona fescue	*Festuca arizonica*
Blue grama	*Bouteloua gracilis*
Clover	*Trifolium* spp.
Geranium	*Geranium* spp.
Gambel oak	*Quercus gambelii*
Junegrass	*Koeleria cristata*
Juniper	*Juniperus* spp.
New Mexican locust	*Robinia neomexicana*
Mountain muhly	*Muhlenbergia montana*
Peavine	*Lathyrus* spp.
Ponderosa pine	*Pinus ponderosa*
Quaking aspen	*Populus tremuloides*

Fauna list

Abert squirrel	*Sciurus aberti*
Badger	*Taxidea taxus*
Beetles	Coleoptera spp.
Black bear	*Ursus americanus*
Bobcat	*Felis rufus*
Chipmunk	*Eutamias* spp.
Coyote	*Canis latrans*
Cottontail rabbit	*Sylvilagus audubonii*
Crickets	Gryllidae spp.
Elk	*Cervus elaphus*
Grasshoppers	Locustidae spp.
Golden-mantled ground squirrel	*Spermophilus lateralis*
Gray fox	*Urocyon cinereoargenteus*
Jackrabbit	*Lepus californicus*
Leopard frog	*Rana pipiens*
Long-tailed weasel	*Mustela frenata*
Mountain lion	*Felis concolor*
Mule deer	*Odocoileus hemionus*
Pronghorn antelope	*Antilocapra americana*
Raccoon	*Procyon lotor*
Rock squirrel	*Spermophilus variegatus*
Red squirrel	*Tamiasciurus hudsonicus*
Striped skunk	*Mephitis mephitis*
White-footed mouse	*Peromyscus leucopus*
Wild turkey	*Meleagris gallopavo*
Woodrat	Neotoma spp.

Agriculture—CSU, Fort Collins

Turkowski, Frank J. 1980. Carnivora food habits and habitat use in ponderosa pine forests. USDA Forest Service Research Paper RM-215, 9 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Major food items of carnivores on the Beaver Creek watershed (with percentage of scats in which each was found) were mammals 50%, birds 6%, reptiles 3%, arthropods 37%, and plants 60%. Although habitat manipulation influenced carnivore use of the treated watersheds, the modifications are not harmful to most carnivore species.

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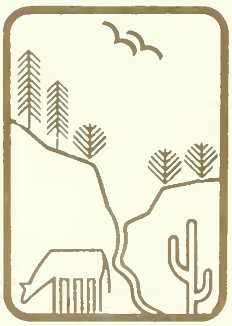
Rocky Mountains



Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

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Research Work Units of the Rocky Mountain Station are operated in cooperation with universities in the following cities:

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Bottineau, North Dakota
Flagstaff, Arizona
Fort Collins, Colorado*
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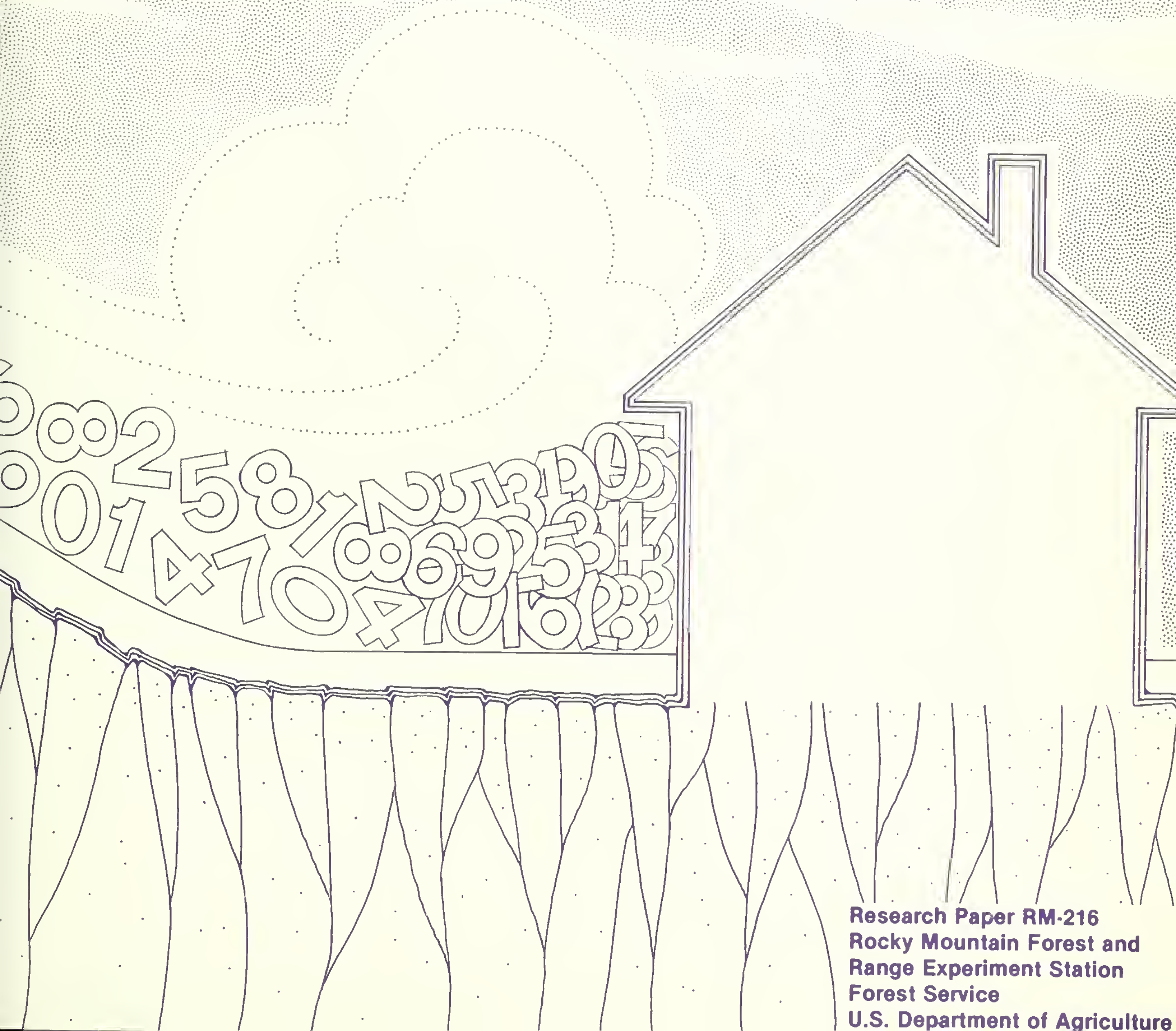
Lincoln, Nebraska
Lubbock, Texas
Rapid City, South Dakota
Tempe, Arizona

*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526

Numerical Simulation of Snow Avalanche Impact on Structures

T. E. Lang and R. L. Brown



Research Paper RM-216
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture

Abstract

A computer model to predict snow avalanche impact on rigid wall structures is developed based on hydrodynamic equations for viscous flow, and admitting a frictional slip-plane lower boundary. Slope normal and vertical wall configurations which extend higher than the height of avalanche flow are evaluated for normal and shear force and overturning moment from avalanche impact. Impact forces and moment time depend upon avalanche leading edge shape.

USDA Forest Service
Research Paper RM-216

June 1980

Numerical Simulation of Snow Avalanche Impact on Structures[1]

T. E. Lang, Professor
Montana State University

and

R. L. Brown, Professor
Montana State University

[1]Research was conducted under Cooperative Agreement 16-627CA between Montana State University and the USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. Headquarters is at Fort Collins in cooperation with Colorado State University.

Contents

Numerical Simulation of Snow Avalanche Impact on Structures

T. E. Lang and R. L. Brown

Management Implications

Power transmission line towers and bases, avalanche sheds, flow diversion barriers, and energy dissipative structures of various shapes are types of structures subject to snow avalanche flow and impact. Design of this type of structure has developed largely from experience and includes large factors of safety, which boost material and labor costs. Little engineering information is available to aid in establishing expected forces and stresses, particularly in situations involving snow impact.

This paper presents results from two analyses of structures impacted by avalanches at various speeds. Forces on the structures are presented in graphical form, so that design specialists may refer to these data to estimate forces and pressures for structures that correspond to those treated in the report.

The computer program developed to obtain the data described above is a general-purpose program available for use by persons involved in structural design. Structures of many different shapes may be input and subjected to snow avalanches of different speeds and depths. Output from the code are contact pressures and forces, flow profiles, and flow velocities of the snow as it impacts and flows around the structure. Thus, an impact becomes a pictorial display of the processes going on.

The numerical approach to representing avalanche flow and impact described in this report is a new development in the methods of dealing with the complex problems of snow avalanche mechanics. Use of the program by others is encouraged so that updates and changes can be made based upon user needs.

Introduction

When snow avalanches impact structures, large forces and pressures are set up that warrant consideration in structural design. Only limited data exist on the forces and pressures that can be expected from avalanches of different speeds and depths of flow. Data are from either actual physical observations of post-avalanche impacted structures, or from planned experiments over limited ranges of the primary parameters of speed-at-impact and flow depth.

Basic contributions to knowledge of snow impact were made by Voellmy (1964), who evaluated evidence from avalanches in Austria. He concluded that pressures in the range of 10 to 20 t/m^2 were necessary to account for the damage noted, and that this pressure range is attributable to the solid core of flowing snow, and not to the airborne component. For calculation of impact pressure, Voellmy proposed a version of the dynamic pressure equation with pressure proportional to the square of the flow velocity (or kinetic energy).

Furukawa (1957) reported results of releasing snow blocks to slide down a slope and impact a wall. Average pressure of impact was measured and correlated to other parameters by the equation

$$p = 3.5\left(1.35v^2 \frac{\varrho^{1.5}}{g}\right)^{0.45}$$

applicable in the range of densities $150<\varrho<550$ kg/m^3 and impact velocity $5<v<20$ m/s. The time constant of the recording oscillograph of these experiments is 0.01 s, so that rapid variations in the loading are smooth. Pressures computed by Furukawa's equation fall into the same range as reported by Voellmy.

Saito et al. (1963) reported the results of experiments made on various avalanche control structures. Avalanche impact forces on posts set up in the avalanche path were measured. Maximum pressure was 30 t/m^2 with a range downward to an average of around 20 t/m^2. No information is given on depth of flow, nor on the nominal density of the impacting snow.

Salm (1964) presented results similar to those of Furukawa, except that force-recording equipment had a shorter time constant, so that millisecond duration pulses were detected. For snow blocks impacting at velocities of 11 to 13 m/s, average pressures were obtained in the range 15 to 20 t/m^2 for impact onto an elastically soft wall. Maximum pressures of load pulses of several milliseconds duration were recorded and found to be two to five times larger than average pressures reported above.

Perhaps the most complete set of data on avalanche impact is reported by Schaerer (1973) based upon a number of avalanche measurements made at Rodgers Pass, British Columbia, Canada.

Pressure gages mounted on posts in avalanche paths were used to monitor average impact pressure. Measurements also were made of depth of flow, nominal density of the snow debris and average avalanche speed. Based upon a dynamic pressure equation, Schaerer compared computed and measured pressures. Average pressures ranged from 3 to 26 t/m^2 for velocity variations from 15 to 53 m/s and flow depths between 1.5 and 1.8 m as evidenced from snow deposits on trees and side walls of the flow channels.

Additional evidence is reported by Mears (1975) based upon analysis of damaged trees in the path of an avalanche in Colorado. For flow speeds in the range of 18 m/s, loading was estimated at 8 to 10 t/m^2 for a flow height of 1.1 m and snow density of 300 kg/m^3.

All of the above results tend to indicate average dynamic pressures up to 30 t/m^2 for flow velocities up to 40 m/s; although incomplete data reporting tends to prevent conclusive ranging. Shimuzu et al. (1973) reported different results based upon measurements of three avalanches in Kurobe Canyon, Japan. Indications from the discussion in this report are that the avalanches were "high speed;" however, no information was presented on the actual range of velocities of the avalanches. Pressures were reported from 32 to 134 t/m^2 depending upon type of recording system, and a maximum pressure of 210 t/m^2 is mentioned without elaboration or explanation. Lacking information on recording system response and velocities of the flows, it is possible to attribute these high pressures to either high impact velocity, or to reporting of maximum pressures of load pulses rather than of pressures averaged over 10 to 100 ms or more, as is done by Salm (1964) and Schaerer (1973).

Having an indication of the nature of the force (distribution in time) of typical avalanche impact, the possibility of computer simulation of the phenomenon was investigated.

This report summarizes new methodology for predicting impact of snow avalanches on structures. The approach involves computer modeling of the flow and impact using an iterative solution of the Navier-Stokes equations of motion for viscous, Newtonian fluid flow. Time and spatial advance of the fluid through the finite difference grid of the flow domain is carried out by iterative refinement of the momentum and mass distributions consistent with the governing equations. Original reporting of a computer algorithm for two-dimensional flow in either a closed or free-surface domain is by Hirt et al. (1975). Modification of this general purpose code to the specific modeling of avalanche flow is reported by Lang et al. (1979), which includes considerable detail on the characteristics and application of the code to avalanche flow problems. This report further modifies this code to facilitate calculation of pressure and force distributions on rigid structures subjected to avalanche impact. Computer simulation data are compared with existing physical information to evaluate its accuracy. Physical properties assumed for snow in the computer model are nominal properties that have been determined to be representative for avalanche runout prediction (Lang et al. 1979).

Computer simulation could be used to develop design criteria for structures without having to accumulate physical data from random avalanches.

Governing Equations and Flow Parameters

The flow characteristics of a possible airborne or snow-dust component of an avalanche must be distinguished from the flow of the denser or core component. Our consideration is directed to the core component, which has a typical velocity range of 20 to 50 m/s. Whether or not the core material behaves the same when surrounded by an airborne component is unknown. For snow having large viscosity, the flow is assumed to be incompressible, which is a conservative approximation when considering pressures and forces of impact upon obstacles.

The numerical analysis of snow avalanche impact is carried out for a "typical" cross-section of the flow, so that it is sufficient to consider two-dimensional forms of the governing equations. For an incompressible, viscous fluid, the equations of motion are the Navier-Stokes equations:

$$\frac{du}{dt} = X - \frac{1}{\varrho}\frac{\partial \varrho}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$$
$$\frac{dv}{dt} = Y - \frac{1}{\varrho}\frac{\partial p}{\partial y} + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \qquad [1]$$

where

u,v = components of velocity (m/s)
t = time (s)
X,Y = components of of body force per unit of density (m^2/s^2)
ϱ = fluid density kg/m^3
p = fluid pressure (Pa)
ν = kinematic viscosity (m^2/s)
x,y = rectangular Cartesian coordinates (m)

and

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y}$$

Equation [1] is not sufficient to solve for the pressure, p, and two components of velocity, u and v. The additional equation needed is the mass continuity equation, which in two dimensions for either homogeneous or heterogenous incompressible flow takes the form

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad [2]$$

This completes the number of equations needed to solve for the unknowns of the problem.

The stresses acting upon a fluid element are:

$$\tau_{xx} = -p + 2\mu\frac{\partial u}{\partial x}$$

$$\tau_{yy} = -p + 2\mu\frac{\partial v}{\partial y} \quad [3]$$

$$\tau_{xy} = \mu\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}$$

where μ is the dynamic viscosity, which is related to the kinematic viscosity by $\nu = \mu/\varrho$. The pressure, p, is assumed to be compressional, and hence a negative contribution to stress. Equation [3] is needed to compute the forces that develop on the impacted obstacle as a result of fluid contact.

Finite difference versions of equations [1] and [2] are actually used in computer code AVALNCH (Lang et al. 1979) to simulate avalanche flow and impact. The code is written so that variable kinematic viscosity and surface friction coefficients can be used to represent the flow. Flow down a slope is simulated by assigning gravity components to the body force intensities, X and Y, of equation [1]. Actual computed parameter values from the code are normalized by material density, so that computed pressure is actually in units p/ϱ (m²/s²), stress is τ_{xx}/ϱ (m²/s²), and total impact force is F_x/ϱ (m⁴/s²). The finite difference grid that represents the flow domain plus a one-cell boundary layer is shown in figure 1.

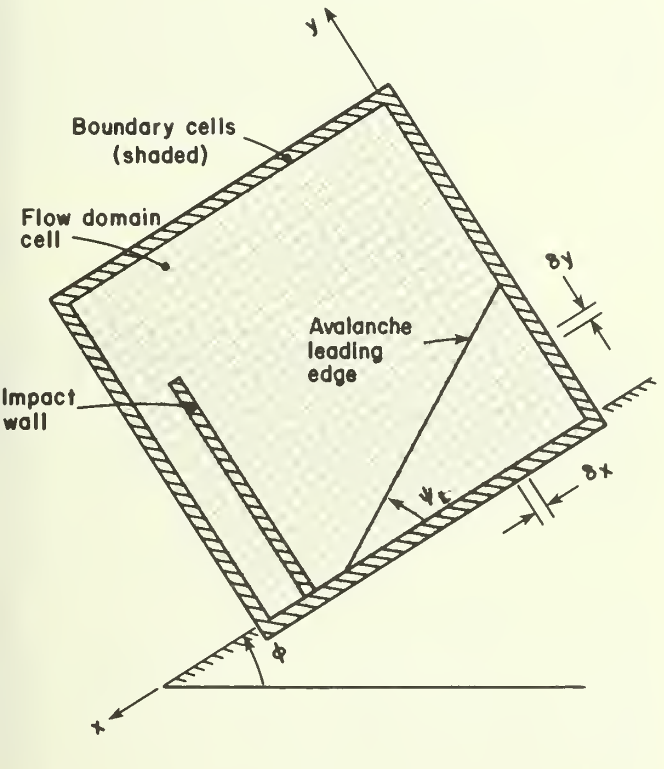


Figure 1.—Arrangement of finite difference grid, avalanche leading edge, and slope-normal impact wall.

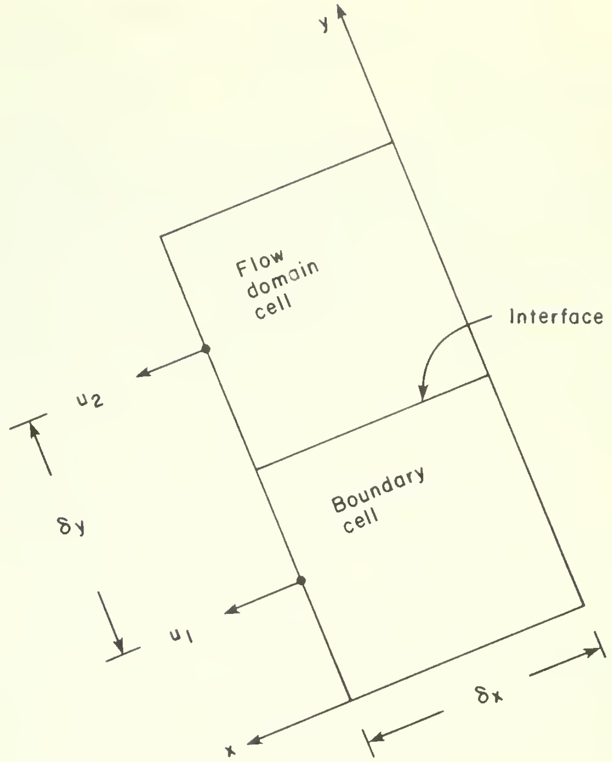


Figure 2.—Boundary cell representation.

Angle ϕ is the angle of the slope on which the avalanche advances. Angle ψ_L is the initial angle of the leading edge of the avalanche, which is assumed to be straight. Parameters δ_x and δ_y are the x and y dimensions, respectively, of an individual cell of the uniform grid. Surface friction is defined by specifying the x component of velocity in the lower boundary cell using the Newtonian shear law. If u_2 is the x component of velocity in the lowest flow domain cell, and u_1 is the corresponding velocity in the lower boundary cell (fig. 2), then

$$u_1 = u_2\ (1 - 2f) \quad [4]$$

where f is the friction coefficient.
If $f = 0$, then $u_1 = u_2$ and the boundary is slip-free.
If $f = 1$, then $u_1 = -u_2$ and velocity at the interface between the cells is zero, which is a no-slip condition. The friction coefficient is related to shear stress at the interface, as follows:

$$\frac{\tau_{xy_0}}{\varrho} = \nu\frac{\partial u}{\partial y} \cong \nu\left(\frac{u_2 - u_1}{\delta_y}\right) = \nu\left(\frac{2u_2 f}{\delta_y}\right) \quad [5]$$

Finally, friction coefficient, f, is assigned to each lower boundary cell individually, so that friction may vary along the slope, depending upon physical circumstances of the problem.

In the remainder of this paper, set $\nu = 0.5$ m²/s and $f = 0.5$, as representative of nominal values for these parameters.

Impact Upon a Slope-Normal Wall

Problem Definition

Much of the experimental data from load cell measurements are taken from test structures in which the sensing elements are arrayed in a line normal to the slope surface. Thus, direct comparison of experimental data and computer simulation data is possible using a slope-normal wall (i.e., a wall perpendicular to the local slope). This geometry is also the simplest case to model using computer code AVALNCH, since the wall representation amounts to a zeroing of velocity components in a single column of cells (fig. 1).

Computer definition of the problem is shown in figure 1. The avalanche leading edge is initially defined by angle ψ_L, and material in all cells to the left of the leading edge are given an initial slope-parallel speed in the range of equilibrium speed for avalanche flow on a slope of angle ϕ. This initial assumption is not correct; but in the first cycle of computations to establish mass continuity, the velocity and pressure values in each cell are adjusted to meet specified compatibility requirements. This results in a change of shape of the leading edge profile from a straight line to other shapes, examples of which are given later as part of the presentation of data. If the initial assumption of slope-parallel speed is close to the nominal speed for a slope of angle ϕ, and with the assumed values for surface friction and viscosity, then the compatibility correction is small. What ensues is a flow in which the leading edge changes shape, but for which the nominal speed of the entire mass does not systematically change with advance of the flow. In all cases, computer runs were made with different initial velocity estimates until the flow showed the persistence in velocity as described above.

Under the driving attraction of gravity, the avalanche flows down the slope, impacts the obstacle, and piles up against it. The numerical algorithm used in program AVALNCH does not admit representation of flow over the top of the obstacle, so, consideration is limited to initial buildup of the impacting snow. A more intricate computer code that admits the overflow condition is being adapted to avalanche flow.

Force Computations

An important consideration is the definition of the resultant forces that act on the impacted wall, as computed from velocity and pressure data determined for each cell. A free body diagram of the normal and shear forces that act between a cell in the i^{th} column and j^{th} row and the wall is shown in figure 3. Also defined are the cell velocity components and the resultant base forces F_N and F_S, and base moment, M_B, needed for equilibrium at the wall. In the case of the slope-normal wall, for the i^{th} column of cells,

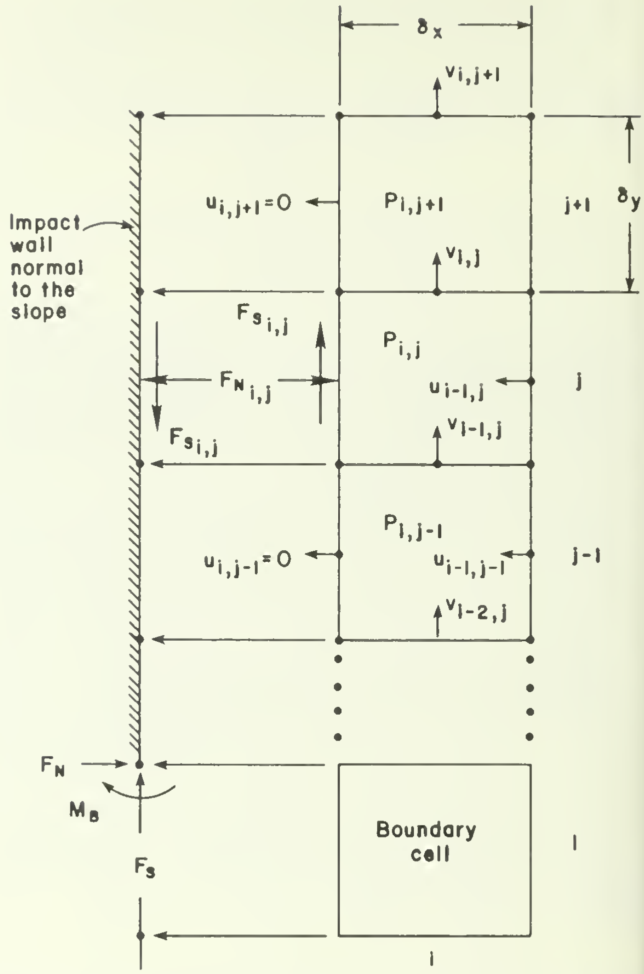


Figure 3.—Parameters and geometry of cells at the impact wall.

$$\frac{M_B}{\varrho} = \sum_{j=2}^{n} \left(\frac{F_{N_{i,j}}}{\varrho} \right) \cdot \delta_y \cdot (j - 1.5) \qquad [6]$$

The upper limit on the sum, n, is the number of cells in the i^{th} column that contains snow. For the top cell that contains snow it may be necessary to use a partial height rather than δ_y in equation 6.

For cell (i, j) the normal force on the wall, using equation 3, is:

$$\frac{F_{N_{i,j}}}{\varrho} = \left(\frac{p_{i,j}}{\varrho} \right) \delta_y - 2\nu \left(\frac{u_{i,j} - u_{i-1,j}}{\delta_x} \right) \delta_y \qquad [7]$$

where $(p_{i,j}/\varrho)$ is the actual quantity computed as "pressure" in AVALNCH. The forces reported are also scaled to unit density by equation [7] so that the units of the term in equation [7] are (m^4/s^2), which assumes force is per unit distance in the third coordinate direction. Total normal force on the wall is then

$$\frac{F_N}{\varrho} = \sum_{j=2}^{n} \frac{F_{N_{i,j}}}{\varrho} \quad [8]$$

Various options can be exercised in computing shear stress (and also shear force). One possibility, which is based on the assumption of a no-slip wall, and a local finite difference definition of the derivatives for shear stress in equation [3] is:

$$\frac{F_{S_{i,j}}}{\varrho} = \nu\left(\frac{u_{i-1,j} - u_{i-1,j-1}}{\delta_y} + \frac{u_{i-1,j+1} - u_{i-1,j}}{\delta_y}\right)\frac{\delta_y}{2} + \nu\left(\frac{v_{i+1,j} + v_{i+1,j-1}}{\delta_x} - \frac{v_{i,j} + v_{i,j-1}}{\delta_x}\right)\delta_y$$

Recognizing zero terms and cancelations in this equation, it reduces to

$$\frac{F_{S_{i,j}}}{\varrho} = \frac{\nu}{2}(u_{i-1,j+1} - u_{i-1,j-1}) - \nu(v_{i,j} + v_{i,j-1}) \quad [9]$$

Alternately, by a coarser grid averaging in which a single shear stress is defined for each cell, the following shear force for cell (i,j) is defined

$$\frac{F_{S_{i,j}}}{\varrho} = \frac{\nu}{4}(u_{i-1,j+1} - u_{i-1,j-1}) - \frac{\nu}{4}(v_{i-1,j} + v_{i-1,j-1}) \quad [10]$$

Although a number of finite-difference methods can be used to define shear stress, equation [9] is used in subsequent evaluations. Using equation [10] implies a surface friction, f, of 0.5, whereas equation [9], with the no-slip condition, implies $f = 1.0$. Total shear force on the wall is then

$$\frac{F_S}{\varrho} = \sum_{j=2}^{n} \frac{F_{S_{i,j}}}{\varrho} \quad [11]$$

Summary and Evaluation of Data for a Slope-Normal Wall

Setup of the problem is shown in figure 1. The total flow domain is modeled by 30 cells along the slope, and 30 cells normal to the slope. All cells are squares 0.05 m on a side. The slope-normal wall is placed in cell number 24, and the leading edge of the avalanche, at the start of flow, is in cell number 21.

Output from program AVALNCH consists of a listing of the pressure per unit density, velocity components, and flow height for each cell at any specified time during the impact. Forces, F_N/ϱ and F_S/ϱ, moment, M_B/ϱ, and maximum pressure, p_M/ϱ, are computed at each time increment of the computations and are listed sequentially. A typical impact condition is considered to outline the results. Slope angle was set at $\phi = 30°$, leading edge angle $\psi_L = 30°$, nominal slope-parallel flow velocity $U_0 = 20$ m/s, and viscosity and friction at $\nu = f = 0.5$. One type of result is the change of shape of the leading edge of the avalanche as the flow progresses (fig. 4). At the instant of impact, the leading elements of the flow have changed from an initial angle of $\psi_L = 30°$, to an impact angle $\psi_I = 76°$. After initial contact, the avalanche front piles against the slope-normal wall with a profile sequence as depicted in figure 4. Maximum pressure and maximum normal force on the wall occur when the flow surface is approximately parallel to the slope (at T = 8.3 ms, for this case). The time histories of the normal and shear forces and the moment at the base of the wall are shown in figure 5. It is seen that a sharp peak in normal force occurs at approximately 8.3 ms into the impact, and persists for approximately 1.5 ms.

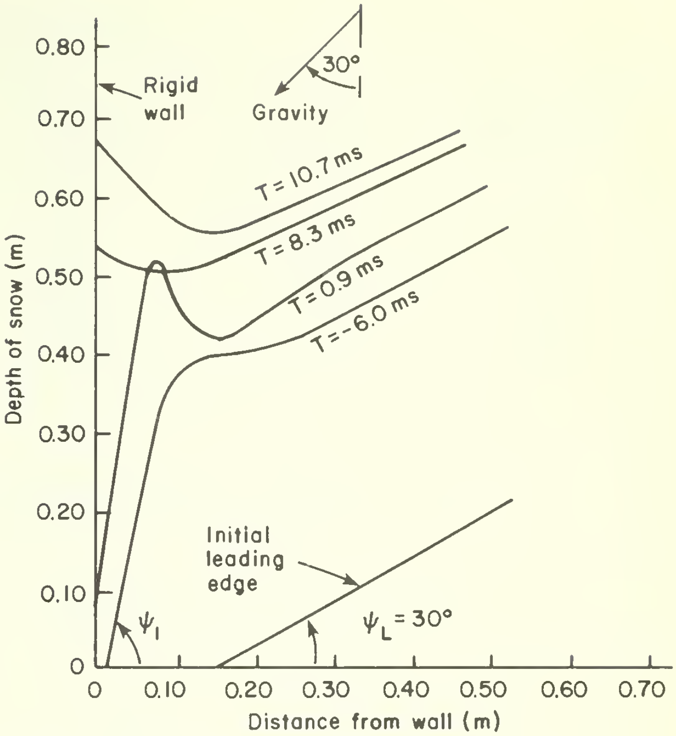


Figure 4.—Distribution of snow upslope from a rigid slope-normal wall of several times measured from time of impact at T = 0.0 s. Slope angle = 30°. Impact velocity = 20 m/s. Kinematic viscosity = 0.5 m²/s. Friction coefficient = 0.5.

The distribution of pressure along the slope-normal wall for the various times into the impact, corresponding to the different snow profiles of figure 4, are shown in figure 6. The pressure distribution corresponding to T = 8.3 ms is 0.1 ms off the time at which the pressure is maximum for the entire impact, at $p_M/\varrho = 2{,}500$ m²/s². Maximum pressure was found to vary with the angle of the leading edge of the avalanche, ψ_L. As ψ_L is changed, the impact angle ψ_I also changes according to the results listed in table 1. Although leading edge angle is more than doubled, impact angle changes by only 13°, but with the angle approaching 90°. Thus, the slope of the frontal face of the avalanche at impact has a pronounced affect on maximum pressure and total force exerted on the wall.

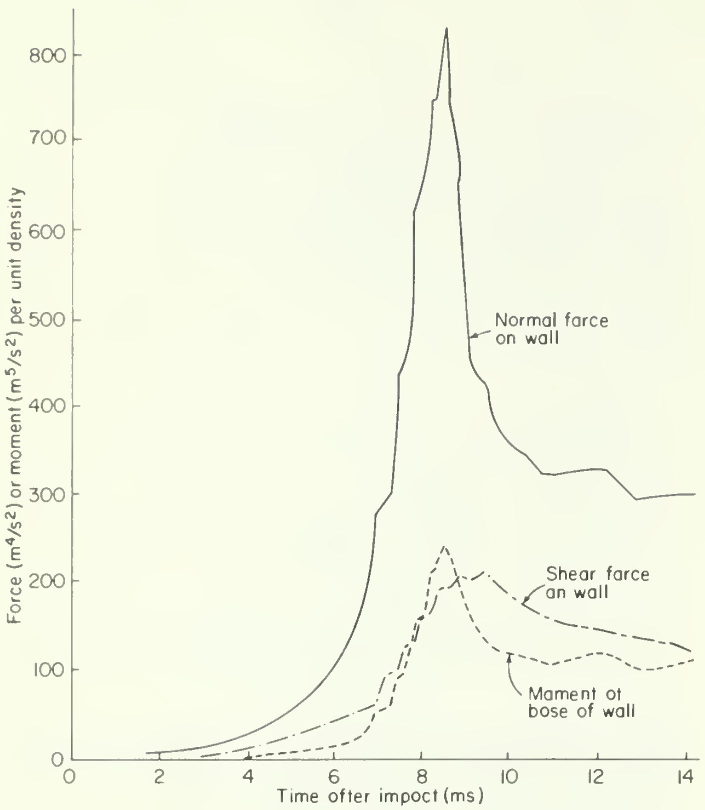


Figure 5.—Force and moment components as functions of time after impact upon a slope-normal wall. Slope angle = 30°. Initial leading edge angle = 30°. Impact velocity = 20 m/s. Kinematic viscosity = 0.5 m²/s. Friction coefficient = 0.5.

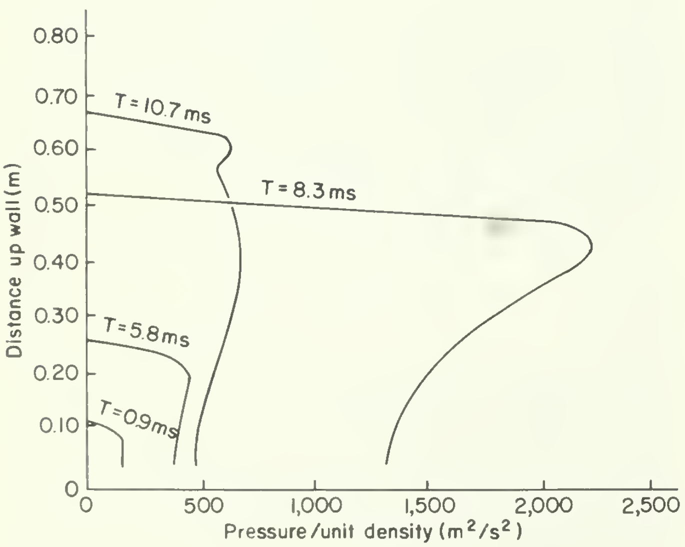


Figure 6.—Distribution of pressure per unit density along slope-normal wall at several times measured from time of impact at T = 0.0 s.

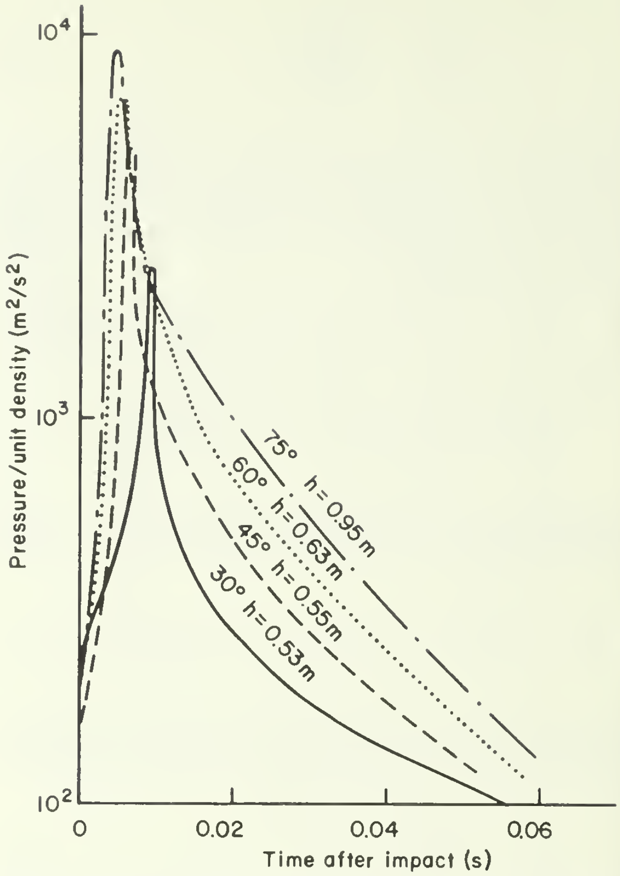


Figure 7.—Pressure profile at height of maximum pressure on wall versus time after impact for avalanche leading edge angles of 30°, 45°, 60°, and 75°.

Using the largest value of maximum pressure per unit density of 9,700 m²/s² (table 1), convert this to an actual pressure value by assuming a nominal snow density of 300 kg/m³ so that

$$P_{act} = \varrho p_M = \left(9{,}700\ \frac{m^2}{s^2}\right)\left(300\frac{kg}{m^3}\right)$$

$$= 2{,}910{,}000\ \text{kg/ms}^2 \text{ or N/m}^2$$

$$= (2{,}910{,}000\ \text{N/m}^2)\ (1\ \text{kg}/9.807\text{N})$$

$$(1\ \text{ton}/1{,}000\ \text{kg})$$

$$p_{act} = 297\ \text{ton/m}^2$$

which is approximately a factor of 10 greater than experimentally measured pressures which are in the range of 30 t/m² as noted in the introduction.

From the physical measurements reported by Schearer (1973), maximum pressure is associated with time durations on the order of 0.1 second. This occurs because of the relatively long time constant of the load-cell type sensor used to monitor force. Thus a pressure peak of 1.5 ms duration would not be detected except in an averaging sense. Therefore, it is necessary to consider the pressure distribution over 0.1 second duration in the analytical results in order to make comparison with experimental data. To this end, the pressure distribution at the height of maximum pres-

Table 1.—Variation in maximum pressure and forces as a function of leading edge angle, ψ_L, for the slope-normal wall geometry

Leading edge angle, ψ_L	Estimated impact angle, ψ_I	Maximum pressure per unit density	Maximum normal force per unit density	Maximum shear force per unit density	Maximum bending moment per unit density
degrees	*degrees*	*m^2/s^2*	*m^4/s^2*	*m^4/s^2*	*m^5/s^2*
30	76	2,500	830	200	240
45	81	4,700	1,750	320	500
60	81	6,700	2,800	500	1,000
75	86	8,700	5,800	1,300	3,600
80	88	9,700	7,200	1,600	5,000

Table 2.—Average pressure on the wall at the height of maximum pressure for different leading edge angles and for a nominal flow velocity of 20 m/s

Leading edge angle	Average pressure per unit density[1]	Average pressure[2]	Height on wall of maximum pressure	Maximum pressure[2]
degrees	*m^2/s^2*	*ton/m^2*	*m*	*ton/m^2*
30	305	9.3	0.53	76.5
45	455	13.9	0.55	144
60	600	18.4	0.63	205
75	815	25.0	0.95	266
80	850	26.0	1.25	297

[1]*Based on 0.1-s time duration since impact.*
[2]*Based upon snow density of 300 kg/m³.*

sure on the wall for four different cases is shown in figure 7. From these data the average pressure can be determined from the area under each curve. The computed values, and the conversion to actual pressures, assuming a snow density of 300 kg/m³, are listed in table 2.

By averaging pressure over 0.1 s, it is seen that computed pressures fall in the same range as experimentally measured pressures. Plotting maximum and average pressures as functions of the estimated impact angles (fig. 8), linear variation, particularly of average pressure, is a good approximation. It should be noted that computation of impact angle is approximate in that the 0.05- by 0.05-m grid assumed in determining these results is not adequate for detailed resolution of the leading edge shape. Because of this limitation, impact angle is based upon straight line approximations of leading edge shape, as depicted in figures 4, A-1, A-3, and A-5.

By changing the angle of the ground surface, avalanches with different nominal flow velocities can be modeled. By doing this, flow velocities of $U_0 = 7$, 10, 15, and 30 m/s were modeled at initial leading edge angles of 30°, 45°, 60°, and 75°. For any given initial leading edge angle, the impact angle for all flow speeds was found to be approximately the same as that reported for the 20 m/s case (table 1). Thus, using different values

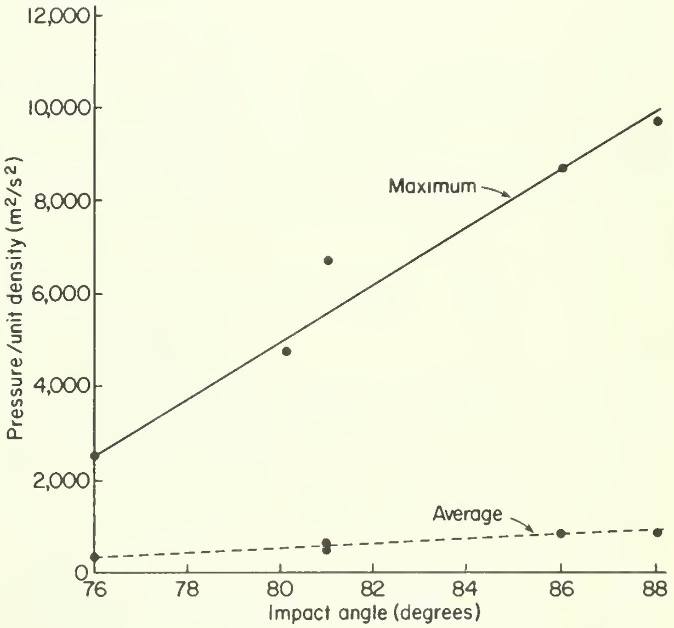


Figure 8.—Variation in maximum and average pressures with estimated leading edge angle for imapct at 20 m/s onto a slope-normal wall. Kinematic viscosity = 0.5 m²/s. Friction coefficient = 0.5.

of leading edge angle at impact, the variation in maximum and average pressure versus the nominal flow speed of the avalanche is shown in figure 9. Results obtained for $U_0 = 7$ m/s show no pressure peak, but rather a monotonic increase in pressure as the snow piles against the wall.

A surface undulation of the snow profile after impact subsides approximately 0.2 m upslope from the impacted wall (fig. 4). Farther upslope from this station, the particles at the surface advance at the nominal speed of 20 m/s. It can be hypothesized that the height of snow at the terminal point of the undulation is representative of the height needed to produce the maximum (or average) pressure of the impact, dependent also upon impact angle. These observed flow heights are summarized for the different nominal flow speeds and impact angles in figure 10. Combining the results of figures 9 and 10 led to the conclusion, for example, that an avalanche moving at 20 m/s and having a nominal leading edge angle at impact of $\psi_I = 76°$, will produce an average pressure of 300 m^2/s^2 per unit of density, a maximum pressure of approximately 2,500 m^2/s^2 per unit of density, and an equivalent flow height of 0.55 m.

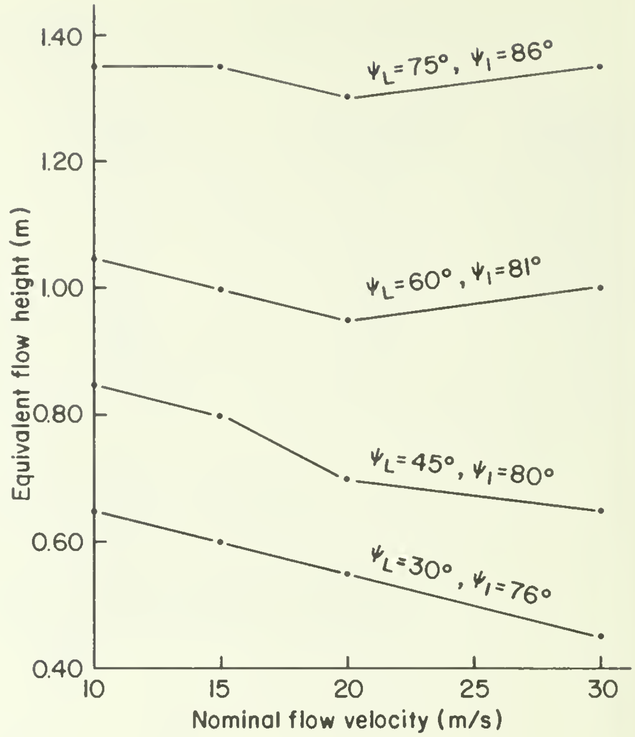


Figure 10.—Equivalent flow height versus nominal flow velocity for different leading edge angles at impact with a slope-normal wall.

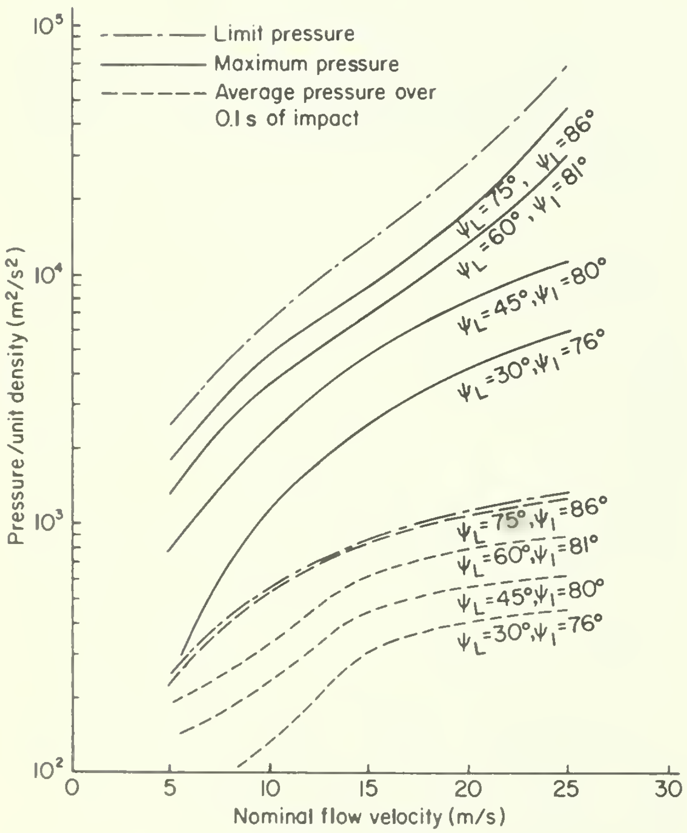


Figure 9.—Variation in pressure versus nominal flow velocity for different leading edge angles at impact with a slope-normal wall.

Impact Upon a Vertical Wall

Problem Description

The vertical wall case represents the geometry when an avalanche impacts against a building or similar type structure. Again, only a two-dimensional approximation of the flow, on what would likely be a three-dimensional problem unless the structure and avalanche are broad, is considered.

As in the slope-normal case, the avalanche is depicted by a constant slope leading edge starting in cell number 21 of a 30 by 30 grid. The case of a nominal flow velocity of 20 m/s is considered to compare maximum pressure and average pressure with the slope-normal case. If differences are not large, then the cost of duplicate computer studies of the vertical wall case are not necessary, and reference can be made to the results of the section on governing equations and flow parameters as typical for both cases. A nominal flow velocity of 20 m/s corresponds to equilibrium flow on a slope of 30°. Thus, to specify a vertical wall, zero velocity cells must be specified in an array as shown in figure 11. Starting at the bottom surface of the grid the 2-2-1 sequencing of steps toward the uphill averages to an equivalent vertical wall.

Listing of the computer code for the vertical wall case is given in Appendix B. Substitute instructions are also inserted for the case of the slope-normal wall. For problem arrays other than 30 by 30 the DIMENSION statement of lines 9 and 10 must be changed. For a nominal impact speed other than 20 m/s, instruction 112 must be changed. If the leading edge of the avalanche is not to start in cell 21, then instruction 110 changes. All remaining data for this code, particularly the input data, is the same as described for program AVALNCH (Lang et al. 1979). Specifically, input instructions are 13, 19, 65, 66, and 68, for which description of the parameters and arrays are given in Appendix A (Lang et al. 1979).

Force Calculations

For the vertical wall geometry it is necessary to distinguish between an open cell and a corner cell (fig. 11). For the open cell, the calculation of normal and shear force at the interface with the wall is that specified by equations 7 and 9. For a corner cell, two normal and two shear forces are specified on the two adjacent fixed boundaries (fig. 12). If the cell number is i,j corresponding to the column and row number, respectively, then the normal forces are computed from the equations

$$\frac{F_{N_1}}{\varrho} = \left(\frac{P_{i,j}}{\varrho}\right)\delta_y - 2\nu\left(\frac{u_{i,j} - u_{i-1,j}}{\delta_x}\right)\delta_y \qquad [12]$$

$$\frac{F_{N_2}}{\varrho} = \left(\frac{P_{i,j}}{\varrho}\right)\delta_y - 2\nu\left(\frac{v_{i,j} - v_{i,j-1}}{\delta_y}\right)\delta_x \qquad [13]$$

where the subscripts follow the order as depicted in figure 3. The two shear forces for the cell are computed by the equations:

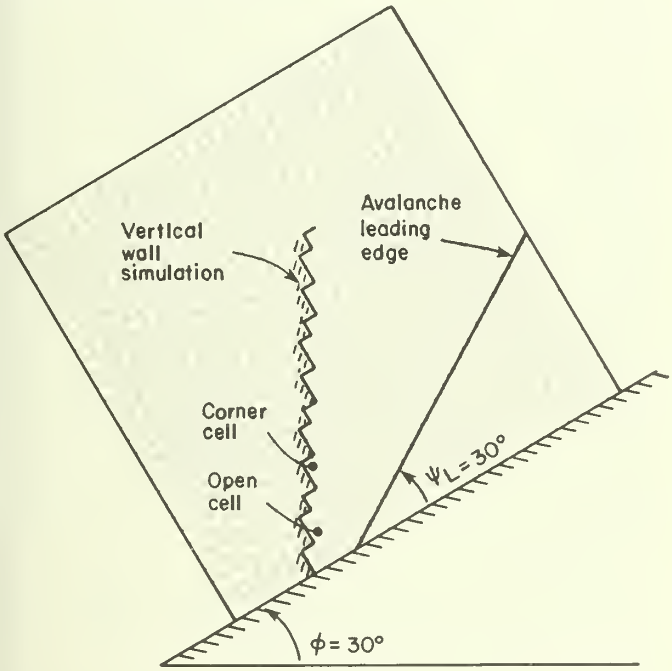


Figure 11.—Grid array and wall geometry for vertical wall impact. Case shown is a 30° slope, for which nominal flow speed is 20 m/s and leading edge angle is $\psi_L = 30°$.

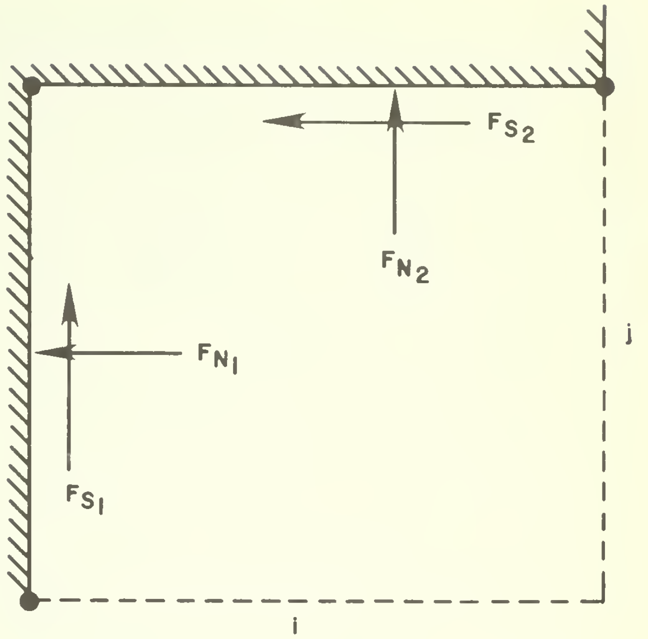


Figure 12.—Forces acting on the boundary of corner cell i, j.

$$\frac{F_{S_1}}{\varrho} = -\frac{\nu}{2}(u_{i-1,j-1} + v_{i,j-1})$$
$$\frac{F_{S_2}}{\varrho} = -\frac{\nu}{2}(u_{i-1,j} + v_{i-1,j-1}) \qquad [14]$$

where $\delta_x = \delta_y$ has resulted in simplification of these equations.

By summing the respective slope-parallel and slope-normal forces of each cell over all cells that contain snow, the total slope-parallel and slope-normal forces are obtained. Total moment at the base of the wall must necessarily include the moment of all force components F_{N_1}, F_{S_1}, F_{N_2}, and F_{S_2} of a corner cell, and F_N and F_S of an open cell as the cells are offset in moving vertically upward.

Summary and Evaluation of Data for a Vertical Wall

The pressure variations at the height of maximum pressure for the four cases of leading edge angles of $\psi_L = 30°$, 45°, 60°, and 75° are shown in figure 13. The evaluation is for the case of a nominal impact velocity $U_o = 20$ m/s, kinematic viscosity $\nu = 0.5$ m²/s, friction at $f = 0.5$, and a slope angle $\phi = 30°$. These values are selected so that the flow in the mainstream of the advancing avalanche is equilibrium flow.

For the case of the vertical wall geometry, the angle between the wall and the upslope ground surface is 60°. For the avalanche cases considered, leading edge angles increase rapidly, and all angles at the instant of impact for the slope-normal geometry equal or exceed $\psi_I = 76°$. At these angles of the leading edge in the case of a vertical wall, upper reaches of the leading edge will contact the wall before the base. This is in contrast to the occurrence in the slope-normal wall geometry in which initial contact is at the base. Thus, different pressure and force histories can be expected for the two geometries. Maximum pressures and average pressures over the initial 100-ms duration of impact as functions of leading edge angle are given in table 3 for the vertical wall geometry. Although peak pressures show a wide variation among the different cases, average pressure varies by less than a factor of 2.0. This is verified by the near equality of areas under the pressure-time curves of figure 13.

Detailed variations in normal force, shear force, and bending moment on the wall for the case of the 30°, leading edge angle avalanche are shown in figure 14. Similar plots for the cases of leading edge angles of 45°, 60°, and 75° are presented in Appendix A (figs. A-7, A-8 and A-9). No attempt is made at plotting the snow surface distribution for the vertical wall case because of uncertainty as to the area of contact at the leading edge as a function of time. To accurately evaluate contact area as a function of time requires only refinement in the finite-difference grid, which is technologically straightforward. Results, at least for the case of $\psi_L = 30°$, show that maximum pressure and force on the vertical wall occur when the impacting snow front piles up until the snow surface is approximately parallel to the ground surface next to the impact surface. This is consistent with the results obtained also for the slope-normal wall.

Table 3.—Variation in pressures as functions of leading edge angle for the vertical wall geometry

Leading edge angle	Maximum pressure per unit density	Average pressure per unit density[1]	Average pressure[2]
degrees	*m²/s²*	*m²/s²*	*ton/m²*
30	730	280	8.6
45	1,200	320	9.8
60	2,200	340	10.4
75	10,600	450	13.8

[1]*Average pressure over initial 100 ms of impact.*
[2]*Based upon snow density weight of 3,000 kg/m³.*

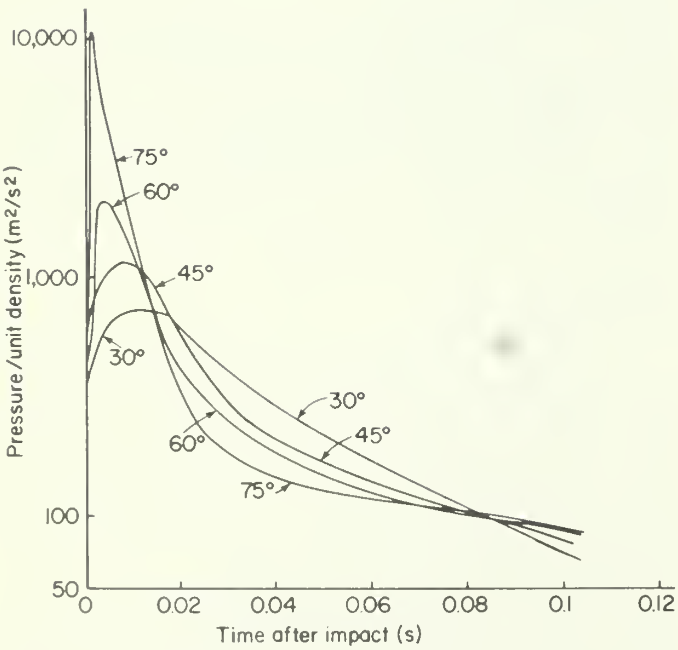


Figure 13.—Pressure profile on vertical wall versus time after impact for avalanche leading edge angles of 30°, 45°, 60°, and 75°. Nominal flow velocity is U_0 = 20 m/s. Kinematic viscosity = 0.5 m²/s. Friction coefficient = 0.5.

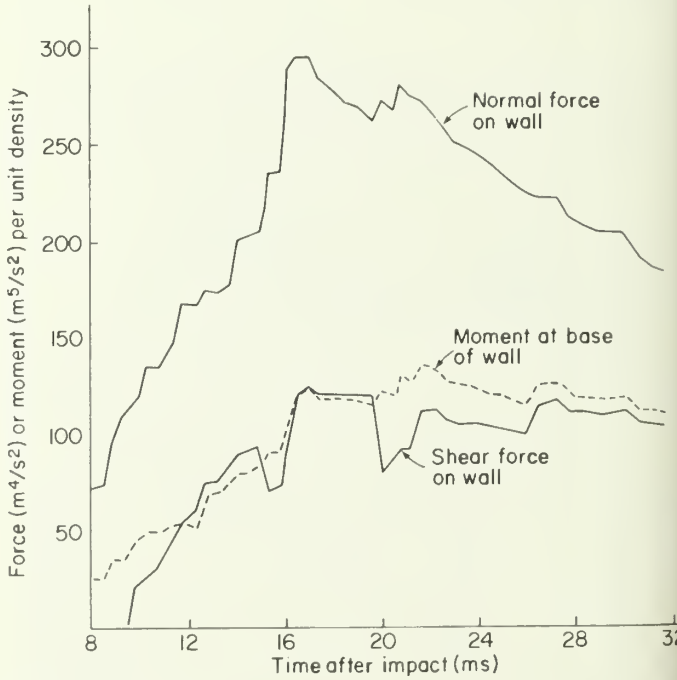


Figure 14.—Force and moment components as functions of time after impact on a vertical wall. Slope angle = 30°. Initial leading edge angle = 30°. Impact speed = 20 m/s. Kinematic viscosity = 0.5 m²/s. Friction coefficient = 0.5.

Table 4.—Average and maximum pressures generated on slope-normal and vertical walls as a function of leading edge impact angle, ψ_l, and for a nominal flow velocity of 20 m/s at impact

	Slope normal wall		Vertical wall	
Leading edge impact angle	Maximum pressure per unit density	Average pressure[1] per unit density	Maximum pressure per unit density	Average pressure[1] per unit density
degrees	m^2/s^2	m^2/s^2	m^2/s^2	m^2/s^2
76	2,500	305	730	280
80	4,700	455	1,200	320
81	6,700	600	2,200	340
86	8,700	815	10,600	450
88	9,700	850	—	—

[1]*Averaged over initial 100 ms of impact.*

Conclusions from Slope-Normal and Vertical Wall Results

Although the computer solutions include calculations of forces and moments on the slope-normal and vertical walls (which is essential information for design), pressure is the fundamental quantity for comparison of the two cases. The average and maximum pressures per unit density for the two cases are given in table 4.

For impact angles of 76°, 80°, and 81°, the slope-normal wall pressures are larger than corresponding vertical wall pressures with larger differences noted for maximum pressures than for average pressures. For an impact angle of 86°, the vertical wall maximum pressure suddenly jumps to a value larger than the corresponding value for the slope-normal case. A plausible explanation for this is that the leading edge of the initial impacting snow is near-parallel to the wall surface at contact. The result of this is a generated maximum pressure of 10,600 m^2/s^2 per unit density that peaks and subsides in less than a millisecond (fig. A-9). This is followed by a pressure tailoff such that average pressure greater than 100 ms is comparable to that of the other impact angle cases. This wave "slapping" action, well recognized in water wave phenomenon, apparently can occur in avalanche impact also, and constitutes the extreme case in pressure generation.

To further verify this occurrence, a fifth case of impact on the slope-normal wall was run. An initial leading edge angle of 80° changes into an estimated impact angle of 88° which results in a maximum pressure of 9,700 m^2/s^2. Assuming a straight-line extrapolation on maximum (and average) pressure versus impact angle (fig. 8), the estimated limit pressure curves of figure 9 are determined for the case of a slope-normal wall. Although not explicitly verified for different nominal flow speeds, computed results indicate that limit pressures for the vertical wall case are of the same order as for the slope-normal case. Since all pressures reported include static pressure plus a velocity gradient term (equation [3]), it is expected that pressures on walls that make small angles with the ground surface would be considerably smaller than the limit pressures reported in figure 9.

It is noted also that the limit pressures cited are based upon avalanche impact with a rigid wall. Any wall flexibility can be expected to decrease the maximum pressure. Additionally, compressibility of the snow itself will also tend to decrease pressure. Neither wall flexibility nor snow compressibility are modeled in the computer representation. Note, if wave reflection inside a specific impacted structural system is considered, internal stresses may develop that are larger than the incident impact pressure.

A more systematic development of pressure peaking is noted in the slope-normal case. There is a sharp peak for all impact angles evaluated. The nominal duration of each peak is from 1.0 to 2.0 ms. Assuming the existence of this type of loading, the question arises whether a pressure pulse of this duration can have significant effect on structural materials. Results of tests on small steel specimens (Newmark and Haltiwanger 1962) show that stresses on the order of twice the yield stress, then applied rapidly, can cause material yielding and fracture within 1.0 ms. However, extrapolation of this to reinforcing steel is not apparent. Although stresses on structures may develop to values beyond yield or fracture values, strains necessary for the failure will not develop because of large inertia effects. Thus, for typical structures made of steel, concrete, or wood, it is unlikely that the millisecond duration pulse will have a significant effect, and design should be predicated upon average pressure response.

From these results we conclude that the specific shape of the leading edge of the avalanche at impact has a significant effect on the maximum pressure that is generated. A worst case geometry has been evaluated from this computer study; however, the statistical probability of its occurrence is not known. To obtain supportive data from field observations, advanced avalanche observation techniques would have to be developed that would allow penetration of the usual snow-air cloud that accompanies all but the slow-moving wet-snow avalanches.

A second recourse, although less accurate than physical measurements, would center on determining the viscous and friction parameters of the flow more accurately than what is currently the case. Then, using this information, steady state flow would be simulated on the computer, and a statistical estimate of the distribution of leading edge angle would be determined by numerical means.

A third (experimental) alternative is to use a number of sensitive pressure transducers with millisecond response capability on a rigid post and measure the relative times of pressure buildup between transducers. This provides a means for estimating the leading edge shape of the more dense flowing snow of an avalanche. From a number of such measurements, a statistical description of leading edge shape would be obtained.

Until such time that more data is available on avalanche flow, recourse to worst case design is the safest approach, although probably not very economical.

Finally, the maximum pressure peaks reported by Salm (1964) and the data given here are compared. The peaks measured by Salm were two to five times greater than average pressures reported, and the pulses show durations on the order of 5 to 10 ms. Results reported here show maximum pressure to be as much as nine times greater than average pressure and the pulses of duration 1 to 2 ms. Whereas, the computed results are for impact upon a rigid wall, the impact in Salm's experiments is against an elastic wall. Based upon physical reasoning, one would expect a decrease in pulse height and spreading of the pulse when impact is changed from a rigid to an elastic wall. Qualitative verification of this is possible in program AVALNCH by inserting a cell at the wall over which velocity is greatly reduced rather than set to zero. Although this has not been done, differences in initial peak-load characteristics between the computer results and those of Salm seem to have a plausible physical basis.

The general conclusion from these computer results is that program AVALNCH has modeling capability for avalanche impact. Uncertainties as to leading edge geometry prevent explicit ranging of expected pressures; however, preliminary results show that upper limits on pressure can be established. Further correlation between computer predictions and field observations are warranted; the types of parameters that need to be measured to provide closer correlations have been identified.

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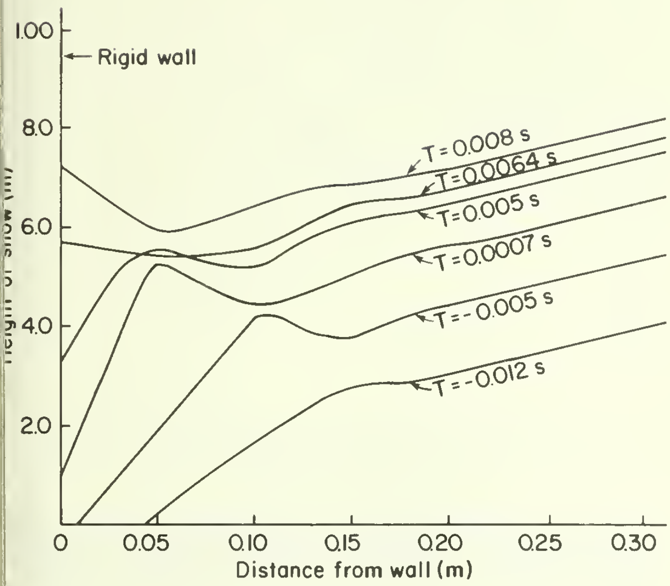
Appendix A

Supplemental Plotted Data



igure A-1.—Distribution of snow upslope from rigid impact wall at several times measured from time-of-impact at T = 0.0. Slope angle = 30°. Leading edge angle = 45°. Flow velocity = 20 m/s. Kinematic viscosity = 0.5 m²/s. Friction coefficient = 0.5.

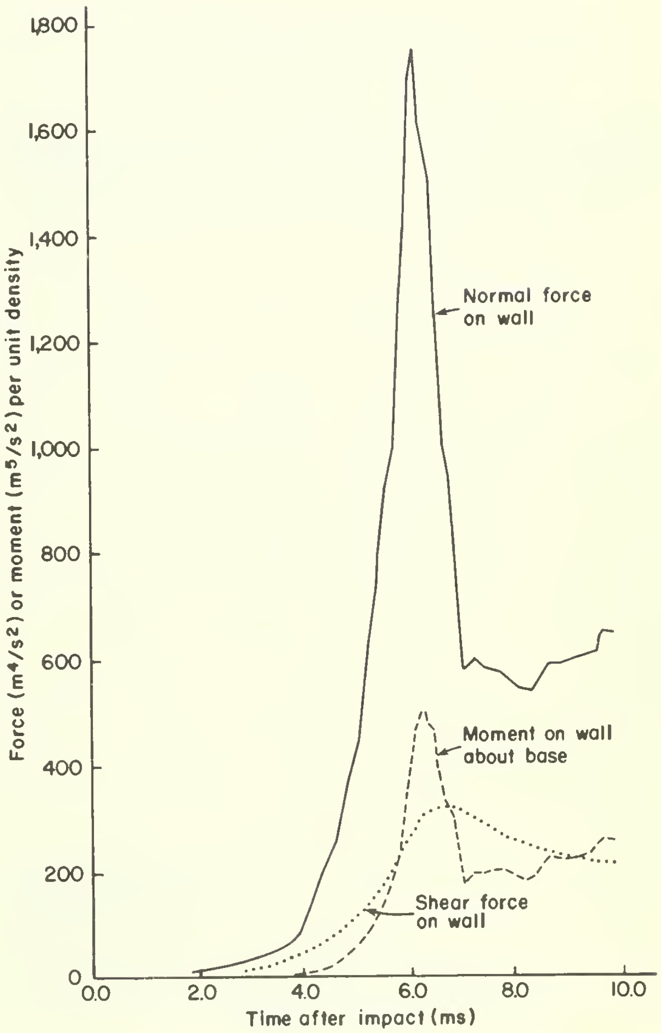


Figure A-2.—Force and moment components as functions of time after impact on a slope-normal wall. Leading edge angle=45°. Flow velocity=20 m/s. Kinematic viscosity=0.5 m²/s. Friction coefficient=0.5.

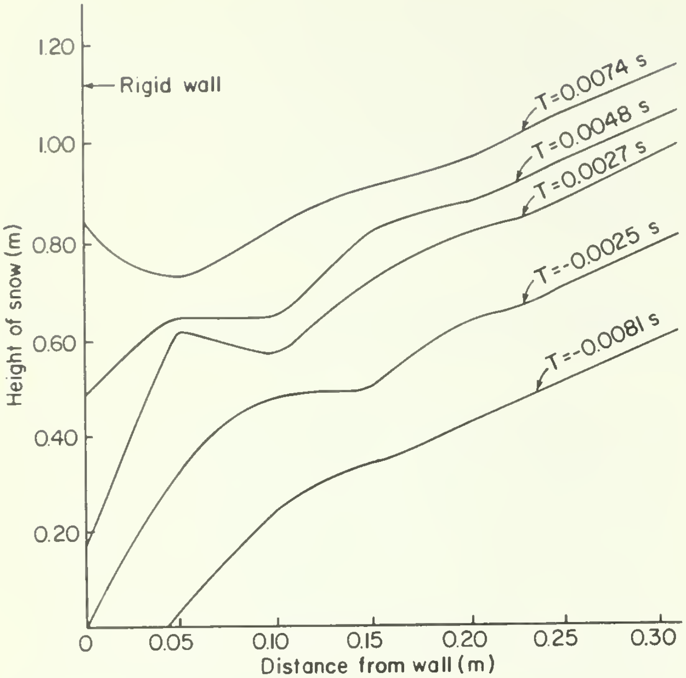


Figure A-3.—Distribution of snow upslope from rigid impact wall at several times measured from time-of-impact at T = 0.0. Slope angle = 30°. Leading edge angle = 60°. Flow velocity = 20 m/s. Kinematic viscosity = 0.5 m^2/s. Friction coefficient = 0.5.

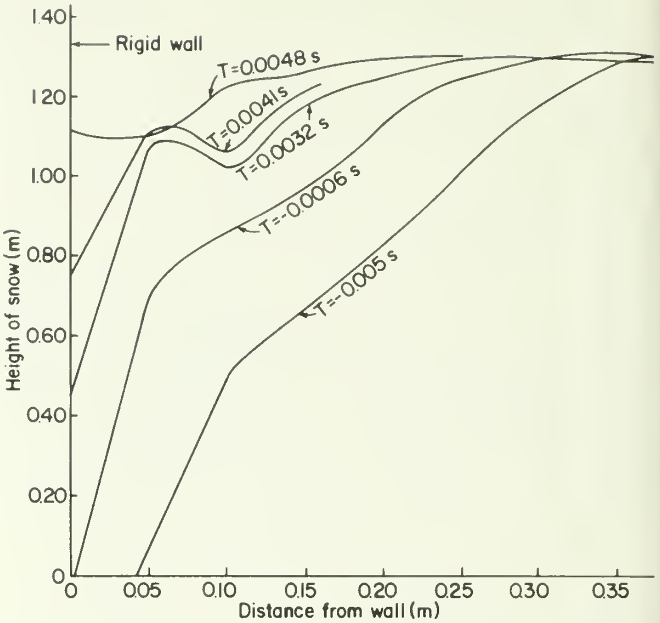


Figure A-5.—Distribution of snow upslope from rigid impact wall at several times measured from time-of-impact at T = 0.0. Slope angle = 30°. Leading edge angle = 75°. Flow velocity = 20 m/s. Kinematic viscosity = 0.5 m^2/s. Friction coefficient = 0.5.

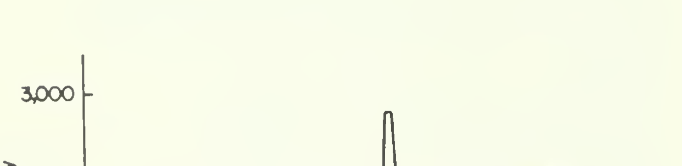
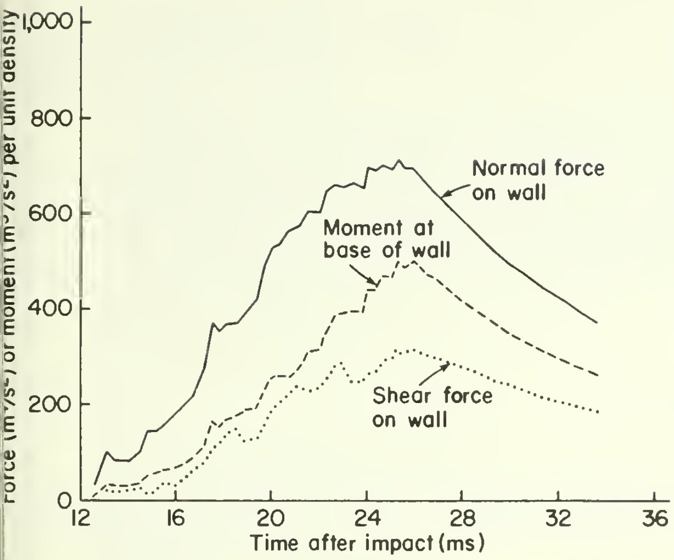


Figure A-4.—Force and moment components as functions of time after impact on a slope-normal wall. Leading edge angle = 60°. Flow velocity = 20 m/s. Kinematic viscosity = 0.5 m^2/s. Friction coefficient = 0.5.

Figure A-6.—Force and moment components as functions of time after impact on a slope-normal wall. Leading edge angle = 75°. Flow velocity = 20 m/s. Kinematic viscosity = 0.5 m^2/s. Friction coefficient = 0.5.



igure A-7.—Force and moment components as functions of time after impact on a slope-vertical wall. Slope angle = 30°. Leading edge angle = 45°. Flow velocity = 20 m/s. Kinematic viscosity = 0.5 m²/s. Friction coefficient = 0.5.

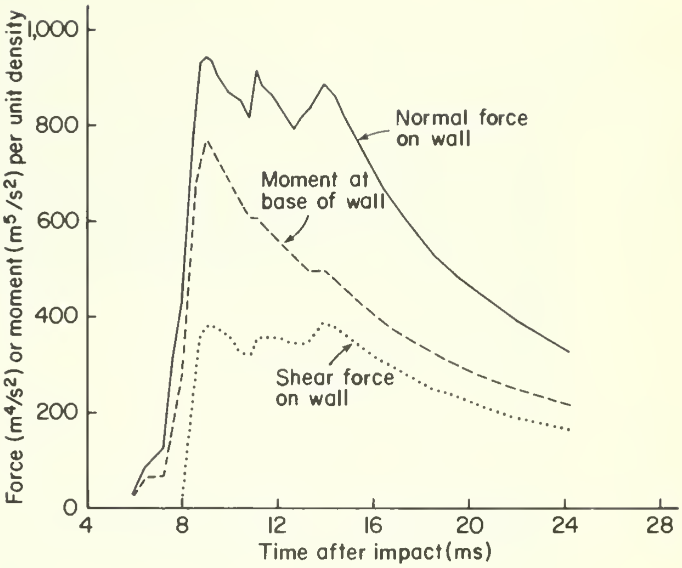


Figure A-8.—Force and moment components as functions of time after impact on a slope-vertical wall. Slope angle = 30°. Leading edge angle = 60°. Flow velocity = 20 m/s. Kinematic viscosity = 0.5 m²/s. Friction coefficient = 0.5.

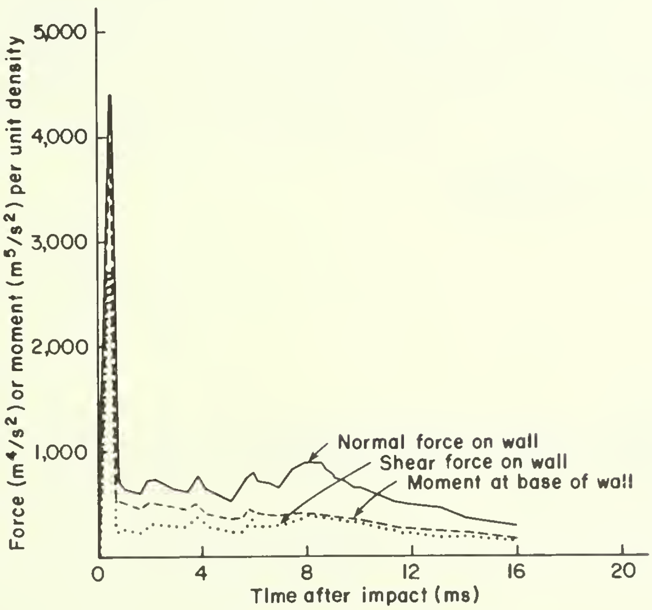


Figure A-9.—Force and moment components as functions of time after impact on a slope-vertical wall. Slope angle = 30°. Leading edge angle = 75°. Flow velocity = 20 m/s. Kinematic viscosity = 0.5 m²/s. Friction coefficient = 0.5.

Appendix B

Listing of Computer Code for Vertical Wall and Inserted Slope-Normal Wall

```
C   PROGRAM IMPACT - VERTICAL WALL.              <------- | SLOPE NORMAL WALL |
*
C    EQUIVALENT HORIZONTAL GRID OPTION
*
C      THIS PROGRAM HAS BEEN DEVELOPED TO NUMERICALLY SOLVE (USING
C      FINITE DIFFERENCE TECHNIQUES) THE NAVIER - STOKES EQUATIONS
C      FOR TRANSIENT FLUID FLOW PROBLEMS.  IT WILL BE USED TO SIMULATE
C      THE PROBLEM OF SNOW AND ICE AVALANCHES ON SLOPES OF VARYING SLOPE.
       DIMENSION U(30,30),V(30,30),UN(30,30),VN(30,30),P(30,30),
      1XPUT( 8),H( 30),HN( 30),JT( 30),NAME(20),GX( 30),GY( 30),FRC( 30)
       REAL NU
       INTEGER CYCLE
       READ (105,45) NAME
       WRITE (108,35)
       WRITE (108,45) NAME
*
C * *  READ AND PRINT INITIAL INPUT DATA
*
       READ(105,25) (XPUT(I),I=1,8)
       IBAR=XPUT(1) ; JBAR=XPUT(2) ; DELX=XPUT(3) ; DELY=XPUT(4)
       NU=XPUT(5)  ;  FRK=XPUT(6)  ;  TWFIN=XPUT(7)  ;  CWPRT=XPUT(8)
       WRITE (108,50) (XPUT(I),I=1,8)
    25 FORMAT(8F10.0)
    35 FORMAT(1H1)
    45 FORMAT(20A4)
    47 FORMAT(6X'I'7X'J'8X'U'13X'V'13X'P'13X'H'9X,'SUR CELL')
    48 FORMAT(4X,I3,5X,I3,4(4X,1PE10.3),6X,I2)
    49 FORMAT(1X'CYCL='I3,1X'ITR='I3,1X'TME='1PE9.2,1X'SNH='E9.2,1X,'UM='
      1E9.2,1X'FX='E9.2,1X'FY='E9.2,1X'TB='E9.2,1X'PM='E9.2)
    50 FORMAT(1H ,1X'IBAR='F4.0,2X'JBAR='F3.0,2X'DELX='F6.2,2X'DELY='F5.2
      1,2X'NU='F4.2,2X'FRK='F4.2,2X'TWFIN='F5.0,2X'CWPRT='F5.0)
    60 FORMAT(8F10.0)
    61 FORMAT(8F10.3)
    70 FORMAT(1H0,35X,'FLOW HEIGHT')
    71 FORMAT(1H0,25X'ELEVATION CHANGE FOR EACH CELL')
    72 FORMAT(1H0,25X,'BOUNDARY FRICTION COEFFICIENTS')
    73 FORMAT(1H0,25X,'SLOPE-PARALLEL GRAVITY COMPONENT')
    74 FORMAT(1H0,25X,'SLOPE-NORMAL GRAVITY COMPONENT')
    75 FORMAT(1H0,30X,'END OF INPUT DATA'//)
    82 FORMAT(5X,'PROBLEM RUNNING TIME EXCEEDED-CALCULATIONS TERMINATED')
*
C * *  COMPUTE CONSTANT TERMS AND INITIALIZE NECESSARY VARIABLES
*
       IMAX=IBAR+2 ; JMAX=JBAR+2
       IM1=IMAX-1  ; JM1=JMAX-1
       RDX=1.0/DELX
       RDY=1.0/DELY
       DELM=DELY/100.
       DELT=.0005
       IM2=IMAX-2
       JM2=JMAX-2
       T=FLG=0.0
       CYCLE=ITER=IND=0
       G=9.8 ; OMG=1.7 ; EPSI=0.5  ; ALPHA=0.1 ; GAMMA=0.1 ; DZRO=1.0
       BETA= OMG/(2.*DELT*(RDX**2+RDY**2))
       ICPRT=INT(CWPRT)
       IF(ICPRT.EQ.1) ICPRT=2
       DO 100 I=1,IMAX
       H(I)=HN(I)=JT(I)=GX(I)=GY(I)=FRC(I)=0.0
       DO 100 J=1,JMAX
   100 U(I,J)=V(I,J)=UN(I,J)=VN(I,J)=P(I,J)=0.0
*
C * *  SPECIAL INPUT DATA
*
       READ(105,60)(H(I),I=2,IM1)
       READ(105,60)(HN(I),I=2,IM1)
       IF(FRK.GT.0.0) GO TO 120
```

```
      READ(105,60) (FRC(I),I=2,IM1)
      GO TO 130
  120 DO 125 I=2,IM1
  125 FRC(I)=FRK
  130 CONTINUE
      DO 150 I=2,IM1
      SP=HN(I)/DELX
      CP=SQRT(1.0-SP*SP)
      GX(I)=G*SP
  150 GY(I)=-G*CP
      WRITE(108,70)
      WRITE(108,61)(H(I),I=2,IM1)
      WRITE(108,71)
      WRITE(108,61)(HN(I),I=2,IM1)
      WRITE(108,72)
      WRITE(108,61) (FRC(I),I=2,IM1)
      WRITE(108,73)
      WRITE(108,61)(GX(I),I=2,IM1)
      WRITE(108,74)
      WRITE(108,61)(GY(I),I=2,IM1)
      WRITE(108,75)

    DETERMINE INITIAL TOP SURFACE INDICES.

      DO 240 I=2,IM1
      JT(I)=INT(H(I)*RDY+1.E-6)+2
      IF(JT(I).GT.JM1) JT(I)=JM1
  240 HN(I)=0.0
      H(1)= H(2)
      H(IMAX)= H(IM1)
      JT(1)= JT(2)
      JT(IMAX)= JT(IM1)

  * * CALCULATE HYDROSTATIC PRESSURE

      DO 280 I=2,IM1
      JT1=JT(I)
      DO 280 J=2,JT1
  280 P(I,J)=-GY(I)*(H(I)-(FLOAT(J)-1.5)*DELY)

  * * SET INITIAL VELOCITY

      DO 310 I=2,21
      DO 310 J=2,JT(I)
      U(I,J)=20.
  310 V(I,J)=0.0
      ASSIGN 4280 TO KRET
      GO TO 2000

  * * START CYCLE

 1000 CONTINUE
      ITER=0
      FLG=1.
      ASSIGN 3000 TO KRET

  * * COMPUTE TEMPORARY U AND V

      DO 1100 I=2,IM1
      JT1=JT(I)
      DO 1100 J=2,JT1
      FUX=((UN(I,J)+UN(I+1,J))*(UN(I,J)+UN(I+1,J))+ALPHA*ABS(UN(I,J)+UN(
     1I+1,J))*(UN(I,J)-UN(I+1,J))-(UN(I-1,J)+UN(I,J))*(UN(I-1,J)+UN(I,J)
     2)-ALPHA*ABS(UN(I-1,J)+UN(I,J))*(UN(I-1,J)-UN(I,J)))/(4.*DELX)
      FUY=((VN(I,J)+VN(I+1,J))*(UN(I,J)+UN(I,J+1))
     1+ALPHA*ABS(VN(I,J)+VN(I+1,J))*(UN(I,J)-UN(I,J+1))
     2-(VN(I,J-1)+VN(I+1,J-1))*(UN(I,J-1)+UN(I,J))
     3-ALPHA*ABS(VN(I,J-1)+VN(I+1,J-1))*(UN(I,J-1)-UN(I,J)))/(4.*DELY)
      FVX=((UN(I,J)+UN(I,J+1))*(VN(I,J)+VN(I+1,J))+ALPHA*ABS(UN(I,J)+UN(
     1I,J+1))*(VN(I,J)-VN(I+1,J))-(UN(I-1,J)+UN(I-1,J+1))*(VN(I-1,J)+VN(
     2I,J))-ALPHA*ABS(UN(I-1,J)+UN(I-1,J+1))*(VN(I-1,J)-VN(I,J)))/(4.*DE
     3LX)
      FVY=((VN(I,J)+VN(I,J+1))*(VN(I,J)+VN(I,J+1))+ALPHA*ABS(VN(I,J)+VN
     1(I,J+1))*(VN(I,J)-VN(I,J+1))-(VN(I,J-1)+VN(I,J))*(VN(I,J-1)+VN(I,J
```

```
     2))-ALPHA*ABS(VN(I,J-1)+VN(I,J))*(VN(I,J-1)-VN(I,J)))/(4.*DELY)
      VISX= NU*((UN(I+1,J)-2.*UN(I,J)+UN(I-1,J))/DELX**2+
     1              (UN(I,J+1)-2.*UN(I,J)+UN(I,J-1))/DELY**2)
      VISY= NU*((VN(I+1,J)-2.*VN(I,J)+VN(I-1,J))/DELX**2+
     1              (VN(I,J+1)-2.*VN(I,J)+VN(I,J-1))/DELY**2)
      U(I,J)= UN(I,J)+DELT*((P(I,J)-P(I+1,J))*RDX + GX(I)-FUX-FUY+VISX)
 1100 V(I,J)= VN(I,J)+DELT*((P(I,J)-P(I,J+1))*RDY + GY(I)-FVX-FVY+VISY)
*
C * * SET BOUNDARY CONDITIONS
*
 2000 CONTINUE
      HN(1)= HN(2)
      HN(IMAX)=HN(IM1)
      JT(1)=JT(2)
      JT(IMAX)=JT(IM1)
C    LEFT WALL CONTINUOUS INFLOW.
C   RIGHT WALL CONTINUOUS OUTFLOW.
      IF(ITER.GT.0) GO TO 2200
      DO 2200  J=1,JMAX
      U(1,J)=U(2,J)
      V(1,J)=V(2,J)
      U(IM1,J)=U(IM2,J)
      V(IMAX,J)=V(IM1,J)
 2200 CONTINUE
C   TOP WALL CONTINUOUS OUTFLOW.
C   BOTTOM WALL RIGID - WITH FRICTION
      DO 2500 I=1,IMAX
      IF(ITER.GT.0) GO TO 2400
      V(I,JM1)=V(I,JM2)
      U(I,JMAX)=U(I,JM1)
 2400 V(I,1)=0.0
 2500 U(I,1)=U(I,2)*(1.0-2.0*FRC(I))
*
C * * FREE SURFACE BOUNDARY CONDITIONS
*
      DO 2650 I=2,IM1
      JT1=JT(I)
      IF(JT(I+1).LT.JT(I)) U(I,JT1)=U(I,JT1-1)
      V(I,JT1)= V(I,JT1-1)-DELY*RDX*(U(I,JT1)-U(I-1,JT1))
 2650 U(I,JT1+1)= U(I,JT1)
*
C * * SPECTAL BOUNDARY CONDITIONS
*
      JNX=1
      J=2
      I=24
 2900 IF(JNX.EQ.6) JNX=1 ; I=I-1
      IF(JNX.EQ.5) I=I-1
      IF(JNX.EQ.3) I=I-1
      IF(J.EQ.21) GO TO 2920
      DO 2910 N=I,IM1
      U(N,J)=0.0
 2910 V(N+1,J)=0.0
      J=J+1
      JNX=JNX+1
      GO TO 2900
 2920 CONTINUE
```

```
      DO 2900 I=24,IM1
      DO 2900 J=1,JM1
      U(I,J)=U0
 2900 V(I+1,J)=0.0
```

```
      GO TO KRET,(3000,4280)
 3000 CONTINUE
*
C * * HAS CONVERGENCE BEEN REACHED
*
      IF(FLG.EQ.0.) GO TO 4000
      ITER=ITER+1
      IF(ITER.LT.500) GO TO 3050
      IF(CYCLE.LT.10) GO TO 4000
      T=1.E+10
      GO TO 4000
 3050 FLG=0.0
*
C * * COMPUTE UPDATED CELL PRESSURE AND VELOCITIES
*
      JB1=2
      DO 3500 I=2,IM1
```

```
      JT1=JT(I)
      DO 3500 J=2,JT1
      IF(J.EQ.JT1) GO TO 3100
      GO TO 3200
3100  ETA=DELY/(HN(I)-(FLOAT(JT1)-2.5)*DELY)
      DELP=(1.0-ETA)*P(I,JT1-1)-P(I,JT1)
      GO TO 3300
3200  D=RDX*(U(I,J)-U(I-1,J))+RDY*(V(I,J)-V(I,J-1))
      IF(ABS(D/DZRO).GE.EPSI) FLG=1.0
      DELP= -BETA*D
3300  P(I,J)=P(I,J)+DELP
      U(I,J)=U(I,J)+DELT*RDX*DELP
      U(I-1,J)=U(I-1,J)-DELT*RDX*DELP
      V(I,J)=V(I,J)+DELT*RDY*DELP
3500  V(I,J-1)=V(I,J-1)-DELT*RDY*DELP
      GO TO 2000
4000  CONTINUE
C
C * * COMPUTE NEW POSITION FOR TOP SURFACE
C
      DO 4100 I=2,IM1
      JT1=JT(I)
      HV= RDY*(HN(I)-FLOAT(JT1-2)*DELY)
      UAV= 0.5*(U(I-1,JT1) + U(I,JT1))
      H(I)=HN(I)              +DELT*(HV*V(I,JT1)+(1.0-HV)*V(I,JT1
     1-1)-0.5*RDX*(UAV*HN(I+1)+GAMMA*ABS(UAV)*(HN(I)-HN(I+1))
     2   -UAV*HN(I-1)-GAMMA*ABS(UAV)*(HN(I-1)-HN(I))))
4100  CONTINUE
C
C * * CALCULATE CELL IN WHICH SURFACE IS LOCATED AND UPDATE ARRAY
C
      DO 4250 I=2,IM1
      JT(I)=INT(H(I)*RDY+1.0E-6)+2
      IF(JT(I).GT.JM1) JT(I)=JM1
4250  CONTINUE
      ASSIGN 4280 TO KRET
      GO TO 2000
4280  CONTINUE
C
C * * CALCULATE TOTAL FLUID VOLUME
C
      FVOL=0.0
      DO 4300 I=2,IM1
4300  FVOL=FVOL+H(I)*DELX
C
C * * ADVANCE U,V,H ARRAYS.
C
4910  UMAX=VMAX=0.0
      DO 4900 I=1,IMAX
      HN(I)=H(I)
      DO 4900 J=1,JMAX
      UN(I,J)=U(I,J)
4900  VN(I,J)=V(I,J)
      DO 4950 I=2,IM2
      DO 4950 J=2,JT(I)
      UT=ABS(UN(I,J))
      VT=ABS(VN(I,J))
      IF(UT.GT.UMAX) UMAX=UT
4950  IF(VT.GT.VMAX) VMAX=VT
```

THESE INSTRUCTIONS REPLACED BY THOSE LISTED ON PAGE 21.

```
*
C * * COMPUTE BASE FORCES AND MOMENT ON WALL
*
      FX=FY=TB=PM=0.0
      JCY=1
      JNX=1
      J=1
      I=24
 4955 J=J+1
      IF(JCY.EQ.5) GO TO 4990
      PA=P(I,J)+2.*NU*U(I-1,J)/DELY
      IF(PA.GT.PM) PM=PA
      IF(P(I,J).GT.0.0.AND.JNX.EQ.1) GO TO 4960
      IF(P(I,J).GT.0.0.AND.JNX.EQ.2) GO TO 4965
      IF(P(I,J).GT.0.0.AND.JNX.EQ.3) GO TO 4960
      IF(P(I,J).GT.0.0.AND.JNX.EQ.4) GO TO 4965
      IF(P(I,J).GT.0.0.AND.JNX.EQ.5) GO TO 4965
      IF(JNX.EQ.1) JNX=2 ; GO TO 4955
      IF(JNX.EQ.2) JNX=3 ; I=I-1 ; GO TO 4955
      IF(JNX.EQ.3) JNX=4 ; GO TO 4955
      IF(JNX.EQ.4) JNX=5 ; I=I-1 ; GO TO 4955
      IF(JNX.EQ.5) JNX=1 ; I=I-1 ; JCY=JCY+1 ; GO TO 4955
 4960 RX=P(I,J)*DELY+2.*NU*U(I-1,J)
      FX=FX+RX
      FY=FY+NU*(U(I-1,J+1)-U(I-1,J-1))/2.-NU*(V(I,J)+V(I,J-1))
      TB=TB+RX*(FLOAT(J)-1.5)*DELY
      JNX=JNX+1
      GO TO 4955
 4965 RX=P(I,J)*DELY+2.*NU*U(I-1,J)
      RY=P(I,J)*DELY+2.*NU*V(I,J-1)
      SX=-NU*(V(I-1,J-1)+U(I-1,J))/2.
      SY=-NU*(U(I-1,J-1)+V(I,J-1))/2.
      FX=FX+RX+SX
      FY=FY+RY+SY
      TB=TB+RX*(FLOAT(J)-1.5)*DELY+SX*(FLOAT(J)-1.)*DELY-RY*(FLOAT(I)-2
     14.5)*DELX
      JNX=JNX+1
      I=I-1
      IF(JNX.EQ.6) JNX=1 ; JCY=JCY+1
      GO TO 4955
 4990 CONTINUE
      SNHT=H(24)
*
C * * LIST VELOCITY, PRESSURE, AND SURFACE POSITION
*
 5000 WRITE(108,49) CYCLE,ITER,T,SNHT,UMAX,FX,FY,TB,PM
      IF(CYCLE.EQ.ICPRT) GO TO 5030
      IF(CYCLE.NE.ICPRT) GO TO 6000
 5030 ICPRT= ICPRT + INT(CWPRT)
 5060 CONTINUE
      WRITE(108,47)
      DO 5250 I=15,25
      JT1= JT(I)
      JT2=JT1+1
      DO 5250 J=1,JT2
      WRITE(108,48) I,J,U(I,J),V(I,J),P(I,J),H(I),JT1
 5250 CONTINUE
      IF(IND.EQ.2) GO TO 6520
*
C * * RECOMPUTE CONTROL PARAMETERS.
*
 6000 IF(CYCLE.EQ.0) GO TO 6300
      DTX=DELX/UMAX
      DTY=DELY/VMAX
      DELT=AMIN1(DTX,DTY)/3.0
      IF(ITER.LT.10) DELT=1.5*DELT
      IF(NU-1.E-6.LT.0.0) GO TO 6300
      DET=(DELX*DELY)**2/(2.*NU*(DELX**2+DELY**2))
      IF(DELT.LT.DET) GO TO 6300
```

```
      DELT=0.9*DET
6300  T=T+DELT
      IF(CYCLE.EQ.0) GO TO 6400
      DAX=UMAX*DELT/DELX
      DAY=VMAX*DELT/DELY
      ALPHA=1.35*AMAX1(DAX,DAY)
      IF(ALPHA.GT.1.0) ALPHA=0.95
      GAMMA=ALPHA
      BETA=OMG/(2.*DELT*(RDX**2+RDY**2))

* * TEST FOR PROGRAM TERMINATION.

6400  IF(T.GT.TWFIN) IND=2
      IF(IND.GT.1) GO TO 6500
6440  CYCLE=CYCLE+1
      GO TO 1000
6500  T=T-DELT
      GO TO 5060
6520  WRITE(108,82)
6600  STOP
      END
```

:HESE INSTRUCTIONS FOR THE SLOPE-NORMAL WALL REPLACE BOXED INSTRUCTIONS ON PAGE 20.

```
      IF(H(24).GT.DELM) GO TO 4960
      FX=FY=TB=PM=0.0
      GO TO 4990
4960  JU=INT(H(24)*RDY+1.E-6)+2
      J=2
      FX=FY=TB=PM=0.0
4970  IF(J.EQ.JU) GO TO 4980
      RX=P(24,J)*DELY-2.0*NU*(U(24,J)-U(23,J))
      FX=FX-RX
      FY=FY+NU*(U(23,J+1)-U(23,J-1))/2.0-NU*(V(24,J)+V(24,J-1))
      TB=TB+RX*(FLOAT(J)-1.5)*DELY
      J=J+1
      GO TO 4970
4980  HH=H(24)-DELY*FLOAT(J-2)
      RX=(P(24,J)-2.*NU*(U(24,J)-U(23,J))/DELX)*HH
      FX=FX-RX
      FY=FY+NU*((U(23,J)-U(23,J-1))/DELY-2.*V(24,J-1)/DELX)*HH
      TB=TB+RX*(H(24)-HH/2.0)
      DO 4985 I=2,JU
      PA=P(24,I)+2.0*NU*U(23,I)/DELY
4985  IF(PA.GT.PM) PM=PA
4990  CONTINUE
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Lang, T. E., and R. L. Brown. 1980. Numerical simulation of snow avalanche impact on structures. USDA Forest Service Research Paper RM-216, 21 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

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Rocky Mountains

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Great Plains

U.S. Department of Agriculture
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Rocky Mountain Forest and Range Experiment Station

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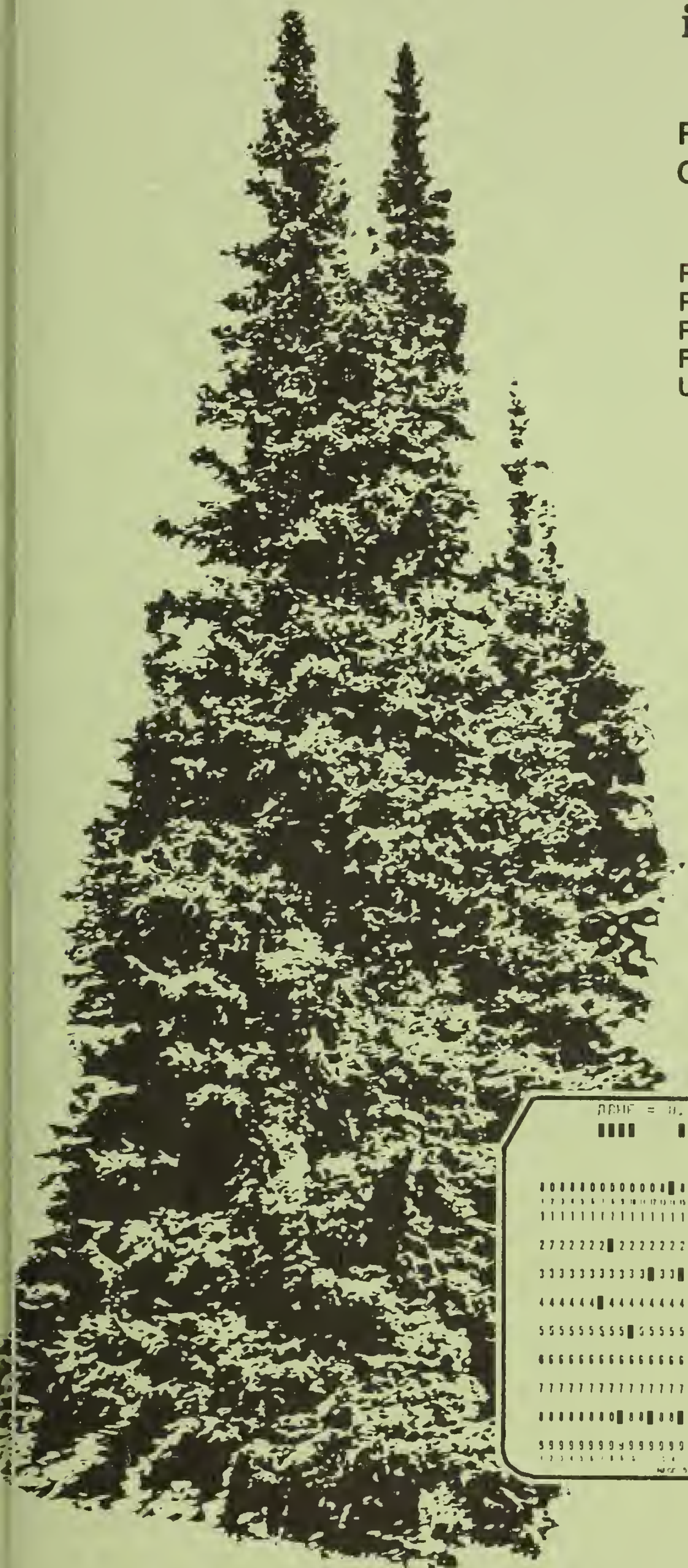

Management of Spruce-Fir in Even-Aged Stands in the Central Rocky Mountains

Robert R. Alexander and
Carleton B. Edminster

Research Paper RM-217
Rocky Mountain Forest and
Range Experiment Station
Forest Service
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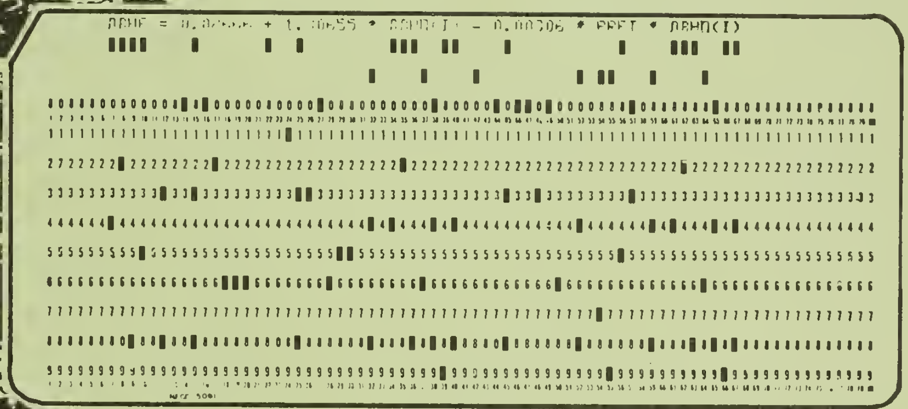

Abstract

Potential production of Engelmann spruce and subalpine fir in the central Rocky Mountains is simulated for various combinations of stand density, site quality, ages, and thinning schedules. Such estimates are needed to project future development of stands managed in different ways for various uses.

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July 1980

Management of Spruce-Fir in Even-Aged Stands in the Central Rocky Mountains

Robert R. Alexander, Chief Silviculturist

and

Carleton B. Edminster, Mensurationist

Rocky Mountain Forest and Range Experiment Station[1]

[1]Headquarters is at Fort Collins, in cooperation with Colorado State University.

Contents

Management of Spruce-Fir in Even-Aged Stands in the Central Rocky Mountains

Robert R. Alexander and Carleton B. Edminster

Silviculture of Spruce-Fir in the Central Rocky Mountains

Engelmann spruce (*Picea engelmannii* Parry)—subalpine-fir (*Abies lasiocarpa* (Hook) Nutt.) forests are the largest and most productive timber resource in the central Rocky Mountains (Choate 1963, Miller and Choate 1964). Spruce and fir reach maximum development above 9,000 feet elevation on north-facing slopes, and are the principal tree species above 10,500 feet on all slopes.

Limited areas of the original spruce-fir forests were logged in the late 1800's to provide fuel, lumber, and props for early mining camps, but only relatively small quantities of timber were harvested on national forests until the 1950's. Cutting has increased since then, primarily for timber products, but spruce-fir forests provide other resources that are becoming increasingly important. These forests grow on areas that yield the most water in the central Rocky Mountains. They also provide habitats for a wide variety of wildlife, forage for livestock, developed and dispersed recreation, and scenic beauty.

How these forests are managed affects all resources and uses (Alexander 1977). For example, if timber production is the primary objective, growing stock levels (GSL)[2] should be kept higher, but forage production and water yield can be substantially increased only at the lower GSL's. Low to medium GSL's are generally considered necessary to improve developed recreational opportunities and enhance foreground esthetics. Although land managers must increasingly direct their practices toward multiple uses, these practices must be based on sound silvicultural principles of the forest types involved. Moreover, land managers must understand the trade-offs between the timber resource and other physical, social, and economic considerations.

[2]Growing stock level (GSL) is defined as the residual square feet of basal area when average stand diameter is 10 inches or more. Basal area retained in a stand with an average diameter of less than 10 inches is less than the designated level (Myers 1971, Edminster 1978). Tables A-1, A-2, and A-3 give the number of trees, basal area, and square spacing for stands with average diameters after thinning of 2 to 10 inches, for GSL levels 40 to 180).

Clearcutting old-growth spruce-fir forests and allowing cutover areas to restock naturally, regardless of the time required or the stocking achieved, was common from the 1950's until recently. Today, management intensity has increased, and managers are concerned with prompt restocking of cutover areas with a new stand, increasing growth of the new stand by control of stand density, and improving yields by periodic thinning to maintain stocking control and growth rates.

Spruce-fir forests are naturally productive. In unmanaged, old-growth stands, average annual growth is 80 to 100 fbm per acre per year, even allowing for mortality normally associated with old-growth forests. Under even-aged management, annual net growth can be increased to 200 to 650 fbm per acre per year by controlling stand density (Edminster 1978).

Stand density control offers the greatest opportunity for increasing wood production by increasing growth and reducing mortality, but harvested stands must be replaced promptly to reduce time required to reach maximum yields. In the past, either long regeneration periods—up to 20 years or more—or regeneration failures have been common in spruce-fir forests because too little attention was paid to the regeneration requirements. Moreover, low stumpage values have hindered intensive management in the central Rocky Mountains. Improving stumpage values and better understanding of regeneration allows the forest manager to do the cultural work needed to increase timber production.

Establishment of Regeneration

Research has been directed toward perpetuating Engelmann spruce, the most valuable timber species of the type (Alexander 1974, Noble and Alexander 1977). Spruce-fir forests can be maintained as a vigorous, productive forest under an even-aged management system. Clearcutting, standard shelterwood, and simulated shelterwood are the cutting methods to use to convert old-growth to managed, even-aged stands. Each cutting method has its use, depending upon stand and site conditions, wind and disease problems, regeneration requirements, and management objectives. Uneven-aged management systems, which include individual tree and group selection cutting methods and their modifications, are also appropriate for use in spruce-fir stands. They are not discussed in this paper because there are no comparable growth and yield prediction tools available for an uneven-aged management system.

Many old-growth forests have an understory of advanced reproduction containing a moderate amount of spruce. These stands can be managed as even-aged by removing the overstory in a simulated shelterwood. Logging damage to established regeneration must be controlled by: (1) locating and marking skid roads on the ground at about 200-foot intervals, and confining skidding equipment to these skid roads to reduce indiscriminate travel over the cutover area; (2) felling trees in a herringbone pattern to the skid road to reduce disturbance when logs are moved onto the skid road; and (3) close coordination between felling and skidding operations, especially in stands with large volumes, where it is necessary to fell and skid one tree before another is felled (Alexander 1957, Roe et al. 1970). This type of cutting simulates the final harvest of a shelterwood method.

In stands without advanced reproduction at harvest, spruce regenerates from seed, provided there is a dependable seed supply, at least 40% of the seedbeds are exposed mineral soil, and environmental conditions are suitable (Roe et al. 1970). Shade is especially important to survival and early growth. Because solar radiation is high at elevations where spruce grows, it does not established readily in the open (Noble and Alexander 1977, Ronco 1970).

If a clearcut option is used, seed is dispersed from trees standing around the perimeter of the opening, but less than 10% of the seed is dispersed beyond 300 feet from its source (Alexander 1969, Noble and Ronco 1978). On shaded mineral soil on north slopes, the maximum clearcut opening likely to restock naturally is 400 to 500 feet in diameter; on south slopes it is only 100 to 200 feet. Adequate stocking usually requires more than one good seed year. On unprepared and unshaded seedbeds, openings 50 to 100 feet in diameter will restock on north slopes, but will require a number of good seed years. On south slopes under similar conditions, few seedlings survive in openings (Alexander 1974, Roe et al. 1970).

If a shelterwood option is used, seed for regeneration is dispersed from trees left standing on the area after the seed cut. At time of final harvest, the same care in logging suggested for management with advanced reproduction is required. A standard shelterwood cutting is more likely to result in more evenly distributed reproduction than clearcutting, but may favor fir over spruce.

Regeneration of Engelmann spruce may be slow to establish and poorly distributed regardless of cutting method or the best efforts of the manager to ensure an adequate seed supply, favorable seedbeds, and suitable environmental conditions. If stands remain unstocked or poorly stocked more than 5 years after the final harvest, the manager must take action under the regulations of the National Forest Management Act of 1976 to artificially regenerate these areas. Guidelines for planting spruce have been prepared by Ronco (1972).

With either a clearcut or shelterwood option, minimum acceptable stocking with spruce-fir is 600 trees per acre after 5 years, with at least one-half of the reproduction spruce. However, at least 850 trees per acre are preferred at age 30 years if spruce-fir stands are to be managed at the higher GSL's.

Need for Early Precommercial Thinning

Establishing a new stand is only the beginning. Trees must have room to grow to reach merchantable size in a reasonable amount of time. Where spruce and fir have regenerated successfully after cutting, stands seldom contain more than 2,000 stems per acre at age 10 years. This density can be maintained early in the life of the stand without appreciable reduction in diameter growth. Precommercial thinning is not required before age 30 years. Where many advanced spruce and fir (4,000-6,000 stems per acre) survive after a simulated shelterwood cutting (Alexander 1963, 1968), early precommercial thinning is desirable to reduce density to 800 to 900 stems per acre to attain acceptable growth rates.

Estimates of Growth Under Intensive Management

Intensive management of spruce-fir forests provides many opportunities for increasing usable wood production, but estimates of future stand development under various management regimes are needed.

The best information available on the growth of spruce and fir from sapling stage to final harvest under even-aged management with either a clearcut or shelterwood cut is provided by field and computer simulation procedures developed by Myers (1971) and Alexander et al. (1975) and refined by Edminster (1978). The procedures were developed from field data on past growth related to stand density, age, and site quality. Data were obtained from a large number of both permanent and temporary plots established in thinned and natural stands throughout the central Rocky Mountains.

The modeling concept used in these programs holds that the whole stand is the primary model unit, characterized by average values. The equations upon which the growth and yield simulations are based are given in Alexander et al. (1975). The programs project stand development by consecutive, 10-year periods and include relationships to project average stand diameter, average dominant and codominant height, and number of trees per acre. Average diameter at the end of a projection period is a function of average diameter at the beginning of the period, site index, and basal area per acre. Periodic average dominant and codominant height growth at managed stand densities is a function of age and site index. Periodic mortality is a function of average diameter and basal area per acre. Stand volume equations are used to compute total cubic feet per acre; factors are computed to convert thus to merchantable cubic feet and board feet. Prediction equations are included to estimate the effects of differing intensities of thinning from below on average diameter, average dominant and codominant height, and trees retained per acre.

Yield simulations discussed in the following paragraphs were made to the same hypothetical initial stand conditions for all growth parameters.

1. Average age at first GSL thinning is 30 years. Note that age in the yield table simulation is measured at breast height (4.5 feet). A minimum of 20 years is allowed for spruce and fir trees to regenerate and grow to 4.5 feet in height. The total age of the stand is, therefore, at least 20 years older than age measured at breast height. The age referred to hereafter in the text, and in all tables and figures, is measured at breast height.
2. Average stand diameter is 4.5 inches d.b.h.[3]
3. Stand density is 800 trees per acre.
4. Site index is 50-, 60-, 70-, 80-, 90- and 100-foot classes, at base age 100 years (Alexander 1967).
5. Projections were made for 70 years (stand age 100 years), 90 years (stand age 120 years), 110 years (stand age 140 years), and 130 years (stand age 160 years).
6. Thinnings from below were made every 20 and 30 years to GSL's of 40, 60, 80, 100, 120, 140, 160, and 180, with initial and subsequent entries made to the same GSL.
7. Clearcut and two-cut shelterwood options were used.
8. Minimum size for inclusion in board foot volume determination was 8 inches d.b.h. to a 6-inch top. Volumes were determined from tables prepared by Myers and Edminster (1972).
9. All entries were made as scheduled even though all thinnings could be precommercial.

Diameter Growth

Periodic mean annual diameter growth of spruce and fir is related to stand density and site quality, but is affected little by the cutting cycles tested. Cutting cycles do influence average stand diameter, however, because thinning from below increases average diameter at each entry. Actual basal area in a stand with an average diameter of less than 10 inches d.b.h.

[3]*Average stand diameter is the diameter of the tree of average basal area; it is not the average of all the tree diameters.*

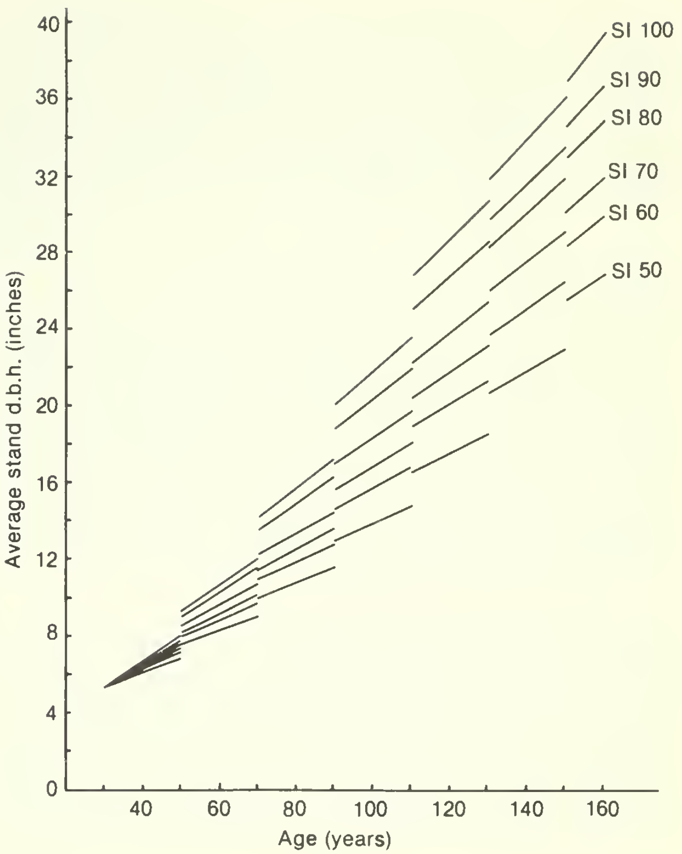

Figure 1.—Estimated average stand diameter in relation to age for different site classes at GSL 100 with a 20-year thinning schedule—clearcut option.

continues to increase, because periodic thinning does not reduce basal area to a fixed (GSL) amount until an average stand diameter of 10 inches d.b.h. is reached. Consequently, the rate of diameter growth for a given GSL is not constant over time and is essentially a negative exponential function of basal area per acre in the program. In contrast, periodic diameter growth is a linear function of site index, so that differences in diameter growth resulting from site quality are constant throughout the range of GSL's and rotations examined.

Growth rates and changes in diameter resulting from thinning frequency were examined to determine average size of trees relative to rotation age. For example, with a clearcut option, at GSL 100 with a 20-year cutting cycle, trees reach average stand diameters of 14.0 to 21.9 inches d.b.h. after 100 years; and 27.0 to 39.7 inches d.b.h. after 160 years for the range of sites tested (fig. 1). On an average site (index 70), with a 20-year cutting cycle, mean stand diameters reached 10 inches d.b.h. at 50 to 82 years of age for the range of GSL's 40 to 180 (fig. 2).

With a shelterwood option, the thinning regimes are the same until 20 years before the final harvest at rotation age, when a heavier cut is made. Since the seed cut is also made from below to reserve the larger trees for seed production, the average stand diameters at rotation age are slightly larger than with a clearcut option (fig. 3). On an average site (index 70), with a 20-year cutting cycle, mean stand diameters under a shelterwood option reach 10 inches at about the same ages with the same range of GSL's as with a clearcut option.

Height Growth

Periodic mean annual height growth of spruce and fir increases with site index and decreases with age, but is influenced little by GSL's, cutting method, or the cutting cycle. However, since fewer and, therefore, taller trees are left after each thinning from below, the mean height of the dominant and codominant trees is increased slightly at each entry. The increase is positively correlated with thinning frequency and negatively correlated with GSL.

Basal Area Growth

Periodic mean annual basal area increment is related to stand density, site quality, and frequency of thinning, but is relatively unaffected by cutting method. Since actual basal area continues to increase

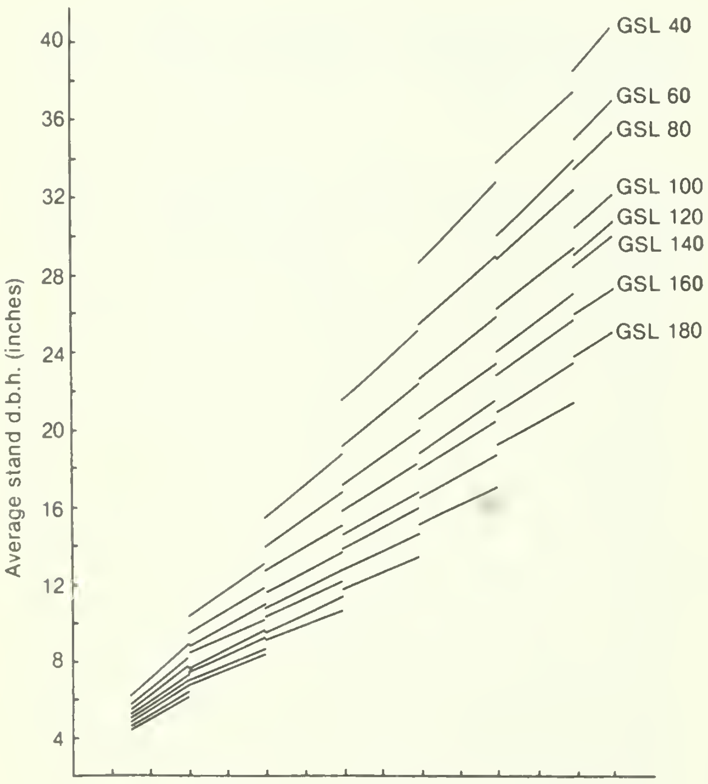

Figure 2.—Estimated average stand diameter in relation to age and growing stock level on site index 70 lands with a 20-year thinning schedule—clearcut option.

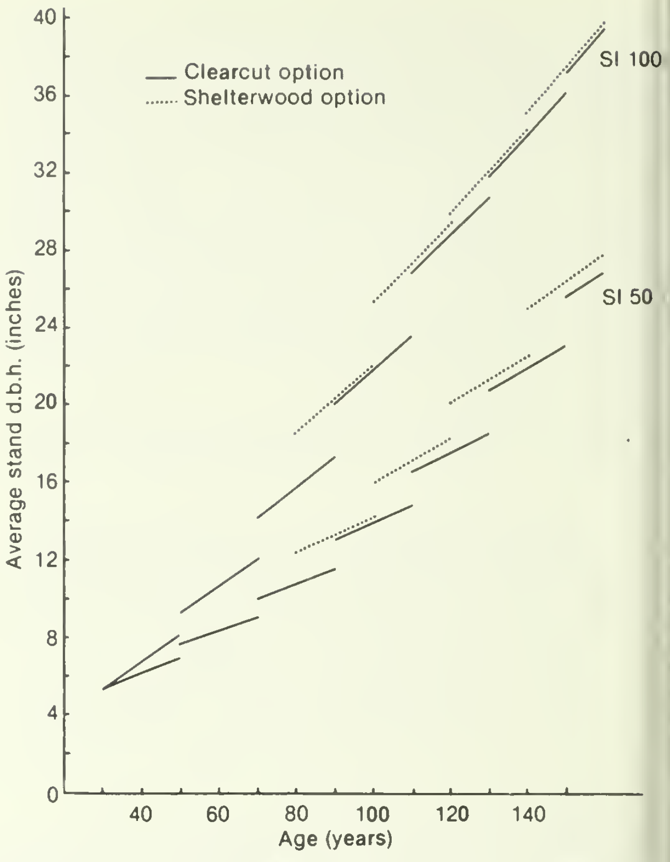

Figure 3.—Estimated average stand diameter with clearcut and shelterwood options in relation to age for site indexes 50 and 100 at GSL 100 with a 20-year schedule.

in a stand until average stand diameter reaches 10 inches d.b.h. and thinning reduces basal area to a fixed amount (GSL), the rate of basal area growth for a given GSL is not constant over time. Periodic basal area increment is greater at higher GSL's, but the rate of increase diminishes at the higher stand densities. Periodic mean basal area growth is also greater at higher site indexes. Moreover, the differences in basal area growth between site classes become progressively greater with higher GSL's. Periodic mean basal area increment is greater with a 30-year cutting cycle than with a 20-year entry at all growing stock levels examined.

Total Cubic-Foot Volume Increment

Cubic-foot volume production is related to stand density, site quality, rotation age, and frequency of thinning (table 1 and table A-4). Cutting methods, however, have little effect on cubic volume growth (fig. 4).

Although mean annual cubic volume increment increases as GSL and site index increase, the rate of increase diminishes as GSL increases, while the differences in growth between site classes becomes greater (fig. 5). Cubic volume increment will apparently continue to increase at GSL's above 180 on all but site index 50 lands.

Table 1.—Estimated total cubic-foot volume production per acre of spruce-fir in relation to growing stock level, site index, rotation age, and cutting cycle, with a clearcut option

Rotation age	Cutting cycle	Growing stock level 40	60	80	100	120	140	160	180
-------years-------		----------thousand cubic feet----------							
		Site index 50							
100	20	2.09	2.56	3.00	3.34	3.58	3.73	3.82	3.74
120		2.42	3.10	3.74	4.22	4.60	4.91	5.04	4.87
140		2.74	3.56	4.33	4.90	5.46	5.95	6.24	6.12
160		3.06	3.98	4.86	5.65	6.37	6.98	7.41	7.36
100	30	2.19	2.71	3.09	3.35	3.52	3.63	3.70	3.58
120		2.62	3.36	3.94	4.34	4.67	4.84	4.92	4.70
140		2.95	3.85	4.54	5.17	5.61	5.96	6.09	5.99
160		3.30	4.32	5.12	5.82	6.53	7.01	7.28	7.18
		Site index 60							
100	20	2.59	3.26	3.89	4.44	4.82	5.08	5.20	5.11
120		3.00	3.95	4.75	5.41	6.00	6.46	6.73	6.94
140		3.37	4.49	5.40	6.24	7.00	7.78	8.27	8.55
160		3.74	4.98	6.08	7.02	7.90	8.67	9.39	9.86
100	30	2.82	3.55	4.11	4.50	4.81	5.06	5.20	5.13
120		3.30	4.31	5.15	5.76	6.24	6.58	6.78	6.90
140		3.70	4.86	5.87	6.69	7.29	7.92	8.27	8.46
160		4.08	5.41	6.58	7.55	8.32	8.94	9.38	9.76
		Site index 70							
100	20	3.30	4.18	4.89	5.55	6.17	6.66	6.99	6.90
120		3.78	4.88	5.87	6.70	7.48	8.22	8.76	9.11
140		4.20	5.49	6.61	7.69	8.65	9.58	10.25	10.82
160		4.62	6.08	7.39	8.61	9.76	10.86	11.68	12.35
100	30	3.42	4.42	5.23	5.94	6.45	6.67	6.97	7.03
120		4.07	5.24	6.38	7.34	8.23	8.76	9.07	9.23
140		4.49	5.87	7.17	8.39	9.42	10.15	10.70	10.98
160		4.93	6.50	8.02	9.42	10.56	11.44	12.06	12.51
		Site index 80							
100	20	3.90	5.00	5.95	6.81	7.62	8.37	8.92	9.15
120		4.46	5.78	6.96	8.00	9.00	10.01	10.80	11.48
140		4.97	6.50	7.92	9.16	10.36	11.56	12.60	13.44
160		5.42	7.18	8.75	10.22	11.68	12.99	14.24	15.30
100	30	4.23	5.44	6.50	7.42	8.14	8.68	9.04	9.15
120		4.88	6.38	7.69	8.86	9.89	10.67	11.24	11.41
140		5.40	7.08	8.55	9.95	11.23	12.28	13.01	13.47
160		5.94	7.82	9.60	11.26	12.72	13.89	14.77	15.26
		Site index 90							
100	20	4.56	5.89	7.06	8.10	9.08	9.97	10.72	11.26
120		5.16	6.77	8.32	9.55	10.79	11.88	12.92	13.76
140		5.73	7.64	9.30	10.81	12.23	13.62	14.90	15.97
160		6.26	8.32	10.30	12.03	13.73	15.23	16.70	18.03
100	30	4.98	6.40	7.74	8.97	10.00	10.70	11.20	11.52
120		5.72	7.49	9.22	10.69	11.89	12.88	13.56	14.02
140		6.31	8.30	10.22	12.04	13.66	14.91	15.95	16.38
160		6.99	9.15	11.34	13.38	15.12	16.11	17.68	18.38
		Site index 100							
100	20	5.33	6.82	8.21	9.54	10.78	11.87	12.81	13.37
120		6.02	7.82	9.52	11.14	12.67	14.11	15.34	16.12
140		6.64	8.74	10.70	12.60	14.42	16.07	17.56	18.58
160		7.28	9.58	11.81	13.95	16.02	17.94	19.58	20.91
100	30	5.75	7.44	9.06	10.60	11.91	12.96	13.70	14.08
120		6.61	8.80	10.66	12.55	14.10	15.47	16.42	16.94
140		7.25	9.65	11.96	14.11	15.99	17.68	18.76	19.57
160		7.87	10.59	13.10	15.54	17.78	19.73	20.98	21.86

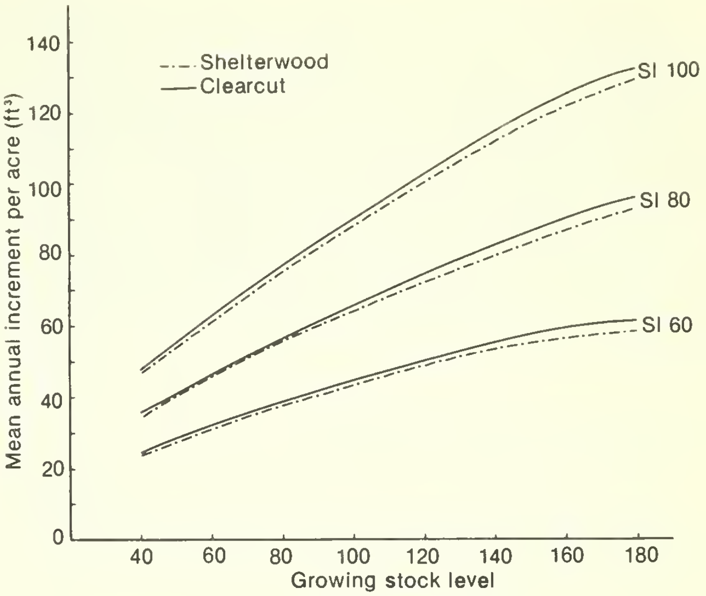

Figure 4.—Estimated mean annual total cubic-foot volume increment per acre with clearcut and shelterwood options in relation to growing stock level and site index classes 60, 80, and 100, for a 140-year rotation with a 20-year thinning schedule.

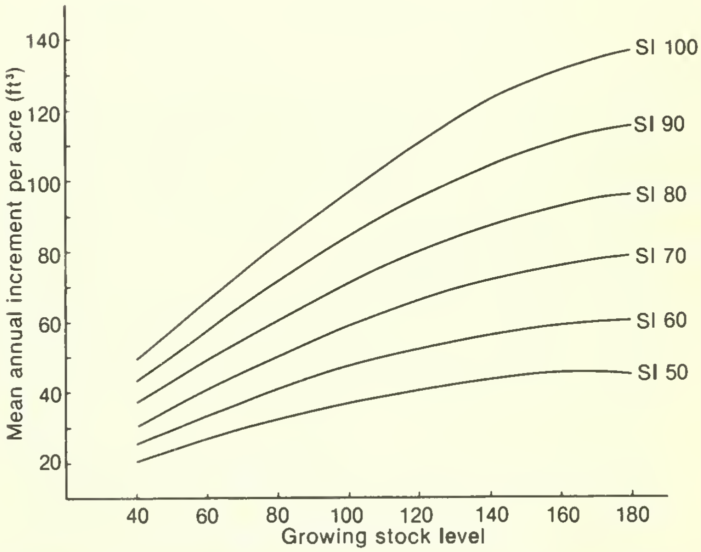

Figure 5.—Estimated mean annual total cubic-foot volume increment per acre in relation to growing stock level and site index for a 120-year rotation with a 30-year thinning schedule—clearcut option.

Average annual cubic volume increment per acre is greater on site index 80 to 100 lands at GSL's 40 to 140 on 100-year rotations. At GSL's above 140, growth is greater on a 120-year rotation. On site index 50 to 70 lands, growth is generally greater on rotations longer than 100 years at GSL's greater than 60.

Mean annual cubic volume increment is always greater with a 30-year cutting cycle for all GSL's at rotations of 120 years or longer. At GSL's greater than 160 with a 100-year rotation, there is little difference in cubic volume between a 20- and a 30-year cutting cycle.

Board-Foot Volume Increment

Board-foot volume production (table 2 and table A-5) is related to all stand parameters evaluated, but there is little difference in average annual increment between clearcut and shelterwood options (fig. 6). Mean annual sawtimber volume growth increases as stand density increases throughout the range of GSL's on site index 70 or better lands, but generally levels off or declines on site index less than or equal to 60 lands at GSL's above 160 (fig. 7).

Board-foot volume growth increases with site quality, and the differences in growth between site classes are greater as GSL increases. Throughout the range of GSL's, average annual board-foot increment per acre is always greater for all site classes on a 160-year rotation (fig. 8).

At GSL's 40 through 160 on rotations longer than 100 years, and at GSL's 40 to 140 on shorter rotations, board-foot volume growth is greater on a 30-year cutting cycle than on a 20-year cycle. At higher GSL's, growth is greater with more frequent thinnings (fig. 9).

Maximizing Board-Foot Volume Yields

What yields can be expected with intensive management of spruce-fir to maximize timber production? If the objective is to integrate timber production with other resources uses, what are the timber trade-offs? How can these objectives be attained with the fewest precommercial thinnings?

The largest volume production per acre (104,800 board feet) is attained with a clearcut option on site index 100 lands, at GSL 180, on a 160-year rotation, with a 30-year cutting cycle (table 2). These stands will contain about 38 trees per acre with an average d.b.h. of nearly 32 inches at rotation age (table 3). Volume production and tree size attained are about the same under a two-cut shelterwood (tables A-5 and A-6).

Volume production substantially declines when GSL is reduced. The decline is greater with each successive reduction. At site indexes 60 to 90, with a clearcut option, largest volume production also occurs at GSL 180 on a 160-year rotation but with a 20-year cutting cycle. On site index 50 lands, greatest production is at

Table 2.—Estimated board-foot volume production per acre of spruce-fir in relation to growing stock level, site index, rotation age and cutting cycle, with a clearcut option (trees 8 inches d.b.h. and larger to a 6 inch top)

Rotation age	Cutting cycle	Growing stock level 40	60	80	100	120	140	160	180
-------*years*-------					------*thousand board feet*------				
					Site index 50				
100	20	7.1	8.9	10.4	11.6	12.0	11.7	11.4	10.9
120		9.2	12.1	14.6	16.4	17.4	17.8	17.4	16.2
140		11.2	14.8	18.1	21.0	22.8	23.7	23.9	23.1
160		13.3	17.9	21.8	25.3	27.8	29.4	30.9	29.9
100	30	7.5	9.1	10.5	11.4	11.6	11.4	11.0	10.3
120		10.0	12.7	15.1	16.8	17.5	17.4	17.2	16.1
140		12.2	15.7	18.8	21.1	23.1	23.5	23.5	22.5
160		14.6	19.0	22.7	26.4	28.6	29.8	30.2	28.8
					Site index 60				
100	20	9.1	12.0	14.1	16.1	17.0	17.4	17.6	17.0
120		11.6	15.6	19.2	21.8	23.6	25.2	26.2	25.8
140		14.1	19.3	23.8	27.2	29.7	31.6	33.3	34.3
160		16.6	22.9	28.3	32.6	36.0	39.2	41.3	42.4
100	30	9.8	12.5	14.3	15.6	16.5	17.0	17.0	16.3
120		12.8	17.0	20.4	22.6	24.0	25.4	26.2	25.2
140		15.4	20.6	25.1	28.6	31.5	33.7	34.9	33.7
160		18.1	24.2	29.1	33.9	37.9	40.8	42.4	41.4
					Site index 70				
100	20	11.7	15.0	17.9	20.6	23.0	24.7	25.4	24.9
120		14.8	19.2	23.6	27.6	31.2	34.1	36.1	35.8
140		17.6	23.8	29.1	34.3	38.9	42.7	45.1	46.2
160		20.6	27.7	34.2	40.6	46.6	50.7	54.2	56.8
100	30	12.4	16.2	19.2	21.6	23.2	24.3	24.6	24.1
120		16.1	21.7	26.0	29.6	32.8	34.8	35.5	34.8
140		19.0	25.5	31.6	36.9	40.7	43.4	44.7	45.1
160		22.1	29.8	37.1	43.0	48.2	52.3	54.9	56.5
					Site index 80				
100	20	13.8	18.2	22.2	26.0	29.6	32.5	34.3	34.1
120		17.4	23.9	29.4	34.2	38.6	42.7	46.4	47.4
140		20.7	28.8	35.7	41.6	47.5	52.9	57.0	60.1
160		24.3	33.4	41.8	49.0	56.0	62.6	68.2	72.6
100	30	15.5	20.0	24.2	27.8	30.6	32.4	33.5	33.0
120		19.8	25.7	31.8	37.4	41.8	45.0	46.4	45.7
140		23.2	31.4	38.1	44.8	50.1	54.6	57.8	58.5
160		27.0	33.3	45.6	53.6	60.2	65.9	69.8	71.2
					Site index 90				
100	20	16.4	22.6	27.8	32.1	35.9	39.1	42.5	44.5
120		20.4	28.6	35.4	41.3	46.9	52.0	56.2	59.9
140		24.4	33.9	42.3	50.1	57.4	63.7	69.3	74.2
160		28.2	39.4	49.4	58.7	67.2	74.7	82.2	89.0
100	30	18.7	25.2	30.7	35.5	39.3	42.2	43.8	43.2
120		23.5	31.9	39.7	46.6	52.2	56.4	58.9	58.2
140		27.4	37.2	46.9	55.6	62.6	68.3	72.1	73.1
160		31.7	43.2	54.4	65.0	73.6	80.6	85.8	87.0
					Site index 100				
100	20	19.6	26.6	32.7	38.4	43.6	48.2	51.8	54.2
120		24.2	33.2	41.5	49.0	56.0	62.4	68.0	71.6
140		28.6	39.5	49.8	59.2	68.0	76.0	83.2	88.1
160		33.1	45.8	57.8	68.5	79.4	88.8	97.6	104.6
100	30	21.9	29.2	36.3	43.3	48.7	52.6	54.2	53.6
120		27.6	37.9	47.6	56.3	63.2	69.2	72.1	71.4
140		32.1	44.4	56.0	66.4	75.3	82.7	87.4	88.9
160		36.6	51.2	64.5	76.5	87.7	96.6	103.0	104.8

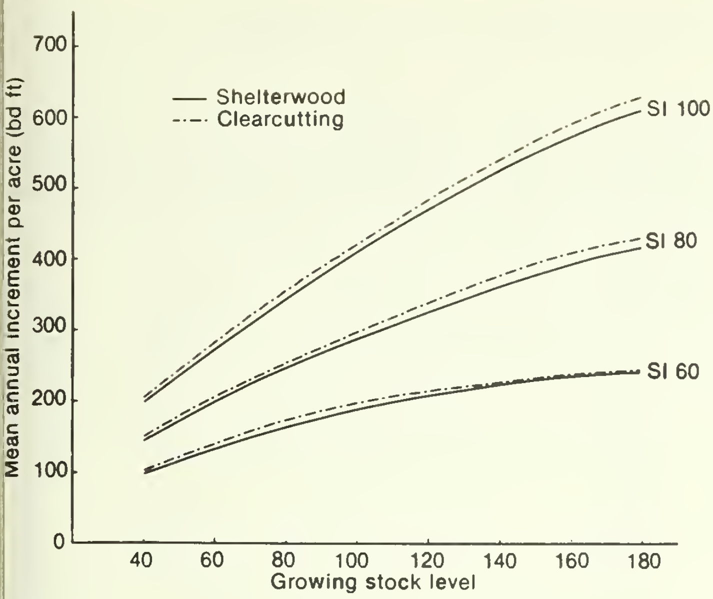

Figure 6.—Estimated mean annual board-foot volume increment per acre with clearcut and shelterwood options in relation to growing stock level for site index classes 60, 80, and 100, for a 140-year rotation with a 20-year thinning schedule.

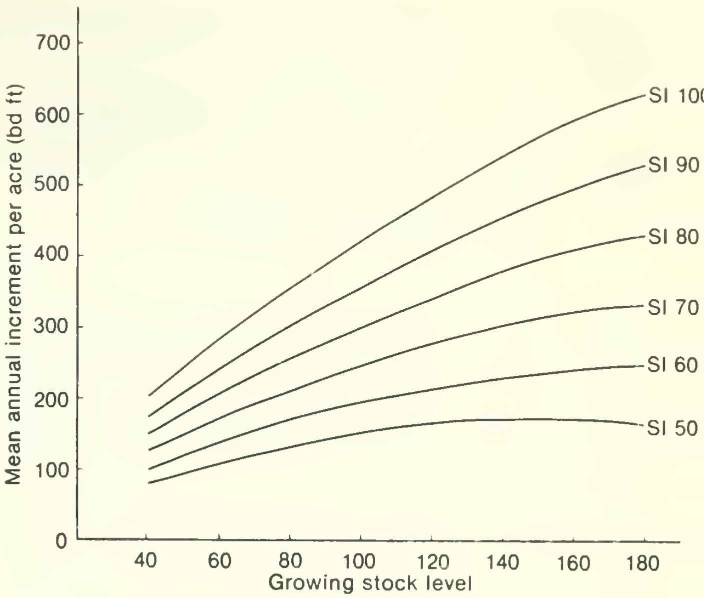

Figure 7.—Estimated mean annual board-foot volume increment per acre in relation to growing stock level and site index for a 140-year rotation with a 20-year thinning schedule—clearcut option.

Figure 8.—Estimated mean annual board-foot volume increment per acre in relation to growing stock level and rotation age on site index 80 lands with a 30-year thinning schedule.

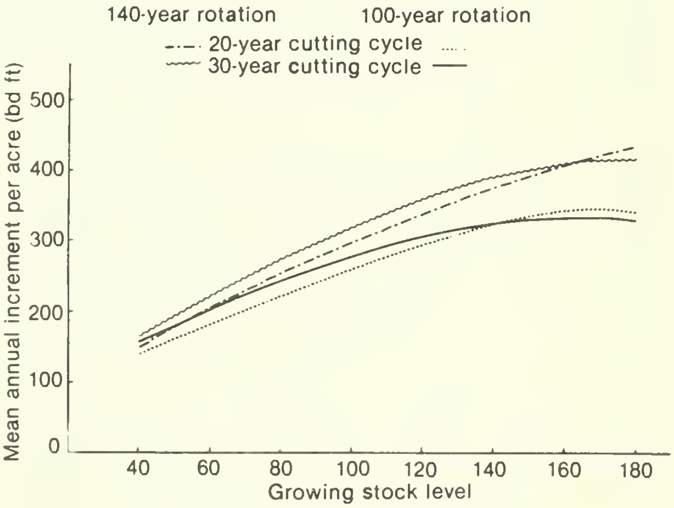

Figure 9.—Estimated mean annual board-foot volume increment per acre in relation to thinning schedules for 100- and 140-year rotations on site index 80 lands.

Table 3.—Estimated average diameter (inches) and number of trees per acre of spruce-fir at final harvest in relation to growing stock level, site index, rotation age, and cutting cycle, with a clearcut option

		Growing stock level															
		40		60		80		100		120		140		160		180	
Rotation age	Cutting cycle	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter
Site index 50																	
100	20	21	20.2	44	17.1	74	15.1	107	14.0	155	12.7	233	11.2	281	10.5	371	9.6
120		13	25.7	25	22.2	45	19.3	67	17.6	97	16.0	145	14.1	200	12.8	294	11.2
140		9	30.1	16	27.9	28	24.2	42	22.0	62	19.8	93	17.5	130	15.8	192	13.8
160		7	34.8	12	32.2	18	30.0	28	27.0	42	24.1	62	21.3	89	19.1	129	16.8
100	30	24	18.9	48	16.3	79	14.6	123	13.1	172	12.1	256	10.7	303	10.1	378	9.5
120		24	21.7	48	18.6	79	16.6	123	14.8	172	13.6	256	11.9	303	11.3	353	10.5
140		12	25.8	24	24.3	40	21.6	63	19.0	90	17.4	139	15.2	182	14.1	254	12.6
160		8	33.1	12	31.4	22	27.4	36	23.8	51	21.9	77	19.2	105	17.5	153	15.4
Site index 60																	
100	20	18	21.6	36	18.8	62	16.6	85	15.8	132	13.9	170	13.2	247	11.7	305	11.1
120		11	27.7	21	24.3	37	21.4	51	20.2	80	17.7	102	16.9	148	15.0	189	14.0
140		8	32.5	13	30.7	23	27.0	32	25.3	50	22.2	64	21.1	93	18.8	121	17.4
160		6	37.6	10	35.4	17	31.5	21	30.1	33	27.3	42	25.9	61	23.1	81	21.2
100	30	20	20.6	39	18.1	68	15.9	98	14.8	143	13.3	191	12.5	251	11.6	336	10.6
120		20	23.8	39	20.8	68	18.2	98	16.8	143	15.1	191	14.1	251	13.0	312	11.9
140		10	31.3	19	27.2	33	23.9	49	21.8	73	19.6	98	18.2	132	16.7	184	15.0
160		6	36.3	12	31.6	17	30.9	27	27.7	39	25.0	54	23.1	73	21.1	104	18.8
Site index 70																	
100	20	16	23.1	30	20.7	50	18.5	74	17.0	105	15.6	135	14.9	182	13.7	241	12.6
120		9	30.6	17	27.1	29	24.1	44	21.9	62	20.1	80	19.1	109	17.5	147	16.0
140		6	36.0	12	31.8	18	30.5	27	27.7	39	25.4	50	24.1	68	22.0	90	20.2
160		6	40.6	9	36.9	13	35.2	20	32.0	25	31.6	32	29.9	44	27.2	59	24.9
100	30	18	21.9	34	19.6	53	18.0	81	16.2	114	15.0	152	14.0	207	12.8	268	12.0
120		18	25.5	34	22.6	53	20.7	81	18.6	114	17.2	152	16.0	207	14.6	266	13.5
140		8	34.0	16	29.8	25	27.2	40	24.4	56	22.5	74	21.0	103	19.1	137	17.5
160		5	39.5	10	34.6	17	31.6	21	31.2	30	28.9	40	26.7	55	24.4	76	22.1
Site index 80																	
100	20	14	25.2	27	21.9	42	20.4	63	18.4	87	17.2	113	16.3	143	15.5	192	14.2
120		9	30.4	15	28.8	23	26.9	37	23.9	50	22.4	65	21.2	83	20.1	112	18.4
140		6	36.0	11	33.9	17	31.6	23	30.3	31	28.4	40	26.9	51	25.5	68	23.4
160		6	40.8	8	39.3	12	36.7	17	35.1	23	32.9	29	31.2	33	31.6	43	29.3
100	30	16	23.6	29	21.1	47	19.2	68	17.8	95	16.5	127	15.4	161	14.6	229	13.0
120		16	27.4	29	24.5	47	22.2	68	20.6	95	19.1	127	17.8	160	16.7	227	14.8
140		9	32.8	13	32.7	22	29.3	32	27.3	45	25.2	60	23.5	79	21.9	113	19.5
160		6	38.4	9	38.0	14	34.1	20	31.9	27	29.4	32	30.2	41	28.3	60	24.9
Site index 90																	
100	20	12	26.7	23	24.0	37	21.7	51	20.5	72	19.0	94	17.9	121	16.9	155	15.8
120		8	32.2	12	32.1	21	28.6	29	2.69	41	25.0	54	23.4	68	22.2	90	20.6
140		6	38.2	9	37.7	15	33.7	21	31.7	25	31.8	33	29.8	41	28.3	54	26.3
160		4	44.6	7	43.6	11	39.2	15	36.9	18	36.8	24	34.6	31	32.8	40	30.6
100	30	14	25.2	26	22.5	41	20.6	57	19.5	77	18.4	108	16.8	136	16.0	181	14.7
120		14	29.4	26	26.3	41	24.0	57	22.7	77	21.4	108	19.5	135	18.5	179	16.8
140		8	35.2	14	31.5	19	31.8	27	30.1	36	28.4	49	26.0	63	24.5	87	22.3
160		5	41.2	9	37.1	12	37.1	17	35.1	23	33.2	31	30.4	33	31.6	46	28.6
Site index 100																	
100	20	11	28.3	20	25.8	32	23.4	45	21.9	59	21.0	81	19.4	121	18.3	132	17.2
120		7	34.3	13	31.2	18	30.9	25	28.9	33	27.7	45	25.7	68	24.3	76	22.5
140		5	40.7	9	37.0	13	36.4	18	34.1	23	32.7	32	30.4	41	31.2	45	28.2
160		5	46.3	7	43.2	9	42.2	13	39.7	17	38.1	23	35.5	31	36.2	33	33.6
100	30	11	25.6	20	24.1	31	22.3	43	21.0	57	19.8	77	18.5	99	17.5	131	16.0
120		11	31.1	20	28.3	31	26.1	43	24.6	57	23.0	77	21.5	98	20.3	128	18.4
140		6	37.3	11	33.9	17	31.5	24	32.9	26	30.5	34	28.7	45	27.0	60	24.5
160		4	43.8	7	39.8	11	37.1	15	38.3	15	35.7	21	33.5	28	31.6	38	31.7

GSL 160 on a 20-year cutting cycle, with GSL's 120 and 140 nearly as favorable.

Table 2 also shows the amount of volume given up as GSL is reduced from 180 to 40 for all combinations of stand parameters examined. Moreover, it shows that more volume can be produced over the same time span with 160-year rotations than with shorter rotations.

Whether the board foot volume production potentials can be achieved depends largely on how much money can be invested in thinning. It is assumed that once a stand reaches a minimum merchantable size of 8 inches average d.b.h. to a 6-inch top, market conditions permit intermediate thinnings to be made as scheduled. If economic constraints limit managers to only one precommercial thinning in the life of the stand, their options are severely restricted, with either a clearcut or shelterwood cut alternative. For example, on site index 50 to 60 lands, stand density must be reduced to GSL's 40 and 60, respectively, and the cutting cycle increased to 30 years (table 4). On site index 80 lands, a GSL of 120 can be maintained with a 30-year cutting cycle, and on site index 100 lands where there is considerable flexibility, a GSL of 160 can be maintained.

Thinnings to a constant GSL have been assumed up to now. However, if only one precommercial thinning is possible, managers can increase their flexibility by changing GSL's with successive re-entries. For example, on site index 70 lands with a 30-year cutting cycle, stand density is initially reduced to GSL 100. At the time of the second thinning, GSL is increased to 120, and increased to GSL 140 with the third thinning. Volume production will be less than maximum, but reasonably close to the volume available from a stand maintained at a constant GSL 140. Attempts to raise the GSL to 140 at the time of the second entry into the stand would result in a second precommercial thinning. By following this procedure, managers can increase GSL on site index 60 lands from 60 to 100.

Where economic conditions permit investment of funds in two precommercial thinnings, the manager has the opportunity to maximize timber production on site index 60 to 100 lands. On site index 50 lands, a GSL of 120 could be maintained or it could be increased to GSL 140 by changing the level with the second entry, provided that the rotation was at least 140 years.

Table 4.—Number of precommercial thinnings of spruce-fir in relation to growing stock level, site index, rotation age, and cutting cycle, with a clearcut or shelterwood option

Cutting cycle	Site index	Growing stock level 40	60	80	100	120	140	160	180
years									
20	50	2	2	2	3	3	4	4	[1]5
	60	2	2	2	2	3	3	3	[1]4
	70	1	2	2	2	2	2	3	3
	80	1	1	2	2	2	2	2	3
	90	1	1	2	2	2	2	2	2
	100	1	1	1	2	2	2	2	2
30	50	1	2	2	2	2	3	3	3
	60	1	1	2	2	2	2	2	3
	70	1	1	1	1	2	2	2	2
	80	1	1	1	1	1	2	2	2
	90	1	1	1	1	1	1	2	2
	100	1	1	1	1	1	1	1	2

[1]*Thinnings on a 100-year rotation would be precommercial.*

Trade-Offs to Increase Values of Other Resources

Understory vegetation in spruce-fir forests is potentially important as forage for big game, but production is lower in stands with high overstory density and closed canopies. To increase forage production, the manager must be willing to trade off timber production. For example, reduction of tree competition by clearcutting old-growth stands to bring them under management produces favorable changes in the amount and composition of understory species used as forage by deer (Regelin and Wallmo 1978, Wallmo 1969, Wallmo et al. 1972). Changes in vegetational composition and the quantities of forage available, rather than any differences in nutritive values, accounts for heavier grazing of cut areas (Regelin et al. 1974). This change in production and composition, which varies considerably with habitat type, persists 15 to 20 years before competition from new tree reproduction begins to reduce understory vegetation (Regelin and Wallmo 1978). Thinning second-growth spruce-fir stands also increases amount and composition of understory species, especially where stand density is reduced to low levels. However, data and methodology are not available to quantify changes in understory production and composition associated with the various habitat types for the range of GSL's, rotation ages, cutting cycles, and site indexes examined here for timber production.

Spruce-fir forests yield the most water in the Rocky Mountains. The proportion of water yield to precipitation is high because of the cold climate, short growing season, and the accumulation of an overwinter snowpack (Leaf 1975). Because most of the water available for streamflow comes from snowmelt, the most efficient pattern of timber harvest for water yield in old-growth stands is to clearcut about 30% to 40% of a drainage (1) in small, irregular-shaped patches about five to eight times tree height in diameter, (2) protected from the wind, and (3) interspersed with uncut patches of about the same size (Leaf 1975). Leaf and Alexander (1975) estimated water available for streamflow after clearcutting in spruce-fir stands under different management strategies using simulations generated by hydrologic and timber yield models (Alexander et al. 1975, Leaf and Brink 1973, Edminster 1978). Projected water yield increases at GSL 100, on a 30-year cutting cycle, on site index 80 lands, for a 140-year rotation are shown in figure 10. Simulation analyses also showed that estimated water yield was influenced little by any combination of initial and subsequent GSL's in managed stands that ranged from

80 to 120. More water should be available for streamflow at lower GSL's because of the reduction in consumptive use by trees, but no comparisons were made at higher or lower GSL's because of limitations in the simulation programs. One unknown factor is water use by competing understory vegetation associated with different habitat types for different GSL's.

Based on information available from research and simulation, it is clear that stand density must be substantially reduced and maintained at a low (GSL 40 to 60) stocking level to benefit water and forage resources. Other resource values may require moderate (GSL 80 to 100) stocking levels. Considerable timber volume production is given up, however, at low to moderate stand density levels. For example, on site index 100 lands, at GSL 80 with a 160-year rotation and a 30-year reentry schedule, 40,300 fewer board feet per acre are produced than with GSL 180. If the GSL is reduced to 40, the loss in volume production is 68,200 fbm per acre (table 2).

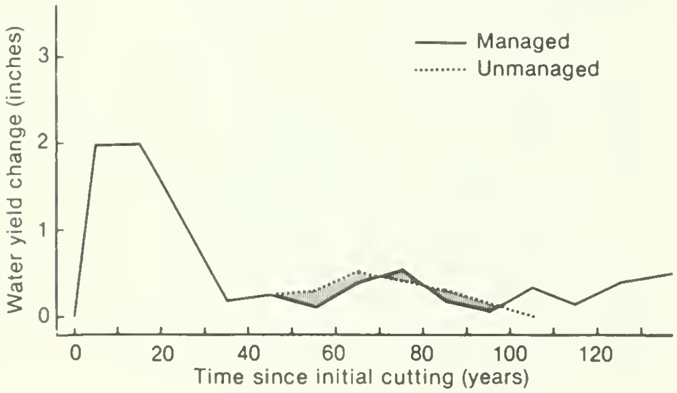

Figure 10.—Project changes in annual water yield from simulation for GSL 100 and site index 70 lands, with a 30-year cutting cycle, and a 140-year rotation (Leaf and Alexander 1975).

Management Caution

This simulation program estimates growth responses to different stand parameters that appear reasonable and consistent within the limits of current knowledge, but no spruce-fir stand has been under management for a long time and simulation extends beyond the limits of the available data base. Comparisons of estimates with actual values from plots established to provide growth information will be needed to verify simulated responses.

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Agriculture—CSU, Fort Collins

Appendix

Table A-1.—Basal areas (square feet per acre) after intermediate cutting in relation to average stand diameter (inches) and growing stock level

Average stand d.b.h. after cutting	Growing stock level										
	40	50	60	70	80	90	100	110	120	140	160
2	6.0	7.5	9.1	10.6	12.1	13.6	15.1	16.7	18.2	21.2	24.2
3	11.8	14.8	17.7	20.6	23.6	26.6	29.5	32.4	35.4	41.5	47.4
4	17.6	22.0	26.4	30.8	35.2	39.6	44.0	48.4	52.8	61.6	70.4
5	23.4	29.2	35.0	40.9	46.7	52.5	58.4	64.2	70.0	81.9	93.6
6	28.3	35.4	42.4	49.5	56.6	63.7	70.8	77.8	84.9	99.0	113.2
7	32.7	40.9	49.1	57.3	65.5	73.7	81.9	90.1	98.2	114.4	130.8
8	36.2	45.3	54.4	63.4	72.5	81.6	90.6	99.7	108.8	126.9	145.0
9	38.8	48.4	58.1	67.8	77.5	87.2	96.9	106.6	116.2	135.6	155.0
10	40.0	50.0	60.0	70.0	80.0	90.0	100.0	110.0	120.0	140.0	160.0

Table A-2.—Number of trees per acre in relation to average diameter (inches) and growing stock level

Average stand d.b.h. after thinning	Growing stock level										
	40	50	60	70	80	90	100	110	120	140	160
2	277	345	418	488	553	626	692	767	836	968	1,107
3	241	301	360	420	481	542	601	660	721	843	964
4	202	252	302	353	403	454	504	554	605	707	808
5	172	214	257	300	342	385	428	471	513	601	687
6	144	180	216	252	288	324	361	396	432	505	577
7	122	153	184	214	245	276	306	337	367	428	489
8	104	130	156	182	208	234	260	286	312	364	415
9	88	110	132	154	175	197	219	241	263	307	351
10	73	92	110	128	147	165	183	202	220	257	293

Table A-3.—Average distance (feet) between residual trees in relation to average diameter (inches) and growing stock level

Average stand d.b.h. after thinning	Growing stock level										
	40	50	60	70	80	90	100	110	120	140	160
2	12.5	11.1	10.2	9.4	8.8	8.3	7.8	7.5	7.2	4.8	4.4
3	13.4	12.0	11.0	10.2	9.5	9.0	8.5	8.1	7.8	6.7	6.3
4	14.7	13.2	12.0	11.1	10.4	9.8	9.3	8.9	8.5	7.2	6.7
5	15.9	14.4	13.0	12.0	11.3	10.6	10.1	9.6	9.2	7.9	7.3
6	17.4	15.6	14.4	13.2	12.3	11.6	11.0	10.5	10.0	8.5	8.0
7	18.9	16.9	15.4	14.3	13.3	12.6	11.9	11.4	10.9	9.3	8.7
8	20.5	18.3	16.7	15.5	14.5	13.6	13.0	12.3	11.8	10.9	10.2
9	22.3	20.1	18.2	16.8	15.8	14.9	14.1	13.4	12.9	11.9	11.1
10	24.4	21.8	20.1	18.4	17.2	16.2	15.4	14.7	14.1	13.0	12.2

Table A-4.—Total cubic foot volume production per acre of spruce-fir in relation to growing stock level, site index, rotation age and cutting cycle with a shelterwood option

Rotation age	Cutting cycle	Growing stock level 40	60	80	100	120	140	160	180
years		thousand cubic feet							
		Site index 50							
100	20	2.00	2.44	2.87	3.23	3.54	3.74	3.80	3.63
120		2.38	2.95	3.54	4.08	4.44	4.72	4.90	4.90
140		2.70	3.42	4.13	4.76	5.33	5.85	6.06	5.92
160		2.99	3.90	4.78	5.54	6.22	6.75	7.09	7.09
100	30	2.08	2.54	2.90	3.20	3.40	3.60	3.68	3.55
120		2.48	3.14	3.71	4.10	4.40	4.60	4.68	4.68
140		2.90	3.78	4.41	5.01	5.47	5.80	5.92	5.82
160		3.22	4.16	4.98	5.74	6.30	6.74	7.09	7.09
		Site index 60							
100	20	2.51	3.16	3.73	4.25	4.61	4.88	5.07	5.26
120		2.90	3.83	4.51	5.21	5.76	6.17	6.48	6.72
140		3.30	4.34	5.31	6.10	6.83	7.49	7.88	8.19
160		3.66	4.91	6.02	7.01	7.78	8.45	9.02	9.52
100	30	2.64	3.29	3.86	4.35	4.70	4.93	5.10	5.22
120		3.14	3.97	4.76	5.40	5.84	6.18	6.48	6.66
140		3.61	4.76	5.74	6.48	7.04	7.55	7.89	8.20
160		4.02	5.36	6.42	7.34	8.22	8.86	9.36	9.49
		Site index 70							
00	20	3.13	3.96	4.64	5.34	5.91	6.40	6.71	6.90
20		3.68	4.70	5.60	6.47	7.24	7.94	8.42	8.77
40		4.14	5.32	6.43	7.50	8.53	9.32	9.97	10.53
60		4.51	5.92	7.26	8.48	9.65	10.59	11.44	12.14
00	30	3.25	4.14	4.95	5.59	6.09	6.42	6.76	7.00
20		3.84	4.98	5.94	6.82	7.52	8.04	8.44	8.76
40		4.47	5.74	6.97	7.27	9.21	9.90	10.36	10.63
60		4.86	6.37	7.86	9.20	10.30	11.17	11.78	12.16
		Site index 80							
00	20	3.75	4.78	5.68	6.46	7.20	7.90	8.55	8.95
20		4.33	5.66	6.68	7.92	8.88	9.82	10.51	10.86
40		4.87	6.38	7.80	9.06	10.09	11.20	12.18	13.05
60		5.31	7.04	8.74	10.13	11.41	12.72	13.82	14.91
00	30	4.00	5.02	5.99	6.89	7.64	8.22	8.64	8.95
20		4.64	6.00	7.25	8.45	9.36	10.04	10.56	10.92
40		5.31	6.97	8.47	9.86	11.05	12.01	12.71	13.12
60		5.87	7.68	9.30	10.85	12.29	13.46	14.37	15.07
		Site index 90							
00	20	4.42	5.67	6.79	7.78	8.61	9.43	10.23	10.82
20		5.06	6.56	8.00	9.34	10.44	11.45	12.38	13.08
40		5.60	7.41	9.09	10.56	11.98	13.24	14.46	15.65
60		6.18	8.18	10.13	11.98	13.52	14.96	16.42	17.76
00	30	4.74	6.02	7.13	8.15	9.08	9.90	10.56	11.04
20		5.58	7.14	8.78	10.13	11.21	12.20	12.98	13.58
40		6.17	8.22	10.07	11.75	13.09	14.36	15.26	15.93
60		6.61	8.94	11.14	13.04	14.64	15.94	17.10	18.06
		Site index 100							
00	20	5.17	6.55	7.91	9.17	10.20	11.10	11.90	12.70
20		5.89	7.63	9.23	10.84	12.40	13.69	14.80	15.60
40		6.55	8.54	10.51	12.33	14.03	15.67	17.05	18.17
60		7.06	9.42	11.55	13.78	15.76	17.63	19.26	20.53
00	30	5.40	7.02	8.45	9.76	10.97	11.97	12.70	13.20
20		6.34	8.24	10.14	11.98	13.44	14.66	15.60	16.26
40		7.17	9.52	11.76	13.89	15.71	17.15	18.34	19.08
60		7.76	10.34	12.83	15.25	17.36	19.14	20.53	21.50

Table A-5.—Estimated total board foot volume production per acre of spruce-fir in relation to growing stock level, site index, rotation age, and cutting cycle with a shelterwood option. (trees 8 inches d.b.h. and larger to a 6-inch top)

Rotation age	Cutting cycle	Growing stock level 40	60	80	100	120	140	160	180
years		thousand board feet							
		Site index 50							
100	20	6.3	8.5	9.7	10.7	11.4	11.7	11.5	10.1
120		8.8	11.5	13.7	15.8	16.8	17.0	16.8	16.2
140		10.9	14.4	17.5	19.9	21.8	23.2	23.0	21.8
160		13.0	17.6	21.1	24.6	26.9	28.8	29.1	28.2
100	30	7.0	8.5	9.7	10.6	11.1	11.2	11.0	10.1
120		9.2	12.0	14.0	15.4	16.1	16.3	16.1	15.6
140		11.8	15.5	18.1	20.6	22.4	22.8	22.5	21.8
160		13.9	17.9	21.8	25.4	28.2	29.8	29.4	28.0
		Site index 60							
100	20	8.5	11.4	13.5	15.3	16.4	17.1	17.7	18.0
120		11.0	15.0	18.4	20.8	22.4	23.9	24.8	25.8
140		13.6	18.5	23.0	26.5	29.3	31.4	33.0	33.9
160		16.0	22.1	27.5	31.9	34.9	37.6	39.8	41.6
100	30	8.9	11.2	13.1	14.8	16.1	16.7	17.2	16.4
120		11.9	15.2	18.2	21.0	22.6	23.6	24.2	23.6
140		14.8	20.0	24.2	27.7	30.5	32.2	33.0	32.2
160		17.6	23.7	28.6	32.6	36.3	39.8	41.1	40.3
		Site index 70							
100	20	10.7	14.3	17.3	19.9	22.0	23.5	24.3	25.0
120		14.0	19.0	23.2	26.9	29.9	32.2	34.1	35.5
140		17.2	22.8	28.4	33.2	37.4	40.5	43.1	45.1
160		20.0	27.0	33.6	39.7	45.0	49.3	53.1	55.2
100	30	11.2	14.8	17.8	20.1	21.6	22.7	27.6	28.1
120		14.8	19.8	23.8	27.1	29.6	31.8	33.1	33.7
140		18.8	24.6	30.5	35.3	39.3	42.1	44.1	44.8
160		21.4	29.0	36.2	42.1	46.9	50.4	52.6	53.6
		Site index 80							
100	20	12.9	17.2	21.1	24.5	27.6	30.0	32.2	33.5
120		16.7	22.9	28.0	32.4	36.7	40.3	43.2	45.0
140		20.2	28.3	34.3	40.0	45.6	50.7	54.9	58.1
160		23.4	32.6	40.6	47.8	54.7	60.9	66.2	70.2
100	30	14.2	18.4	22.4	25.7	28.2	30.0	31.2	31.8
120		18.4	24.2	29.8	34.9	38.5	41.3	43.0	43.8
140		22.7	30.5	37.7	44.0	49.0	53.5	56.0	57.4
160		26.1	35.4	43.7	51.7	58.4	63.5	67.2	69.0
		Site index 90							
100	20	15.7	20.8	25.9	30.3	33.9	36.9	39.8	42.0
120		19.8	26.8	33.4	39.7	44.6	49.4	53.5	57.0
140		24.1	32.6	40.7	48.2	55.3	61.5	67.2	71.7
160		24.1	38.1	48.2	57.4	65.6	72.9	80.0	86.6
100	30	17.2	22.6	27.4	31.5	34.9	37.3	39.4	40.7
120		22.0	29.8	37.2	43.0	48.2	52.2	55.0	55.9
140		26.7	36.8	45.6	53.9	61.5	65.1	69.0	70.6
160		30.4	42.1	52.8	62.6	71.8	78.2	83.2	85.0
		Site index 100							
100	20	18.5	24.6	30.7	36.1	40.3	44.0	47.4	50.5
120		23.4	31.8	39.5	47.0	54.0	60.0	64.8	68.4
140		27.9	38.2	48.4	57.7	65.9	73.5	80.5	85.7
160		31.8	44.5	56.2	66.9	77.4	87.0	95.4	101.8
100	30	19.8	26.8	33.4	39.0	43.7	46.8	49.0	50.4
120		26.0	35.0	43.8	51.8	59.0	64.1	66.8	68.2
140		31.4	43.1	54.2	64.7	73.2	79.8	84.6	86.1
160		36.5	49.4	61.8	73.9	84.8	93.8	100.0	102.6

Table A-6.—Estimated average diameter (inches) and number of trees per acre of spruce-fir of final harvest in relation to growing stock levels, site indexes, rotation age, and cutting cycle with a shelterwood option

		Growing stock level															
		40		60		80		100		120		140		160		180	
Rotation age	Cutting cycle	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter
Site index 50																	
100	20	19	20.6	39	17.5	65	15.6	95	14.3	135	13.1	194	11.8	236	11.1	289	10.1
120		11	26.7	22	22.6	39	19.7	57	18.2	84	16.5	125	14.5	169	13.3	226	12.2
140		7	33.5	13	28.8	24	24.9	36	22.6	53	20.5	79	18.1	110	16.3	161	14.3
160		6	35.1	11	32.3	16	30.7	23	27.9	35	24.9	52	22.1	72	20.0	107	17.4
100	30	22	19.3	43	16.7	72	14.9	107	13.6	151	12.4	208	11.2	250	10.8	295	10.0
120		12	25.2	25	21.6	42	19.1	65	17.1	91	15.8	136	13.9	181	12.9	235	12.0
140		9	29.6	18	25.3	29	22.6	46	20.1	65	18.4	100	16.1	131	15.0	180	13.5
160		7	33.3	11	31.8	18	28.3	30	24.7	44	22.5	66	19.7	87	18.2	122	16.3
Site index 60																	
100	20	17	21.8	34	19.0	57	16.9	76	16.2	116	14.3	153	13.4	209	12.3	259	10.1
120		9	28.7	19	24.7	33	21.8	45	20.7	70	18.1	90	17.2	131	15.3	164	12.2
140		7	32.7	11	31.8	19	27.9	27	26.1	43	22.2	55	21.9	79	19.4	103	14.3
160		5	37.9	9	35.6	15	31.4	18	32.0	28	28.0	36	26.8	51	23.8	67	17.4
100	30	19	20.8	36	18.4	62	16.2	85	15.3	129	13.7	164	13.0	217	12.1	264	13.3
120		10	27.6	20	24.1	35	21.1	51	19.5	76	17.4	99	16.4	133	15.1	183	13.7
140		7	32.8	14	28.5	24	25.0	36	23.1	53	20.7	70	19.3	95	17.0	133	15.9
160		6	36.5	11	31.9	15	31.1	23	28.3	34	25.6	46	23.8	62	21.8	86	19.5
Site index 70																	
100	20	15	23.4	28	21.0	46	18.7	69	17.2	97	15.9	123	15.1	166	13.9	210	13.1
120		8	31.0	15	27.5	26	24.5	39	22.5	55	20.5	70	19.6	94	18.1	126	16.7
140		6	36.1	11	32.1	15	31.5	23	28.5	33	26.0	43	24.7	59	22.6	79	20.7
160		4	42.0	8	37.1	12	35.5	18	32.5	21	32.3	27	30.8	38	28.0	50	25.8
100	30	17	22.3	30	20.2	49	18.2	75	16.6	103	15.5	138	14.4	184	13.3	231	12.5
120		9	29.3	17	26.2	27	24.0	42	21.4	59	19.9	79	18.5	109	16.9	139	15.8
140		7	34.4	11	31.8	19	28.4	29	25.7	41	23.6	55	22.0	75	20.1	99	18.5
160		5	39.7	9	35.0	15	31.9	18	32.1	25	29.5	34	27.5	48	25.0	63	23.0
Site index 80																	
100	20	13	25.3	25	22.3	39	20.6	59	18.8	79	17.7	103	16.7	133	15.7	177	14.4
120		7	33.7	14	29.3	21	27.2	32	24.7	44	22.9	58	21.6	74	20.5	99	18.8
140		6	36.2	10	34.1	14	31.9	19	31.4	27	29.1	35	27.5	44	26.0	59	23.9
160		4	42.2	7	39.6	11	36.9	15	35.3	20	33.2	25	31.5	28	32.6	37	29.9
100	30	15	24.0	27	21.5	44	19.6	63	18.2	87	16.9	118	15.7	145	15.1	196	13.8
120		8	31.7	15	28.4	24	25.8	35	23.7	48	22.1	66	20.5	83	19.4	117	17.4
140		7	33.0	10	34.0	16	30.8	23	28.6	33	26.6	44	24.7	58	23.0	81	20.6
160		5	38.8	8	38.3	13	34.4	18	32.1	20	33.2	28	30.6	36	28.7	51	25.8
Site index 90																	
100	20	12	26.7	22	24.0	35	21.9	48	20.8	67	19.3	89	18.1	110	17.4	139	16.4
120		7	34.7	11	32.2	19	29.1	26	27.5	37	25.3	48	23.8	62	22.4	80	21.1
140		5	38.5	8	37.9	13	34.0	18	31.9	21	32.9	29	30.5	36	29.0	47	26.8
160		4	44.7	6	43.9	10	39.4	14	37.1	16	37.0	22	34.8	27	33.1	30	33.6
100	30	13	25.6	25	22.7	38	21.0	63	19.7	71	18.7	100	17.1	125	16.4	164	15.2
120		7	33.9	13	30.4	21	27.8	35	26.1	39	24.7	55	22.6	69	21.4	91	19.8
140		6	35.4	12	31.7	13	33.9	23	31.7	26	29.8	37	27.1	46	25.9	64	23.3
160		4	41.6	8	37.3	11	37.4	18	35.3	20	33.4	25	30.8	29	32.0	39	29.4
Site index 100																	
100	20	11	28.1	19	25.7	30	23.7	43	22.0	57	21.0	77	19.5	99	18.4	119	17.9
120		7	34.6	10	31.4	16	34.4	23	29.5	30	28.3	41	26.0	53	24.5	67	23.0
140		5	40.8	8	37.2	12	36.7	16	34.3	21	32.9	23	33.9	30	31.8	40	29.5
160		3	47.8	6	43.4	8	42.6	12	39.9	15	38.3	21	35.7	23	34.6	30	33.8
100	30	11	27.2	22	24.3	34	22.4	47	21.3	63	20.7	83	18.9	106	17.9	139	16.6
120		7	35.2	11	32.7	18	30.2	25	28.3	34	26.7	45	25.0	58	23.6	77	21.7
140		6	37.4	10	34.1	16	31.5	17	34.2	23	32.1	30	30.3	38	28.5	53	25.7
160		4	44.1	7	40.1	11	37.3	13	36.6	18	35.9	23	33.9	30	32.0	32	32.5

Alexander, Robert R., and Carleton B. Edminster. 1980. Management of spruce-fir in even-aged stands in the central Rocky Mountains. USDA Forest Service Research Paper RM-217, 14 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Potential production of Engelmann spruce and subalpine fir in the central Rocky Mountains is simulated for various combinations of stand density, site quality, ages, and thinning schedules. Such estimates are needed to project future development of stands managed in different ways for various uses.

Keywords: stand growth, stand yield, forest management, *Picea engelmannii, Abies lasiocarpa*

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U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

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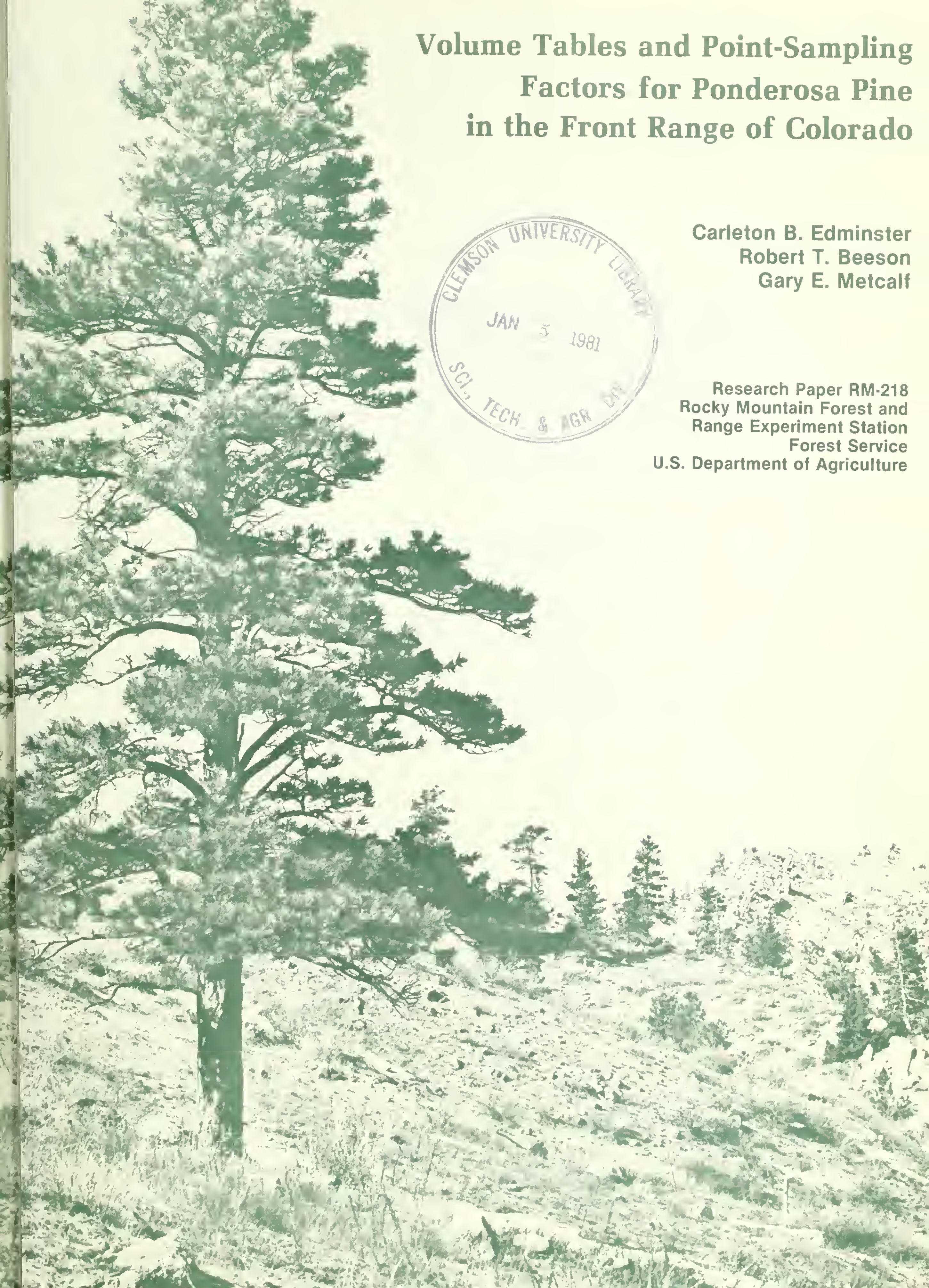
Volume Tables and Point-Sampling Factors for Ponderosa Pine in the Front Range of Colorado

Carleton B. Edminster
Robert T. Beeson
Gary E. Metcalf

Research Paper RM-218
Rocky Mountain Forest and Range Experiment Station
Forest Service
U.S. Department of Agriculture



Abstract

Volume tables are presented for total cubic feet, merchantable cubic feet to a 4-inch top, board feet Scribner Rule to a 6-inch top, and board feet International 1/4-inch Rule to a 6-inch top. Point-sampling factor tables are given for merchantable volumes per square foot of basal area. Tree heights are expressed as total height in feet and merchantable height in numbers of logs. Volume equations are the form $V = a + bD^2H$.

Acknowledgment

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Volume Tables and Point-Sampling Factors for Ponderosa Pine in the Front Range of Colorado

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Contents

Plant a tree! Mark the 75th birthday of the Forest Service by giving a living gift to future generations.

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Management Highlights

Eleven tables presented here give values and equations needed to determine the volumes of ponderosa pine (*Pinus ponderosa* var. *scopulorum* Engelm.) trees in the Front Range of the Rocky Mountains in Colorado. The tables provide:

1. Gross volumes, in cubic feet, of the entire stem.
2. Gross merchantable volumes, in cubic feet, to a 4-inch top.
3. Gross merchantable volumes, in board feet, Scribner and International 1/4-inch Rules, to a 6-inch top.
4. Point-sampling factors giving merchantable volumes in cubic feet and board feet per square foot of basal area.

Stand volumes on an area may be determined from: (1) measurements of all tree diameters and heights, (2) measurements of all tree diameters and sufficient heights to convert the appropriate volume tables to local volume tables (Chapman and Meyer 1949), or (3) tree tallies obtained by point sampling.

Definitions and Standards

Diameter at breast height (d.b.h.).—Measured to the nearest 0.1 inch, outside the bark, at 4.5 feet above ground level, on the uphill side of the tree. Full-inch-diameter classes, with class midpoints at the 1/2-inch marks, are used in the tables.

Total height.—Measured, in whole feet to the nearest foot, from ground level on the uphill side of the tree upward to the tip. Trees forked below utilization limits described below, stag-topped, or severely deformed were not included in the sample. The midpoints of total height classes in the tables are multiples of 10 feet.

Scaling diameter of logs.—Average diameter inside bark to nearest 0.1 inch, measured at the small end of logs or half-logs.

Minimum top diameters for merchantable volumes.—Minimum top diameter inside bark for computation of merchantable cubic-foot volume was 4 inches. For board-foot volume, a minimum top diameter inside bark of 6 inches was used to conform to local practice. Logs with a scaling diameter smaller than 5.6 inches usually were not included in saw-log volume. A few logs with smaller scaling diameters were included to satisfy the "4-foot rule" described below.

Merchantable length in logs.—Measured from 1 foot above ground level on the uphill side of the tree, upward to the limit of saw-log utilization. Each tree was sectioned into as many 16.5-foot-long logs as possible. An additional half-log, if available, was taken from the uppermost part of the merchantable length. Portions of the bole above the height of minimum top diameter inside bark were included in the uppermost saw-log if the standard log or half-log length ended within 4 feet above this height. This "4-foot rule" was used to avoid a negative bias in volume determination (Chapman and Meyer 1949).

Explanation of Tables

General definitions and standards given above apply to all tables listed in the appendix. Explanation of each type of table and suggestions for use follow.

Volume Tables

Headings and footnotes of each volume table (table 1 and even-numbered tables) give units of volume and height measurement, utilization standards, and volume equations used in compilation. Full-inch-diameter classes and 10-foot-height classes or half-log-length classes were used in all tables.

The volume tables were developed from linear regressions of V and D^2H or D^2L of the form:

$$V = a + bD^2H \text{ or } V = a + bD^2L$$

where:

V = gross volume inside bark in the appropriate unit
D = d.b.h. outside bark in inches
H = total height in feet
L = merchantable length in standard logs and half-logs
a, b = regression coefficients

Graphs of V versus D^2H or D^2L for all volume relationships did not indicate a nonlinear expression was needed to cover the full range of the basic data. Unfortunately, the linear regression equations for board-foot volumes gave negative estimates for small values of D^2H or D^2L. To correct this, the volume of a half-log with minimum top diameter has been substituted as described in the footnotes for tables 4, 6, 8, and 10.

The number of logs in a tree shown in tables 6 and 10 is not necessarily the number that will actually be cut from it. It is the number of logs between the 1-foot above ground level and the height of minimum top diameter. Volume of nonmerchantable logs below the height of minimum top diameter should be deducted from tree volume by: (1) estimation of scaling diameters and deduction of appropriate log volumes, or (2) use of taper tables to determine scaling diameters and deduction of log volumes. Volume should not be reduced by tallying fewer logs in the tree.

Point-Samping Factors

Odd-numbered tables from tables 3 through 11 give point-sampling factors for combinations of tree d.b.h. and height or merchantable length. Tabulated volumes per square foot of basal area were obtained from equations given in the table footnotes. These equations were derived by dividing each term of the corresponding tree volume equation by tree basal area in square feet ($B = 0.0054542\ D^2$).

Point-sample cruising to estimate stand volume can be done in several ways: (1) measure the d.b.h. and height of each tree tallied through the prism, angle gage, or relascope; (2) measure the height of each tallied tree and estimate its d.b.h.; or (3) measure the heights of the tallied trees and make no record of d.b.h.'s. The procedure selected will depend on the precision desired. Relative precision is usually in the order listed above. If the d.b.h. and height of each tallied tree are measured, a volume conversion factor can be selected from the tables or computed from the appropriate equations for each combination of d.b.h. and height. Volume per acre is then computed as follows:

1. Multiply the number of tallied trees in each d.b.h.-height class by the point-sampling factor for the class.
2. Total the products of step 1.
3. Multiply the total of step 2 by the basal area factor of the angle gage used.
4. Divide the product of step 3 by the number of points sampled on the tract.

Considerable time often can be saved if the heights of tallied trees are measured, while d.b.h.'s are estimated and recorded by broad classes. Inspection of the point-sampling factor tables shows that volumes per square foot of basal area, for trees larger than 15 inches d.b.h., often do not differ greatly among trees of a single height class. The increased time spent measuring d.b.h.'s may not increase precision materially. When the distribution of d.b.h.'s and heights inventoried indicates there is little change in volume per square foot within a height class, it is recommended that d.b.h.'s not be recorded at all. Point-sampling factors for each height class can be computed using a procedure similar to deriving a local volume table from a standard table (Chapman and Meyer 1949).

The techniques of point sampling have been described in numerous publications (Dilworth and Bell 1971; Grosenbaugh 1952, 1955, 1958). Procedures for computing tree volumes and point-sampling factors using programmable calculators have been developed by Shepperd (1980).

Metric Equations for Cubic Volume

The following equations are the metric equivalents (Myers and Edminster 1974) of the cubic-foot volume equations used to develop tables 1-3.

Gross volume of the entire stem in cubic meters:

$$V_m = 0.0000325\ D_m^2 H_m$$

Gross merchantable volume in cubic meters to a 10-cm top:

$$V_m = 0.0000311\ D_m^2 H_m - 0.01265$$

Gross merchantable volume in cubic meters per square meter of basal area:

$$V_m/B_m = 0.39618\ H_m - 161.14650/D_m^2$$

where:

V_m = gross volume inside bark in cubic meters
D_m = d.b.h. outside bark in centimeters
H_m = total height in meters
B_m = tree basal area in square meters

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Table 1.—Gross volumes, in cubic feet inside bark, of entire stem including stump and top, ponderosa pine in the Front Range of Colorado

d.b.h.	Total height (feet) above ground										Basis:
	10	20	30	40	50	60	70	80	90	100	trees
inches											
1	0.1	0.1									18
2	0.1	0.3	0.4	0.6							21
3	0.3	0.6	0.8	1.1							29
4	0.5	0.9	1.4	1.8							36
5	0.7	1.4	2.1	2.7	3.4						41
6		1.9	2.9	3.8	4.8						36
7		2.5	3.8	5.1	6.4	7.6					40
8		3.3	4.9	6.5	8.2	9.8	11.4				64
9		4.1	6.1	8.2	10.2	12.2	14.3				59
10		5.0	7.5	10.0	12.5	14.9	17.4				77
11		6.0	9.0	12.0	14.9	17.9	20.9	23.9			55
12		7.1	10.6	14.1	17.7	21.2	24.7	28.3			80
13		8.2	12.4	16.5	20.6	24.7	28.8	33.0			83
14			14.3	19.0	23.8	28.5	33.3	38.0			68
15			16.3	21.7	27.1	32.6	38.0	43.4			58
16			18.5	24.6	30.8	36.9	43.1	49.2	55.4		52
17			20.8	27.7	34.6	41.5	48.4	55.4	62.3		58
18			23.2	30.9	38.7	46.4	54.1	61.9	69.6		35
19			25.8	34.4	43.0	51.6	60.2	68.7	77.3		18
20			28.5	38.0	47.5	57.0	66.5	76.0	85.5		18
21				41.8	52.2	62.7	73.1	83.6	94.0		19
22				45.8	57.2	68.6	80.1	91.5	103.0	114.4	20
23				49.9	62.4	74.9	87.4	99.8	112.3	124.8	8
24					67.8	81.4	95.0	108.5	122.1	135.7	4
25					73.5	88.2	102.9	117.6	132.3	147.0	5
26					79.4	95.2	111.1	127.0	142.8	158.7	3
27					85.5	102.5	119.6	136.7	153.8	170.9	2
28						110.1	128.5	146.9	165.2	183.6	0
29						118.0	137.7	157.3	177.0	196.7	1
30						126.1	147.2	168.2	189.2	210.2	0
Basis: trees	30	60	157	269	278	166	38	9	1	0	1,008

Block indicates extent of data.
Computed from: $V = 0.00226\ D^2H$
Standard error of estimate: ± 14.16% of mean; ± 2.9 cubic feet
Coefficient of determination: 0.9787
Diameter classes full-inch (e.g., 20-inch class includes 20.0 to 20.9 inches d.b.h.)

Table 2.—Gross merchantable volumes, in cubic feet inside bark, merchantable stem excluding stump and top, ponderosa pine in the Front Range of Colorado. Top diameter 4 inches inside bark. Stump height 1 foot

d.b.h.	Total height (feet) above ground									Basis:
	20	30	40	50	60	70	80	90	100	trees
inches										
5	0.9	1.5	2.2	2.8						41
6	1.4	2.3	3.2	4.1						36
7	2.0	3.2	4.4	5.6	6.8					40
8	2.7	4.2	5.8	7.4	8.9	10.5				64
9	3.5	5.4	7.4	9.3	11.2	13.2				59
10	4.3	6.7	9.1	11.5	13.8	16.2				77
11	5.3	8.1	11.0	13.8	16.7	19.5	22.4			55
12	6.3	9.7	13.1	16.4	19.8	23.2	26.6			80
13	7.4	11.4	15.3	19.2	23.2	27.1	31.0			83
14		13.2	17.7	22.3	26.8	31.3	35.9			68
15		15.1	20.3	25.5	30.7	35.9	41.1			58
16		17.2	23.1	29.0	34.8	40.7	46.6	52.5		52
17		19.4	26.0	32.6	39.2	45.9	52.5	59.1		58
18		21.7	29.1	36.5	43.9	51.3	58.7	66.1		35
19		24.2	32.4	40.6	48.8	57.0	65.3	73.5		18
20		26.8	35.9	44.9	54.0	63.1	72.2	81.2		18
21			39.5	49.5	59.5	69.4	79.4	89.4		19
22			43.3	54.2	65.2	76.1	87.0	98.0	108.9	20
23			47.3	59.2	71.1	83.1	95.0	106.9	118.8	8
24				64.4	77.3	90.3	103.3	116.2	129.2	4
25				69.8	83.8	97.9	111.9	126.0	140.0	5
26				75.4	90.6	105.7	120.9	136.1	151.2	3
27				81.2	97.6	113.9	130.2	146.6	162.9	2
28					104.8	122.4	139.9	157.5	175.0	0
29					112.3	131.1	149.9	168.7	187.5	1
30					120.1	140.2	160.3	180.4	200.5	0
Basis: trees	11	132	269	278	166	38	9	1	0	904

Block indicates extent of data.
Computed from: $V = 0.00216 D^2H - 0.44670$
Standard error of estimate: ± 14.29% of mean; ± 3.0 cubic feet
Coefficient of determination: 0.9744
Diameter classes full-inch (e.g., 20-inch class includes 20.0 to 20.9 inches d.b.h.)

Table 3.—Gross merchantable volumes, in cubic feet inside bark per square foot of basal area, merchantable stem excluding stump and top, ponderosa pine in the Front Range of Colorado. Top diameter 4 inches inside bark. Stump height 1 foot

d.b.h.	Total height (feet) above ground								
	20	30	40	50	60	70	80	90	100
inches									
5	5.2	9.2	13.1	17.1					
6	6.0	9.9	13.9	17.9					
7	6.5	10.4	14.4	18.3	22.3				
8	6.8	10.7	14.7	18.7	22.6	26.6			
9	7.0	11.0	14.9	18.9	22.9	26.8			
10	7.2	11.1	15.1	19.1	23.0	27.0			
11	7.3	11.3	15.2	19.2	23.1	27.1	31.1		
12	7.4	11.4	15.3	19.3	23.2	27.2	31.2		
13	7.5	11.4	15.4	19.4	23.3	27.3	31.2		
14		11.5	15.5	19.4	23.4	27.3	31.3		
15		11.5	15.5	19.5	23.4	27.4	31.3		
16		11.6	15.5	19.5	23.5	27.4	31.4	35.3	
17		11.6	15.6	19.5	23.5	27.5	31.4	35.4	
18		11.6	15.6	19.6	23.5	27.5	31.4	35.4	
19		11.7	15.6	19.6	23.5	27.5	31.5	35.4	
20		11.7	15.6	19.6	23.6	27.5	31.5	35.4	
21			15.7	19.6	23.6	27.5	31.5	35.5	
22			15.7	19.6	23.6	27.6	31.5	35.5	39.4
23			15.7	19.7	23.6	27.6	31.5	35.5	39.5
24				19.7	23.6	27.6	31.5	35.5	39.5
25				19.7	23.6	27.6	31.6	35.5	39.5
26				19.7	23.6	27.6	31.6	35.5	39.5
27				19.7	23.7	27.6	31.6	35.5	39.5
28					23.7	27.6	31.6	35.5	39.5
29					23.7	27.6	31.6	35.5	39.5
30					23.7	27.6	31.6	35.6	39.5

Computed from: $V/B = 0.39603H - 81.90019/D^2$
Diameter classes full-inch (e.g., 20-inch class includes 20.0 to 20.9 inches d.b.h.)

Table 4.—Gross volumes, in board feet inside bark Scribner Rule, merchantable stem excluding stump and top, ponderosa pine in the Front Range of Colorado. Top diameter 6 inches inside bark. Stump height 1 foot

d.b.h.	Total height (feet) above ground								Basis:
	30	40	50	60	70	80	90	100	trees
inches									
7	8	8	8	14					26
8	8	9	17	25	34				63
9	8	17	27	38	48				58
10	13	26	39	51	64				77
11	21	36	51	67	82	97			55
12	29	47	65	83	101	119			77
13	38	59	80	101	122	143			83
14	48	72	96	120	145	169			68
15	58	86	113	141	169	196			58
16	69	101	132	163	194	226	257		51
17	81	116	151	187	222	257	292		58
18	93	133	172	211	251	290	329		35
19	107	150	194	238	281	325	369		18
20	120	169	217	265	313	362	410		18
21		188	241	294	347	400	453		19
22		208	266	324	383	441	499	557	20
23		229	293	356	420	483	547	610	8
24			320	389	458	527	596	665	4
25			349	424	498	573	648	723	5
26			379	460	540	621	702	782	3
27			410	497	584	671	757	844	2
28				535	629	722	815	909	0
29				575	675	775	875	975	1
30				617	724	831	937	1,044	0
Basis: trees	70	247	276	166	38	9	1	0	807

Block indicates extent of data
Computed from: $V = 8$ for D^2H to 2,830; $V = 0.01149\ D^2H - 24.5404$ for D^2H larger than 2,830
Standard error of estimate: ±25.36% of mean; ±26 board feet
Coefficient of determination: 0.9351
Diameter classes full-inch (e.g., 20-inch class includes 20.0 to 20.9 inches d.b.h.)

Table 5.—Gross volumes, in board feet inside bark Scribner Rule per square foot of basal area, merchantable stem excluding stump and top, ponderosa pine in the Front Range of Colorado. Top diameter 6 inches inside bark. Stump height 1 foot

	Total height (feet) above ground							
d.b.h.	30	40	50	60	70	80	90	100
inches								
7	26	26	26	46				
8	20	22	43	64	85			
9	16	34	55	77	98			
10	22	43	65	86	107			
11	29	50	71	92	113	135		
12	34	55	77	98	119	140		
13	39	60	81	102	123	144		
14	42	63	84	105	126	147		
15	44	66	87	108	129	150		
16	47	68	89	110	131	152	173	
17	49	70	91	112	133	154	175	
18	50	71	92	113	134	155	176	
19	51	72	93	115	136	157	178	
20	52	74	95	116	137	158	179	
21		75	96	117	138	159	180	
22		75	96	118	139	160	181	202
23		76	97	118	139	160	181	203
24			98	119	140	161	182	203
25			98	119	141	162	183	204
26			99	120	141	162	183	204
27			99	120	142	163	184	205
28				121	142	163	184	205
29				121	142	163	184	205
30				122	143	164	185	206

Computed from: $V/B = 1{,}466.75956/D^2$ for D^2H to 2,830; $V/B = 2.10663H - 4{,}499.35829/D^2$ for D^2H larger than 2,830

Diameter classes full-inch (e.g., 20-inch class includes 20.0 to 20.9 inches d.b.h.)

Table 6.—Gross volumes, in board feet inside Scribner Rule, merchantable stem excluding stump and top, ponderosa pine in the Front Range of Colorado. Top diameter 6 inches inside bark. Stump height 1 foot

d.b.h.	Number of 16-foot logs to 6-inch top										Basis: trees
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	
inches											
7	8	8	13	19							26
8	8	10	18	26	35						63
9	8	14	24	34	45						58
10	8	19	31	44	56						77
11	9	24	39	53	68	83					55
12	11	29	47	64	82	100	117				77
13	14	35	55	76	97	117	138	158			83
14		41	65	89	112	136	160	183			68
15		48	75	102	129	156	183	211			58
16		55	86	117	147	178	209	239	270		51
17		63	97	132	166	201	236	270	305		58
18		71	110	148	187	225	264	303	341		35
19		80	122	165	208	251	294	337	380		18
20		89	136	183	231	278	326	373	420		18
21			150	202	254	307	359	411	463		19
22			165	222	279	336	393	451	508	565	20
23			181	243	305	367	430	492	554	617	8
24				265	332	400	468	535	603	671	4
25					360	434	507	580	654	727	5
26					390	469	548	627	707	786	3
27					420	506	591	676	761	847	2
28					452	543	635	727	818	910	0
29					485	583	681	779	877	975	1
30						623	728	833	938	1,043	0
Basis: trees	44	104	187	212	150	87	18	4	1	0	807

Block indicates extent of data.
Computed from: $V = 8$ for D^2L to 63; $V = 0.22556\ D^2L - 6.22508$ for D^2L larger than 63
Standard error of estimate: ± 23.15% of mean; ± 24 board feet
Coefficient of determination: 0.9459
Diameter classes full-inch (e.g., 20-inch class includes 20.0 to 20.9 inches d.b.h.)

Table 7.—Gross volumes, in board feet inside bark Scribner Rule per square foot of basal area, merchantable stem excluding stump and top, ponderosa pine in the Front Range of Colorado. Top diameter 6 inches inside bark. Stump height 1 foot

	Number of 16-foot logs to 6-inch top									
d.b.h.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
inches										
7	26	26	42	62						
8	20	26	46	67	88					
9	16	29	49	70	91					
10	13	31	52	72	93					
11	12	33	53	74	95	115				
12	13	34	55	75	96	117	137			
13	14	35	56	76	97	118	138	159		
14		36	57	77	98	119	139	160		
15		37	57	78	99	119	140	161		
16		37	58	79	99	120	141	161	182	
17		38	58	79	100	120	141	162	182	
18		38	59	79	100	121	141	162	183	
19		38	59	80	100	121	142	162	183	
20		39	59	80	101	121	142	163	183	
21			60	80	101	122	142	163	184	
22			60	80	101	122	142	163	184	205
23			60	81	101	122	143	163	184	205
24				81	101	122	143	164	184	205
25					102	122	143	164	184	205
26					102	122	143	164	184	205
27					102	123	143	164	185	205
28					102	123	143	164	185	205
29					102	123	143	164	185	205
30						123	144	164	185	206

Computed from: $V/B = 1,466.75956/D^2$ *for* D^2L *to 63;* $V/B = 41.35529L - 1,141.33695/D^2$ *for* D^2L *larger than 63*
Diameter classes full-inch (e.g., 20-inch class includes 20.0 to 20.9 inches d.b.h.)

Table 8.—Gross volumes, in board feet inside bark International 1/4-inch Rule, merchantable stem excluding stump and top, ponderosa pine in the Front Range of Colorado. Top diameter 6 inches inside bark. Stump height 1 foot

d.b.h.	Total height (feet) above ground								Basis:
	30	40	50	60	70	80	90	100	trees
inches									
7	9	9	13	20					26
8	9	14	23	32	41				63
9	11	23	34	46	58				58
10	19	33	47	61	76				77
11	27	44	61	78	95	112			55
12	37	57	77	97	117	137			77
13	47	70	94	117	140	164			83
14	58	85	112	139	166	193			68
15	69	100	131	162	193	224			58
16	81	116	151	186	221	256	292		51
17	95	134	173	213	252	291	331		58
18	108	152	196	240	285	329	373		35
19	123	172	221	270	319	368	417		18
20	139	193	247	301	355	409	463		18
21		214	274	333	393	452	511		19
22		237	302	367	432	497	562	627	20
23		260	332	403	474	545	616	687	8
24			362	440	517	594	671	748	4
25			395	478	562	645	729	813	5
26			428	518	609	699	789	880	3
27			463	560	657	754	852	949	2
28				603	708	812	917	1,021	0
29				648	760	872	984	1,096	1
30				694	814	933	1,053	1,173	0
Basis: trees	70	247	276	166	38	9	1	0	807

Block indicates extent of data
Computed from: V = 9 for D^2H to 2,535; V = 0.01286 D^2H – 23.5932 for D^2H larger than 2,535
Standard error of estimate: ± 23.36% of mean; ± 28 board feet
Coefficient of determination: 0.9408
Diameter classes full-inch (e.g., 20-inch class includes 20.0 to 20.9 inches d.b.h.)

Table 9.—Gross volumes, in board feet inside bark International 1/4-inch Rule per square foot of basal area, merchantable stem excluding stump and top, ponderosa pine in the Front Range of Colorado. Top diameter 6 inches inside bark. Stump height 1 foot

	Total height (feet) above ground							
d.b.h.	30	40	50	60	70	80	90	100
inches								
7	29	29	41	65				
8	23	34	58	82	105			
9	23	46	70	94	117			
10	31	55	79	102	126			
11	38	62	85	109	132	156		
12	43	67	90	114	137	161		
13	47	71	94	118	141	165		
14	50	74	97	121	144	168		
15	53	76	100	123	147	171		
16	55	78	102	126	149	173	196	
17	57	80	104	127	151	175	198	
18	58	82	105	129	152	176	200	
19	59	83	107	130	154	177	201	
20	60	84	108	131	155	178	202	
21		85	109	132	156	179	203	
22		86	109	133	157	180	204	227
23		86	110	134	157	181	204	228
24			111	134	158	181	205	229
25			111	135	158	182	206	229
26			112	135	159	182	206	230
27			112	136	159	183	206	230
28				136	160	183	207	230
29				136	160	184	207	231
30				137	160	184	208	231

Computed from: $V/B = 1{,}650.10451/D^2$ for D^2H to 2,535; $V/B = 2.35782H - 4{,}325.69396/D^2$ for D^2H larger than 2,535

Diameter classes full-inch (e.g., 20-inch class includes 20.0 to 20.9 inches d.b.h.)

Table 10.—Gross volumes, in board feet inside bark International 1/4-inch Rule, merchantable stem excluding stump and top, ponderosa pine in the Front Range of Colorado. Top diameter 6 inches inside bark. Stump height 1 foot

	Number of 16-foot logs to 6-inch top										Basis:
d.b.h.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	trees
inches											
7	9	11	18	25							26
8	9	15	24	33	43						63
9	9	20	31	43	54						58
10	11	25	39	53	67						77
11	14	30	47	64	80	97					55
12	17	36	56	76	96	115	135				77
13	20	43	66	89	112	135	158	181			83
14		50	77	103	130	156	183	209			68
15		58	88	118	149	179	209	240			58
16		66	100	134	169	203	238	272	306		51
17		74	113	152	190	229	268	306	345		58
18		83	127	170	213	256	299	343	386		35
19		93	141	189	237	285	333	381	429		18
20		103	156	209	262	315	368	421	474		18
21			172	230	289	347	405	464	522		19
22			189	253	316	380	444	508	572	636	20
23			206	276	346	415	485	555	624	694	8
24				300	376	452	527	603	679	755	4
25					407	489	572	654	736	818	5
26					440	529	618	706	795	883	3
27					474	570	665	761	856	952	2
28					510	612	715	817	920	1,022	0
29					546	656	766	876	986	1,096	1
30						702	819	936	1,054	1,171	0
Basis: trees	44	104	187	212	150	87	18	4	1	0	807

Block indicates extent of data.
Computed from: V = 9 for D^2L to 48; V = 0.25248 D^2L – 3.05798 for D^2L larger than 48
Standard error of estimate: ± 21.20% of mean; ± 25 board feet
Coefficient of determination: 0.9512
Diameter classes full-inch (e.g., 20-inch class includes 20.0 to 20.9 inches d.b.h.)

Table 11.—Gross volumes, in board feet inside bark International 1/4-inch Rule per square foot of basal area, merchantable stem excluding stump and top, ponderosa pine in the Front Range of Colorado. Top diameter 6 inches inside bark. Stump height 1 foot

d.b.h.	Number of 16-foot logs to 6-inch top									
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
inches										
7	29	36	59	83						
8	23	39	62	85	108					
9	18	40	63	86	110					
10	18	41	64	87	111					
11	19	42	65	88	111	135				
12	20	43	66	89	112	135	158			
13	20	43	66	90	113	136	159	182		
14		44	67	90	113	136	159	182		
15		44	67	90	113	137	160	183		
16		44	67	91	114	137	160	183	206	
17		44	68	91	114	137	160	183	206	
18		45	68	91	114	137	160	184	207	
19		45	68	91	114	137	161	184	207	
20		45	68	91	114	138	161	184	207	
21			68	91	115	138	161	184	207	
22			68	91	115	138	161	184	207	230
23			68	92	115	138	161	184	207	230
24				92	115	138	161	184	207	231
25					115	138	161	184	207	231
26					115	138	161	184	208	231
27					115	138	161	184	208	231
28					115	138	161	184	208	231
29					115	138	161	185	208	231
30						138	161	185	208	231

Computed from: $V/B = 1{,}650.10451/D^2$ for D^2L to 48; $V/B = 46.29093H - 560.66518/D^2$ for D^2L larger than 48
Diameter classes full-inch (e.g., 20-inch class includes 20.0 to 20.9 inches d.b.h.)

Edminster, Carleton B., Robert T. Beeson, and Gary E. Metcalf. 1980. Volume tables and point-sampling factors for ponderosa pine in the Front Range of Colorado. USDA Forest Service Research Paper RM-218, 14 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Volume tables are presented for total cubic feet, merchantable cubic feet to a 4-inch top, board feet Scribner Rule to a 6-inch top, and board feet International 1/4-inch Rule to a 6-inch top. Point-sampling factor tables are given for merchantable volumes per square foot of basal area. Tree heights are expressed as total height in feet and merchantable height in numbers of logs. Volume equations are the form $V = a + bD^2H$.

Keywords: tree volume tables, point-sampling factors, stand volume estimates, *Pinus ponderosa* var. *scopulorum*

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U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

Rocky Mountains

Southwest

Great Plains

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*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526