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SIMULATING TIMBER YIELDS AND HYDROLOGIC IMPACTS RESULTING FROM TIMBER HARVEST ON SUBALPINE WATERSHEDS

by Charles F. Leaf
Robert R. Alexander

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ABSTRACT

A dynamic simulation model which has been specifically designed to determine the hydrologic changes resulting from timber harvesting and correlary models which simulate timber yields are described. Emphasis is placed on the "planning unit" which is defined by environmental characteristics, including combinations of slope, aspect, elevation, and forest cover. The models are intended for use on subalpine watersheds where the primary source of streamflow is from melting snow. The hydrologic model simulates winter snow accumulation, the short- and longwave radiation balance, snowpack condition, snowmelt, and subsequent runoff in time and space. The timber models simulate projected timber yields in response to changes in cultural treatments and/or variations in original stand and site conditions.

The models are capable of simulating a broad array of timber harvesting alternatives. Hydrologic changes and timber yields can be determined for intervals of time which can vary from a few years to the rotation age of subalpine forests (120 years and longer). In the hydrologic model, this is accomplished by means of time trend functions which compute changes in evapotranspiration, soil water, forest cover density, reflectivity, interception, and snow redistribution as the forest stands respond to management.

The models have been used to simulate the effects of forest and watershed management on several representative drainage basins in the Rocky Mountain Region of the United States. Projected hydrologic changes and growth and yield subsequent to timber harvesting in lodgepole pine and spruce-fir are described in this report.

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Contents

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Charles F. Leaf, Principal Hydrologist
and
Robert R. Alexander, Principal Silviculturist

Introduction

Watershed management research during the past 50 years has shown that subalpine forests exert a significant effect on water yields. Hence, man-caused changes in the forest environment can be expected to affect the water resource. When timber is harvested, the magnitude of the resulting hydrologic change is highly sensitive to the pattern in which a given volume of wood is removed.

Because water from snowmelt is a primary resource in the Rocky Mountain Region of the United States, the need for a planning tool to evaluate the potential hydrologic effects of various timber harvesting strategies is obvious in view of the U.S. Forest Service goal of sound multi-resource management.

Some progress has been made in the development of dynamic simulation models which predict the short-term effects of timber harvesting on snowmelt and water yield (Leaf and Brink 1972, 1973a, 1973b). This work has recently been expanded to determine the long-term interactions between the water and timber resources with regard to initial partial cutting in old-growth subalpine forests, and subsequent management of these stands.

The system described in this report utilizes output from a water balance model (Leaf and Brink 1973b, 1975) to simulate both the immediate and long-term effects of forest and watershed management, in areas where runoff is derived primarily from melting snow. Considerable flexibility is provided for simulating alternative silvicultural systems. Moreover, yield tables can be produced which show how projected timber volumes will vary in response to various timber management alternatives (Myers 1971).

The hydrologic model is described first, followed by examples of projected hydrologic changes from timber harvesting on two watersheds in Colorado and Wyoming. A discussion of the timber models, which simulate growth and yield once old-growth subalpine forests are converted to managed stands is also presented. The models simulate stand growth and response to intermediate cuttings from the regeneration period to final harvest for timber production. Finally, examples are given which illustrate how the models can be used simultaneously to provide the manager with multi-resource response data for timber and water.

Hydrologic Model

Model Configuration

The analytical framework of the system is based on a "planning unit" which is defined by environmental characteristics including combinations of slope, aspect, elevation, and the species, form, and structure of the forest cover. The model is designed to simulate the hydrologic effects of timber harvesting in order to develop management strategies for planning intervals which can vary from a few years to the rotation age of subalpine forests (120 years and longer).

Management strategies may subdivide a given planning unit into as many as eight distinct areas or "response units," which may be managed independently at varying points in time during the planning interval. Provision is also made so that different cutting practices may be imposed on the response units, and finally, any number of cuttings may be made on a given response unit at specified years during the planning interval.

Hydrologic integrity is maintained as management strategies are formulated, since all interactions between the various response units are accounted for in time and space. The interactive effects of a new decision on ones previously implemented are simulated, as are the effects of time, as demonstrated through reforestation. Moreover the overall hydrologic effects resulting from each management decision on the planning unit are projected to the end of the planning interval as though it were the final decision in the strategy. Thus, the singular effects of each decision can be evaluated.

A core model simulates the water balance on a daily basis. On those areas where forest cover has been removed, the parameters which define soil water availability, forest cover density, reflectivity, interception, and snow distribution are adjusted on an annual basis by means of time-trend relationships described later in this report.

Because climatological observations are rarely available for the long periods of time simulated, the system has the capability to extend a sample data base by a randomized selection of water years until the desired planning interval is completed.

Theory

The discussion which follows is necessarily brief and intended to give the reader a general idea of the scope of the model. Detailed flow chart descriptions and more complete hydrologic theory have been published by Leaf and Brink (1973a, 1973b, 1975). The reader is referred to these publications for a more comprehensive treatment of the concepts which follow. At the present time, the model is being used in selected areas throughout the Rocky Mountain Region. A flow chart of the core model in the system is shown in figure 1. Figure 2 shows how the core model is used in executing alternative management strategies.

Snowmelt. — Previous work in high-elevation coniferous forests has shown that radiation is the major source of energy for snowmelt. Accordingly, short- and longwave radiation represent the energy components available for snowmelt. Shortwave radiation to the snow or ground surface beneath the forest canopy is controlled by a transmissivity coefficient to be discussed later, and which varies according to forest cover characteristics. The incident shortwave radiation as measured on a horizontal surface is adjusted according to the slope and aspect of each hydrologic response unit. Longwave radiation is computed by the Stefan-Boltzmann equation.

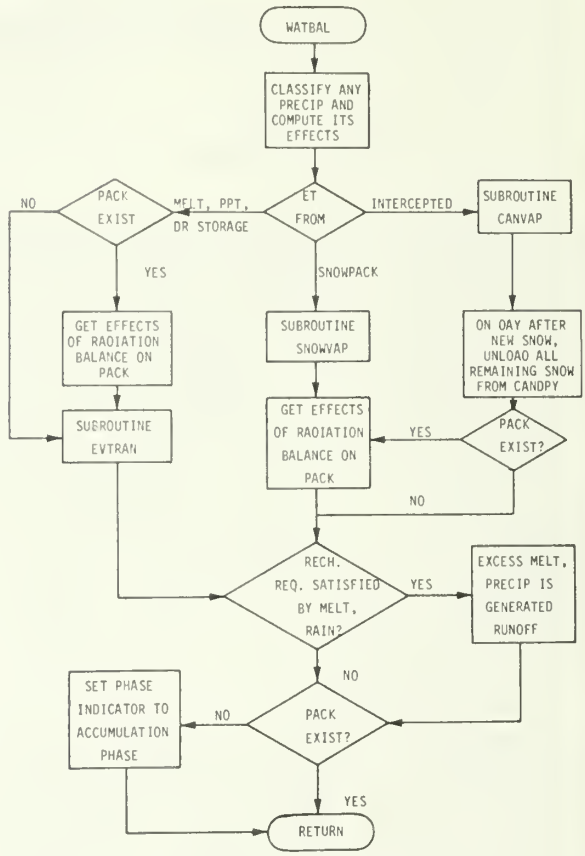


Figure 1. — Flow chart showing system core model.

Snowpack reflectivity is varied according to precipitation form, air temperature, and the energy balance. During the winter months, temperatures within the snow cover are simulated using unsteady heat flow theory. The snowpack will yield melt water only when it has become isothermal at 0°C, and its free water holding capacity is reached.

The generalized equation for snowmelt can be written as:

$$M = S_W(1.0 - R)T + C_d(\sigma T_a{}^4 - \sigma T_s{}^4) + (1.0 - C_d)(\alpha\sigma T_a{}^4 - \sigma T_s{}^4) \qquad [1]$$

where

M = Daily snowmelt in calories per cm^2,

S_W = Incoming solar radiation in ly per day;

R = Reflectivity of snowpack, expressed as a decimal;

T = Shortwave radiation transmissivity coefficient, expressed as a decimal;

C_d = Forest cover density, expressed as a decimal;

σ = Stefan-Boltzmann Constant;

T_a = Air temperature in °K;

T_s = Snow surface temperature in °K;

α = Coefficient for computing sky radiation, expressed as a decimal. On clear days, α = 1.00.

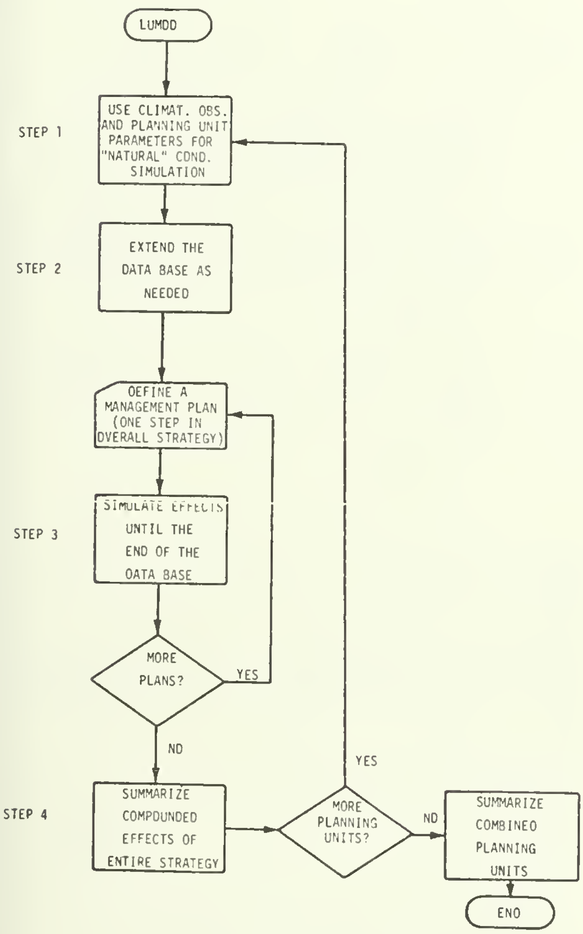


Figure 2. — Flow chart showing how core model is used to execute alternative management strategies

Evapotranspiration. — A "potential" evapotranspiration function was developed for the model based on the empirical Hamon equation (Hamon 1961), which requires latitude, converted to day length; and mean monthly temperature, converted to saturation vapor density. The coefficient, C, in Hamon's equation was modified in order to obtain an expression for potential evapotranspiration, E_s under "unlimited" solar input, assumed herein as potential radiation. The evapotranspiration computed by this expression is reduced in proportion to the radiation actually received each day according to the expression:

$$E_s = (C'D^2p_t)(\frac{SW}{P}) \qquad [2]$$

where

C' = the modified coefficient defined above,

D = possible sunshine in units of 12 hours,

p_t = saturated water vapor density (absolute humidity) at the daily mean temperature in grams per cubic meter,

SW = daily shortwave radiation in langleys, and

P = potential shortwave radiation for the day as computed by Frank and Lee (1966).

The adjusted evapotranspiration is then redefined according to its source, which can include: (1) evaporation from snow intercepted by the forest canopy; (2) evaporation from the snowpack surface; and (3) evapotranspiration during the growing season.

Input to the watershed system is derived from snowmelt and rainfall. Once evapotranspiration requirements have been satisfied, any remaining input is used to satisfy soil water recharge requirements. When field capacity is reached, the residual input becomes water available for streamflow (generated runoff).

With regard to evapotranspiration, it was assumed that water use by old-growth forest during the growing season proceeds at rates limited only by available energy until the soil water is depleted to 50 percent of the maximum "available" for transpiration (field capacity index). Thereafter, transpiration is decreased in proportion to the amount of soil water below one-half of the field capacity index. In open or cutover areas, it was reasoned that the absence of dense vegetation and a shallow rooting depth enables evapotranspiration to proceed at maximum rates only when the soil mantle is completely recharged. Thereafter, evapotranspiration is linearly decreased to zero at an assumed three-fourths of the field capacity index. These relationships are shown graphically in figure 3a. As forest vegetation reoccupies cutover areas, and consumptive use is increased, the relationship in figure 3a changes until ultimately, as the forest cover is reestablished, it approaches that of the old-growth forest curve. It is this phenomenon which is primarily responsible for diminishing water yield increases over time following timber harvest. The rate at which this transition takes place depends upon forest species, climate, stand conditions, and the objectives of management.

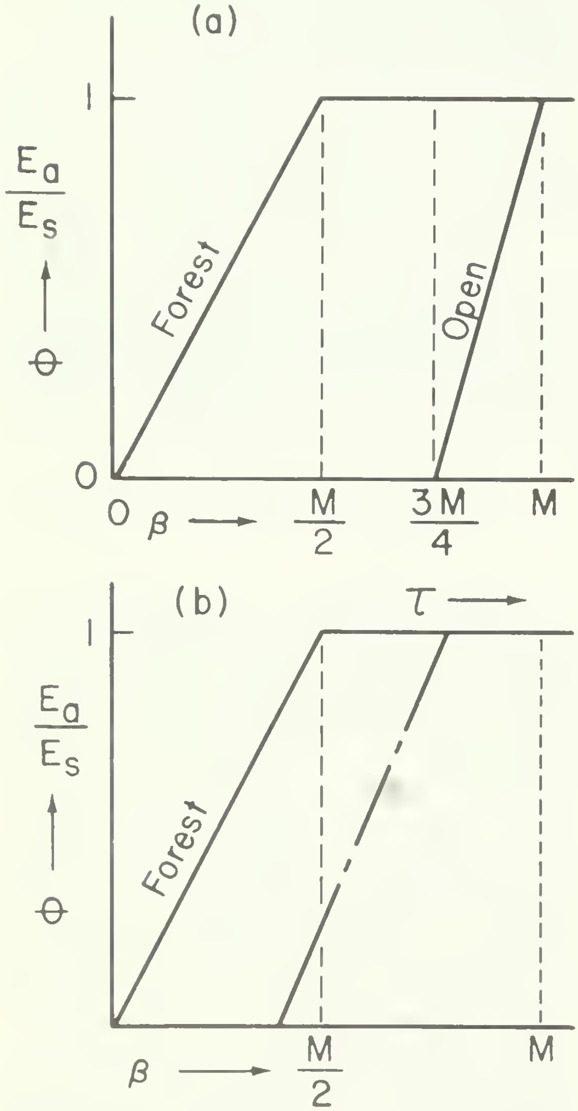


Figure 3. — Evapotranspiration as a function of available soil water for: (a) old-growth forest and open conditions, and (b) old-growth forest and some intermediate forest cover condition several years after timber harvesting.

A general expression for the relations shown in figure 3 can be written as follows:

$$\theta = \Delta\left[\beta - \left(\tau - \frac{1}{\Delta}\right)\right] = \Delta\left(\beta - \tau\right) + 1$$

$$\beta > \tau,\ \theta = 1$$

$$\tau - \frac{1}{\Delta} < \beta < \tau$$

$$\beta < \tau - \frac{1}{\Delta},\ \theta = 0 \qquad [3]$$

where

- θ = the ratio, $\frac{E_a}{E_s}$. E_a is the evapotranspiration rate adjusted for available soil water, and E_s is computed in this model by a modified version of the Hamon equation.
- β = the available soil water at any time during a given water year. $0 \leq \beta \leq M$ where M is the "field capacity index,"
- τ = the critical point at which available soil water begins to limit evapotranspiration. $M/2 \leq \tau \leq M$, and
- Δ = the slope of the relationship between $E_a/E_s = 0$ and 1.

It appears from the Fool Creek watershed study in central Colorado that hydrologic changes resulting from timber harvest in the subalpine zone persist for many years. The Fool Creek study showed that water yield increases did not decrease significantly more than 16 years after treatment (Hoover and Leaf 1967). These results and results from timber management research were used to develop the time-trend relationships discussed below. As seen below, the procedure used in formulating each time-trend relationship was to: (a) establish plateaus, and maximum and minimum values for each hydrologic variable; (b) establish critical times at which a transition begins to occur; and (c) assume a functional relationship which determines all intermediate values.

It should be emphasized that, due to a lack of understanding of long-term hydrologic phenomena, the time-trend equations are not exact in any intrinsic or mathematical way (Forrester 1961). They should be considered only as relationships which represent rational estimates of how the most significant processes vary over a long period of time. These time-trend relationships are logically plausible, but additional research is needed before more precice equations can be developed.

Soil Water. — The critical point at which available soil water begins to limit evapotranspiration (τ), was assumed to vary with time and forest tree species. These relationships were expressed as

$$\tau = Me^{-k(t - t_{c_1})} \qquad \tau = M, t \leq t_{c_1} \qquad \tau = M/2, t \geq t_r \qquad [4]$$

where

k = an index of the rate of decline of τ

t_{c_1} = the time at which available soil water begins to limit evapotranspiration in years, and

t_r = the time at which the hydrologic effect of timber harvesting becomes insignificant.

The parameters, k and t_{c_1}, vary according to tree species. The assumed relationship between Δ and τ is given by

$$\Delta = \frac{4\tau}{M^2} \qquad [5]$$

Substituting equations [4] and [5] into equation [3] yields

$$\theta = 4e^{-k(t - t_{c_1})}\left[\beta/M - e^{-k(t - t_{c_1})}\right] + 1 \qquad [6]$$

which is a general equation for θ as a function of forest cover type, field capacity index, and time.

Forest Cover Density. — Forest cover density plays an important role in the simulation model. It is the major descriptive parameter of the form, structure, and arrangement of forest stands, and therefore controls the energy balance, interception, and evapotranspiration. This parameter is also related to basal area which is pertinent to timber production, as discussed later. Forest cover density as used in the model is not defined as "canopy" or "crown" closure, but rather as a tree parameter which integrates the net effects of the overstory on the transmission of solar radiation to the forest floor. Forest cover density varies according to crown closure, the vertical foliage distribution, species, season, and stocking (Reifsnyder and Lull 1965). Empirical relationships between various timber stand variables and percent radiation beneath the forest canopy (transmissivity coefficient) have been derived for the three major subalpine tree species in the process of model calibration and from solar radiation transmission studies in central Colorado. The resulting equation from this work is given by

$$T = 0.19\, C_{dmx}^{-0.6} \qquad [7]$$

where

T = the transmissivity of the forest canopy expressed as a decimal fraction of the amount of solar radiation available above the forest canopy, and,

C_{dmx} = the natural old-growth forest cover density expressed as a decimal.

Combinations of C_{dmx} and T for the three major subalpine forest species are given in Leaf and Brink (1975).

As trees reoccupy cutover areas, forest cover density (C_d) increases with time until it reaches a maximum value. Research has shown that the rate at which forest cover density reaches this plateau depends on environmental conditions, stocking levels, and species. In subalpine coniferous forests in the Rocky Mountains, it can vary from 30 to more than 80 years (Alexander 1974). Accordingly, C_d was assumed to vary as a function of time according to the following equation:

$$C_d = \frac{C_{dmx}}{\Phi^2}\left(t - t_{c_2}\right)^2 \qquad t_{c_2} \leq t \leq \Phi \qquad [8]$$

where

C_d = intermediate forest cover density expressed as a decimal

Φ = the time in years from t_{c_2} at which maximum forest cover density (C_{dmx}) is reached, and

t_{c_2} = critical time at which regeneration is sufficient to reestablish the stand. When $t \leq t_{c_2}$, $c_d = 0$.

Reflectivity. — Studies of the energy balance and associated vapor loss indicate that the major variations with regard to latent heat flux are associated with reflectivity (Baumgartner 1967). Accordingly, a relationship between reflectivity and forest cover density was derived as follows:

$$R_f = R_{fo} \exp \left[\frac{-\omega C_{dmx}(t - t_{c_2})^2}{\Phi^2} \right] \qquad [9]$$

where

R_f = the reflectivity of the forest stand,
R_{fo} = the reflectivity of a forest opening (assumed herein as 0.5). When $t \leq t_{c_2}$, $R_f = 0.5$, and
ω = $1.609\ C_{dmx}^{-1}$.

Equation [9] is used to adjust equation [6] for net available energy.
Thus:

$$\theta' = \frac{E_a'}{E_s} = \theta(1 - R_f) \qquad [10]$$

where Ea′ is the actual evapotranspiration adjusted for both available soil-water and energy.

Interception. — In the interception portion of the model, it is assumed that:

1. The amount of snow intercepted varies according to forest cover density, C_d;
2. The intercepted snow rests on the canopy for only 1 day following the day of the snow event due to turbulent winds which remove snow from the crowns; and
3. The residual intercepted snow which is not vaporized after that period of time is added to the snowpack.

The second and third assumptions are based on field studies which indicate that snowfall is strongly influenced by wind interacting with the forest and local topography (Hoover and Leaf 1967, Hoover 1969).

Evaporation from the snow surface and from snow intercepted by the forest canopy is computed by the following rational relationships (Leaf and Brink 1975):

$$V_s = (1 - C_d)E_s \qquad [11]$$

$$V_c = \frac{1}{C_d} E_s \qquad C_d \geq \frac{C_{dmx}}{2} \qquad [12]$$

where
V_s = evaporation from the snow surface
V_c = intercepted snow evaporation,
C_d = intermediate forest cover density as = defined in equation [8]; and
E_s = potential evapotranspiration as defined in equation [2].

When $C_d \geq \frac{C_{dmx}}{2}$, and snow rests on the canopy, evaporation is computed by equation [12], whereas during conditions when the canopy is free of snow, evaporation takes place according to equation [11]

However, when $0 < C_d \leq \frac{C_{dmx}}{2}$, and snow rests on the canopy, both equations [11] and [12] are used as follows:

$$V_t = E_s \left[\frac{2}{C_{dmx}} + \left(1 - \frac{2C_d}{C_{dmx}}\right)\left(1 - C_d\right) \right] \qquad [13]$$

where
V_t = combined evaporation from snow surface and intercepted snow in cutover areas.

Equation [13] more realistically represents the evaporation from cutover areas which are not completely occupied by trees. Equation [13] applies only when $C_d > 0$. When $C_d = 0$, $V_t = V_s$. By substituting equation [8] into equation [13] the following relationship is obtained:

$$V_t = E_s \left\{ \frac{2}{C_{dmx}} + 1 - \left[\frac{2\left(t - t_{c_2}\right)^2}{\Phi^2} \right] \left[1 - \frac{C_{dmx}}{\Phi^2} \left(t - t_{c_2}\right)^2 \right] \right\} \qquad [14]$$

which expresses V_t as a function of C_{dmx} and time.

Snow Redistribution. — Redistribution of snow as a result of patch-cutting is a significant factor influencing runoff. Moreover, in the lodgepole pine type in Colorado, this phenomenon is not greatly diminished more than 30 years after timber harvest in spite of regrowth of trees and associated increase in forest cover density (Hoover and Leaf 1967, Hoover 1969). It is believed that changes in natural snow accumulation patterns produced by timber harvest will persist until the new crop of trees approaches the height of the remaining virgin forest. Moreover, optimum redistribution of snow results when old-growth subalpine forests are (a) harvested in small patches less than 8 tree-heights in diameter; (b) protected from wind; and (c) interspersed so that they are 5 to 8 tree-heights apart. More snow is deposited in the openings, and less snow accumulates in the uncut forest so that total snow on headwater basins is not significantly increased. Accordingly, the following relationships were developed for simulating snow redistribution effects with time and the three primary tree species:

$$\rho = \rho_{mx} \exp\left[-k_1(t - t_{c_3})\right] \qquad \rho = \rho_{mx}, t \leq t_{c_3} \qquad \rho = 1,\ t \geq t_{r_1} \qquad [15]$$

where

ρ = snow redistribution factor in the cutover area which varies according to the silvicultural system used.
ρ_{mx} = the redistribution factor immediately after timber harvesting.
k_1 = an index of the rate of decline of ρ,
t_{c_3} = the time at which forest regrowth begins to reduce snow redistribution in years, and
t_{r_1} = the time at which forest regrowth causes snow redistribution to become insignificant.

The parameters, k, tr_1, and tc_3 vary according to tree type. When $t \leq t_{c_3}$, no adjustments are made in the redistribution, since field studies in the Rocky Mountain Region indicate that a correction is not warranted for several years after harvest cutting.

It should be emphasized that redistribution theory is valid only when timber is harvested in small patches (5 to 8 tree-heights in diameter) which occupy less than 50 percent of a given planning unit. An optimum redistribution factor is approximately 1.30, which corresponds to 5 to 8 H patches which occupy 40 percent of the planning unit. In this situation, the snowpack is increased 30 percent in the openings and decreased 20 percent in the uncut forest.

When openings are larger, snow is scoured from the center, whereas smaller openings also do not trap snow efficiently.

Individual-tree Selection Cutting.— Selection cutting in the model corresponds to a reduction of the forest cover density (C_d). The degree that C_d is reduced depends on characteristics of the stand and the volume of timber removed. In old-growth stands, if C_d is reduced by 50 percent or less from C_{dmx}, it is assumed that forest canopy density does not increase subsequent to harvest cutting. However, if C_d is reduced more than 50 percent from C_{dmx}, equation [8] is used to simulate redevelopment of the canopy with time. Solving equation [8] for time yields:

$$t_\eta = \left[\frac{\Phi^2 C_d}{C_{dmx}}\right]^{1/2} + t_{c_2} \qquad [16]$$

If the degree to which thinning reduces Cdmx is given by η, then Cd is given by

$$C_d = C_{dmx}(1 - \eta)$$

Hence, equation [16] can be written as:

$$t_\eta = \Phi\left[(1 - \eta)\right]^{1/2} + t_{c_2} \qquad [17]$$

where
t_η = the time required to reach the reduced forest cover density as if the stand were initially patch-cut, and
η = the degree that C_d is reduced from C_{dmx} expressed as a decimal.

All of the time trend relationships are then initialized at t_η in order to simulate the hydrologic effects of selection cutting.

Applications

Field Studies. — Watershed studies in the Central Rocky Mountains show that timber harvesting significantly affects the hydrologic system. For example, on the 714-acre Fool Creek watershed where 39 percent of the area was clearcut in strips 1 to 6 tree-heights wide (fig. 4), snow accumulation, melt, and subsequent water yield were all affected. Hoover and Leaf (1967) report that total snow storage on Fool Creek did not increase after harvest cutting. Strip cutting caused more snow to accumulate in the openings, however, and less in the uncut forest. When regressed against a 1,984-acre control watershed, it was determined that the average annual runoff increased more than 3 inches after treatment (fig. 5). Seasonal peak flows were not increased, nor were summer recession flows diminished (Leaf and Brink 1972). Timber harvesting caused higher snowmelt rates in early spring and more efficient water yield.

Figure 4. — Fool Creek experimental watershed, Fraser Experimental Forest. Control watershed is to the right of Fool Creek.

Model Studies of Snowmelt. — Dynamic hydrologic models are useful tools for quantifying the effects of watershed changes on runoff. We have used this procedure to study the effects of hypothetical watershed management practices on undisturbed watersheds in the Rocky Mountain Region using our best information from field studies and the model described above.

Short-Term Hydrologic Impacts of Timber Harvesting

In simulating a hypothetical timber harvest on the 667-acre Deadhorse Creek watershed in central Colorado, the snowmelt portion of the model has produced results similar to those observed from the Fool Creek experiment. Elevations on Deadhorse Creek vary from 9,450 feet msl to 11,600 feet msl. Soils are derived from gneiss and schist rocks; the forest cover is old-growth lodgepole pine and spruce-fir.

Leaf and Brink (1972) assumed that 40 percent of the watershed area was uniformly patch-cut in openings 5 to 8 tree-heights in diameter. Because field studies have shown that total snow storage is not changed following harvesting, the snowpack was increased 30 percent in the openings and decreased 20 percent in the uncut forest. In addition to redistributing the snowpack to represent the harvesting system, the forest canopy density parameter (C_{dmx}) was reduced to zero on 40 percent of the area in each of 10 hydrologic subunits.

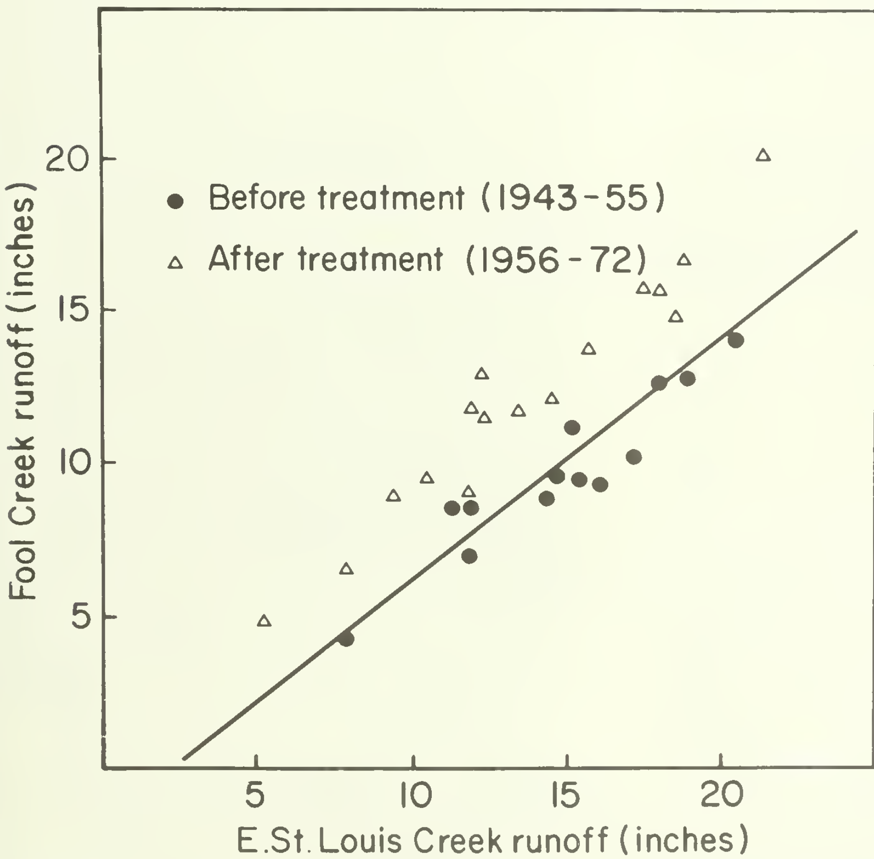
Results obtained through manipulating the input and forest cover parameters in the calibrated model indicated that patch-cutting small openings in mature lodgepole pine and spruce-fir forest results in increased snowmelt early in the melt season with diminished snowmelt later. Although timber cutting affected the timing of snowmelt, it apparently did not significantly change the duration of the snowmelt season. Under comparable conditions, snowmelt began a few days earlier in small openings, but in both the natural forest and cutover areas, the last snow melted out at about the same time. Because melt rates in openings were higher early in the snowmelt season, peak streamflow would not increase appreciably, if at all, under the assumed timber harvesting alternative. Figure 6a summarizes the predicted change in snowmelt input resulting from this practice for the 1947-71 period of record.

In addition to redistributing the snowpack and accelerating snowmelt runoff, the assumed timber harvesting practice also affected evapotranspiration in two respects. First, during the snow accumulation and melt seasons, evaporation from the snowpack in the small openings was higher, resulting in greater moisture losses than from snow in uncut forest. Secondly, evapotranspiration and interception losses were reduced in proportion to the amount of forest cover removed. This reduced evapotranspiration resulted in lower soil water deficits on the basin. The net effect was an overall reduction in evapotranspiration and resultant increased water yields. Simulated data for 1947-71 water years are shown in table 1. (Note that with the exception of snowpack water equivalent, all hydrologic components are plotted as 6-day means in fig. 6.)

The simulated average runoff increase for the 1947-71 record period was 2.2 inches, which resulted from a 2.2-inch decrease in evapotranspiration losses, with no change in storage during the average water year. Average soil water requirements on September 30 were decreased by 1.1 inches. As discussed above, snowmelt timing and resultant streamflow were also changed. From figure 6b, it is seen that generated runoff was increased during April, May, and the first part of June and diminished somewhat thereafter. Because the generated flows in figure 6c are routed through natural storage in the watershed to produce the hydrograph, it is reasonable to expect that the recession limb of the seasonal hydrograph would not be significantly changed due to treatment. However, on the rising limb, stream discharges would be higher, as observed from watershed studies in the area.

Table 1.--Simulated hydrologic changes resulting from timber harvesting on Deadhorse Creek, Fraser Experimental Forest (average of 1947-71 water years)

Hydrologic component	Water balance		
	Natural	Treated	Change
	- - *Inches* - -		
Precipitation	30.5	30.5	0
Evapotranspiration	16.8	14.6	-2.2
Soil water recharge requirement			
beginning (10/1)	3.5	2.4	-1.1
end (9/30)	3.5	2.4	-1.1
Water yield	13.7	15.9	+2.2



April - Sept. Runoff Increase Since Harvest	
Year	Inches
1956	3.3
1957	5.2
1958	3.7
1959	4.6
1960	5.4
1961	3.4
1962	3.9
1963	2.9
1964	3.5
1965	4.0
1966	2.6
1967	3.1
1968	1.9
1969	2.5
1970	2.1
1971	3.6
1972	3.9
Mean	3.5 $\pm$0.8*

*95 Percent level of confidence

Figure 5. — Pretreatment and posttreatment correlations of seasonal runoff between Fool Creek and adjacent control watershed, Fraser Experimental Forest.

Long-Term Hydrologic Impacts of Timber Harvesting

The model described above has also been used to simulate the long-term effects of forest and watershed management on a 2,461-acre tributary of the South Tongue River in northcentral Wyoming. Pertinent hydrologic characteristics of a typical forested watershed are as follows:

Average maximum snowpack water equivalent	15.5 inches
Average annual precipitation	29.6 inches
Average annual evapotranspiration	15.8 inches
Average annual runoff	13.8 inches

Elevations vary from 8,000 feet msl to 8,900 feet msl. Soils are derived from granitic rocks; virtually all of the forest cover is lodgepole pine. To illustrate how the model was used, results from the analysis of one planning unit will be summarized.

In addition to improving water yield, the management strategy selected for this example essentially has followed recommendations published by Alexander (1972), which

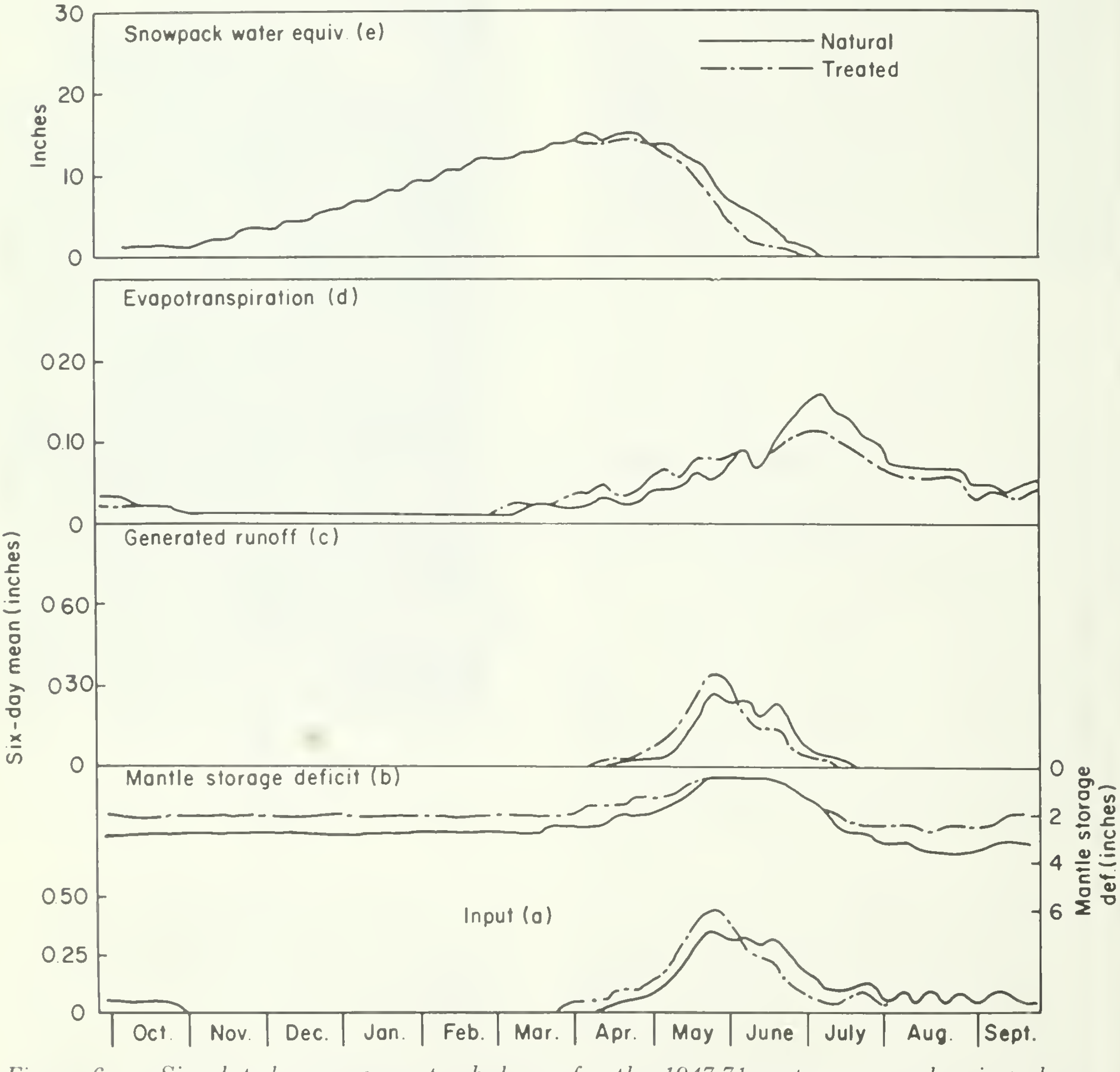


Figure 6. — Simulated average water balance for the 1947-71 water years, showing changes resulting from patch-cutting in mature subalpine forest.

are keyed to stand descriptions, insect and disease problems, and windfall risk situations.

Under this strategy, all of the old-growth timber would be harvested in a series of patch-cuts spread over a planning interval of 120 years. At intervals of 30 years, approximately one-third of the area would be harvested in small openings — five to eight times tree height — distributed over the watershed (table 2). Forest openings would be constructed in a balanced and unified pattern which complements the natural landscape.

Table 2.--Watershed management strategy, South Tongue River planning unit, Bighorn National Forest, Wyoming

Management strategy		Response unit[1]		
		1	2	3
Treatment I				
Patch[2]	1st yr.	X		
Treatment II				
Patch[2]	31st yr.		X	
Thin[3]		X		
Treatment III				
Patch[2]	61st yr.			X
Thin[3]		X	X	
Treatment IV				
Thin[3]	91st yr.	X	X	X

[1]Each unit includes 1/3 of the total area.
[2]33 percent of area occupied by openings which are 5 to 8 tree-heights in diameter.
[3]Thin to $C_{dmx/4}$

As each one-third of the old-growth forest cover on the planning unit is patch-cut, the forest cover density on the previously cutover areas would be reduced to one-fourth of the natural old-growth forest cover density (C_{dmx}). At the end of the planning interval, all of the openings will have regenerated and the watershed would contain groups of trees in several age classes from reproduction to those ready for harvesting on the originally cutover areas. The management strategy would maintain a forest cover throughout the planning interval, and would insure sufficient seed for regeneration from trees cut on the area, or standing around the perimeters of the forest openings.

Projected average annual water yield increases in 10-year increments under this management strategy for the 120-year planning interval are tabulated in table 3. The increases above the heavy diagonal line in table 3 at any given time represent the overall response resulting from preceding management decisions. The data below the line reflect the singular effect of the initial patch-cut on one-third of the planning unit, assuming that it were the final decision in the strategy.

Table 3.--Projected changes in annual water yield resulting from timber harvesting, South Tongue River planning unit, Bighorn National Forest, Wyoming

Interval (years)	Water yield increase, by treatment			
	I	II	III	IV
	- - - - - *Inches* - - - - -			
0-10	1.33			
11-20	1.59			
21-30	0.95			
31-40	0.74	2.08		
41-50	0.61	2.07		
51-60	0.51	1.72		
61-70	0.33		3.37	
71-80	0.08		2.86	
81-90	0.04		2.21	
91-100	-0.03			2.90
101-110				2.29
111-120				1.76

Water yields are improved throughout the planning interval, with the highest increase occurring after Treatment III. Projected runoff increases in relation to the pretreatment base period during each treatment interval are as follows:

Treatment	Runoff Increase Percent
I	9.2
II	14.2
III	20.2
IV	16.8

As seen from table 3, the effect of the initial patch-cut (Treatment I) apparently persists for at least 50, and perhaps 60 or more years. Thereafter, the effect on water yield would for all practical purposes be negligible. (On Fool Creek, in central Colorado, runoff increases have not diminished significantly more than 16 years after strip cutting.)

The projected effects of timber harvesting on the distribution of water available for streamflow are summarized in table 4. These values represent increments of generated runoff and not routed streamflow. Hence, the effects of watershed storage must be considered in interpreting the data. As seen in table 4, inputs from snowmelt are significantly increased during April and May, and diminished in June. Minor inputs to streamflow apparently also occur in July, while none occur in the natural state due to the less favorable hydrologic condition of the watershed.

Table 4.--Projected changes in distribution of water available for streamflow, South Tongue River, Bighorn National Forest, Wyoming

Month	Natural runoff	Average change in runoff, by treatment			
		I	II	III	IV
	- - - - - - - - *Inches* - - - - - - - -				
April	0.1	+0.9	+1.2	+1.2	+0.7
May	7.5	+2.0	+2.2	+2.1	+1.3
June	6.2	-2.8	-2.3	-2.7	-1.3
July	0	+0.03	+0.05		

The hydrologic analysis in this example indicated that the magnitude of peak flows would be changed little if at all under the proposed management strategy. However, seasonal peaks would occur approximately one week earlier:

Treatment	Change in peak 7-day generated runoff	Change in timing
	Inches	*Days*
I	-0.3	- 9
II	-0.5	-10
III	-0.3	- 7
IV	+0.3	- 5

To sum up, the projected overall hydrologic impact of the proposed management strategy would be to increase streamflow in April and May each year throughout the 120-year planning interval. This accelerated input would enlarge early spring flows and cause the hydrograph to peak approximately one week earlier than under natural conditions. Hydrograph peaks would apparently not be increased, however, and runoff on the recession side of the hydrograph during the summer months would be slightly diminished.

Discussion

The hydrologic impacts of the watershed management practices discussed above are but two examples of numerous alternatives which have been simulated with the model described in this paper. The model has been tested and calibrated on several representative drainage basins in Colorado and Wyoming. The areas include:

Wyoming: South Tongue River, Bighorn National Forest; East Fork of the Encampment River, Medicine Bow National Forest.

Colorado: Fraser River, Arapahoe National Forest; Wolf Creek, San Juan National Forest.

Timber Models

In addition to improving the water yields in lodgepole pine and spruce-fir forests, it should be emphasized that the strategies selected for water production are compatible with the conversion of old-growth to stands managed from the regeneration period to final harvest for timber production. Yield tables that report probable yields of wood that result from specified combinations of site quality, frequency and intensity of thinning and utilization standards provide goals toward which conversion can be directed. Procedures for deriving yield tables for managed stands and descriptions of the main program and subroutines have been presented for lodgepole pine by Myers et al. (1971) (Program LPMIST) and for spruce-fir by Alexander et al. (1975) (Program SPRYLD). These were adapted from field and computer procedures for managed stand yield tables originally developed by Myers (1971).

These computer programs have the capacity of producing a series of yield tables which show how projected outcomes will vary in response to changes in cultural treatments and/or variations in original stand and site conditions. Large numbers of tables each based on a specific set of alternatives can be computed and printed at the cost of a few cents each. This provides the manager with the opportunity to examine the probable results of his operations, make necessary changes in management goals, and study the effect of these changes before money is spent on them (Myers 1971).

Linkage Between Hydrologic and Timber Models

The hydrologic model and the timber models (LPMIST and SPRYLD) are linked by means of the forest cover density variable (C_d) as defined previously. Forest cover density is assumed to vary as a function of time according to the expression (eq. [8]):

$$C_d = \frac{C_{dmx}}{\Phi^2}\left(t - t_{c_2}\right)^2 \qquad t_{c_2} \le t \le \Phi$$

where

C_d = intermediate forest cover density after cutting is sufficient to reestablish the stand. When $t \le t_{c_2}$, $C_d = 0.$,

Φ = the time in years from t_{c_2} at which maximum forest cover density is reached. This parameter will vary according to tree species, local environment, and stand condition. and,

C_{dmx} = maximum (natural old growth) forest cover density expressed as a decimal.

In the hydrologic model, logging corresponds to a reduction of the forest cover density (C_d). Thus, the degree that C_d is reduced depends on the relative changes in basal area. As stated previously, in old-growth stands, if C_d is reduced by 50 percent or less from C_{dmx}, it is assumed that forest cover density does not increase subsequent to cutting. However, if C_d is reduced more than 50 percent from C_{dmx}, but not clearcut, equation [8] is used to simulate redevelopment of the canopy with time. In the event that C_d is reduced to zero (clearcut), Φ is replaced by a new parameter, Φ' in equation [8], which then computes redevelopment of the canopy with time under "managed stand" conditions.

No relationship has been established between C_d and basal area, average diameter, and site index. However, calibration studies indicate it is reasonable to assume that a given percentage reduction in cover density corresponds reasonably well to a similar reduction in basal area. Comparisons between basal area levels after patch-cutting and forest cover density are summarized for a specified set of stand conditions in table 5.

Table 5.--Comparisons of basal area[1] after initial clearcutting with forest cover density

Years since initial cut	Basal area (ft^2/ac)		Forest cover density (C_d)	
	Before	After	Before	After
	Lodgepole pine (ϕ' = 30 years)			
0	130	0	0.30	0
30	110	61	.30	0.16
60	129	92	.30	.21
90	146	100	.30	.21
120	146	0	.30	0
	Spruce-fir (ϕ' = 60 years)			
0	325	0	.55	0
50	94	63	.38	.24
80	153	99	.55	.35
110	176	100	.55	.31
140	160	0	.55	0

[1]Basal areas for lodgepole pine computed from Program LPMIST for site index 60, and initial and subsequent growing stock levels of 100.

Basal areas for spruce-fir computed from Program SPRYLD for site index 80, and initial and subsequent growing stock levels of 100.

Applications

Lodgepole Pine. — The management strategy (table 6) is similar to that in table 2 for the Bighorn National Forest, but for another area in central Colorado.

Similar to the watershed management strategy in the previous example, water available for streamflow on each response unit is substantially increased by the patch-cutting of lodgepole pine (table 7, fig. 7). In the cleared areas, the increase in water available for streamflow is maintained at a higher level by frequent intermediate thinnings throughout the rotation than if the forest was allowed to return to preharvest conditions naturally. Figure 8 shows projected water yield changes from initial patch-cutting and subsequent thinning on one response unit. In the example used here, the forest manager also wishes to determine the growing stock levels that will maximize volume production in board feet within the limits imposed by the cutting strategy for water production. Since water yield is unaffected by site quality, an average site index (60) has been chosen. Furthermore, simulation analyses indicate that water yields are little affected by any combination of initial and subsequent growing stock levels in managed stands that range from ≤ 80 to ≥ 120 ft²/ac. Length of rotation is 120 years with a 30-year cutting cycle. Alternatives that call for more than one precommercial thinning are unacceptable. Minimum commercial volumes per acre are 400 cubic feet and 1500 board feet. The manager expects that his procedures for regenerating each patch-cut will result in a new stand that contains 1,000 trees per acre by age 30, with an average stand diameter of 4.5 inches. Furthermore, dwarf mistletoe infection will not occur during the life of the stand.

Table 6.--Watershed management strategy for lodgepole pine, Deadhorse Creek planning unit, Fraser Experimental Forest, Colorado[1]

Management strategy		Response unit		
		1	2	3
Treatment I				
Patch[2]	1st yr.	X		
Treatment II				
Patch[2]	31st yr.		X	
Thin[3]		X		
Treatment III				
Patch[2]	61st yr.			X
Thin[3]		X	X	
Treatment IV				
Thin[3]	91st yr.	X	X	X
Treatment V				
Harvest[2]	121st yr.	X		
Thin[3]			X	X

[1]Aspect: SSE
Elevation: 10,500 ft. msl
Slope: 30 percent
[2]33 percent of the area cut in openings 5 to 8 times tree height.
[3]Thin to growing stock levels specified under section on Timber Management Alternatives.

A few of the yield tables produced by LPMIST are reproduced in Appendix A. For the situation described above, yields and number of precommercial thinnings are of greatest interest. These items are summarized in tables 8 and 9 for the 9 yield tables produced. Only the combination of low initial and low subsequent growing stock levels meets the requirement of only one precommercial thinning.

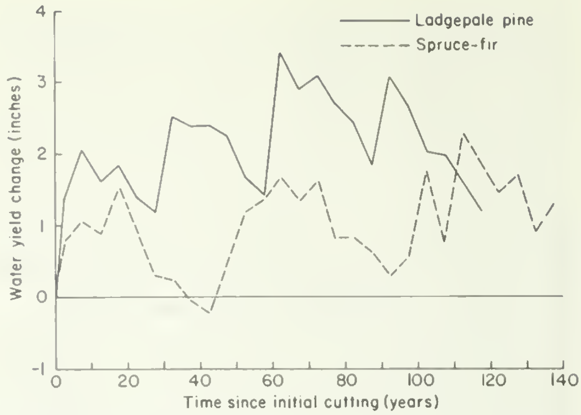


Figure 7. — Projected water yield changes from management strategies outlined in tables 7 and 11.

Table 7.--Projected changes in annual water yield resulting from tiber harvesting in lodgepole pine, Deadhorse Creek planning unit, Fraser Experimental Forest, Colorado

Interval (years)	Water yield increase, by treatment			
	I	II	III	IV
	- - - - - *Inches* - - - - -			
0-10	1.72			
11-20	1.73			
21-30	1.29			
31-40		2.44		
41-50		2.30		
51-60		1.54		
61-70			3.12	
71-80			2.86	
81-90			2.11	
91-100				2.84
101-110				1.98
111-120				1.38

Additional comparisons can be made to include such factors as probable thinning costs, cubic yields from thinnings not commercial for board feet, and the average size of tree produced. As expected, the current crop produces more board feet in 120 years at high subsequent levels of growing stock, but two precommercial thinnings would be required.

Spruce-fir. — Water available for streamflow on each response unit is also substantially increased by patch-cutting spruce-fir in small openings 5 to 8 times tree height according to the management strategy outlined in table 10 (table 11, fig. 7). However, on the cleared areas, water available for streamflow decreases after the initial cutting at about the same rate whether or not intermediate thinnings are made throughout the rotation. This is illustrated by figure 9, which shows projected water yield changes from initial patch-cutting and subsequent thinning on one response unit compared with no thinning after initial harvest. There are, however, other advantages to thinning spruce-fir. Growth is concentrated on fewer stems, and total yields of usable products are increased. In the example here, the forest manager also wishes to determine the growing stock levels that will maximize volume production in board feet within the limits imposed by the watershed management strategy. Water yields are little affected in spruce-fir forests by either site quality or the growing stock levels that are likely to be timber management goals. An average site index of 80 was chosen. Length of rotation is 120 years (breast height age) with a 30-year cutting cycle.[2] Alternatives that call for more than one precommercial thinning are unacceptable. Minimum commercial volumes per acre are 400 cubic feet and 2,000 board feet. The manager expects that his procedure

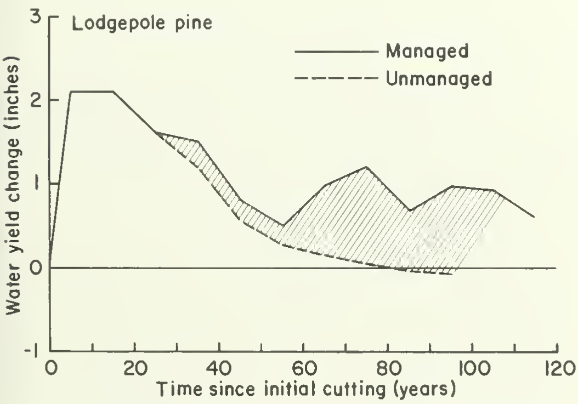


Figure 8. — Projected water yield changes for managed (all options) and unmanaged lodgepole pine following initial patch-cutting on one response unit. Cutting cycle 30 years; site index 60 feet; all initial and subsequent stocking levels likely to be timber management goals.

[2]Age in SPRYLD is age at breast height. The 50-year interval between patch-cutting and the first thinning in table 11 is to allow a minimum of 20 years for spruce and fir trees to regenerate and grow to 4.5 feet in height. A 120-year rotation is therefore at least 140 years in the total age of the stand.

for regenerating each patch-cut will result in a new stand that contains 850 trees per acre with an average stand diameter of 4.5 inches by b.h. age 30 years.

Table 8.--Number of precommercial thinnings based on minimum board feet volumes, if each of the 9 combinations of initial and subsequent growing stock levels is executed as specified by the data decks for spruce-fir (SPRYLD) and lodgepole pine (LPMIST)

Initial thinning basal area level (ft^2/ac)	Subsequent basal area level (ft^2/ac)		
	80	100	120
Spruce-fir (Program SPRYLD)			
80	1	2	2
100	1	1	2
120	1	1	2
Lodgepole pine (Program LPMIST)			
80	1	2	2
100	2	2	2
120	2	2	2

Table 9.--Yields in thousand board feet, including commercial thinning of 9 combinations of initial and subsequent growing stock levels, spruce-fir and lodgepole pine

Initial thinning basal area level (ft^2/ac)	Subsequent basal area level (ft^2/ac)		
	80	100	120
Spruce-fir (Program SPRYLD)			
80	32.7	36.2	41.3
100	33.3	37.4	40.6
120	33.5	37.6	40.4
Lodgepole pine (Program LPMIST)			
80	24.2	25.0	27.5
100	21.0	24.8	27.3
120	20.8	24.0	27.0

A few of the yield tables produced by SPRYLD are reproduced in Appendix B. For the situation described above, yields and number of precommercial thinnings are summarized in tables 8 and 9 for the 9 tables produced. The combination of high initial and intermediate subsequent growing stock levels produces the greatest volume with one precommercial thinning.

Comparisons can also be made to include thinning costs, cubic yields from thinnings not commercial for board feet and the average size of tree produced. The current crop produces more board feet with the combination of low initial and high subsequent growing stock levels, but two precommercial thinnings will be required.

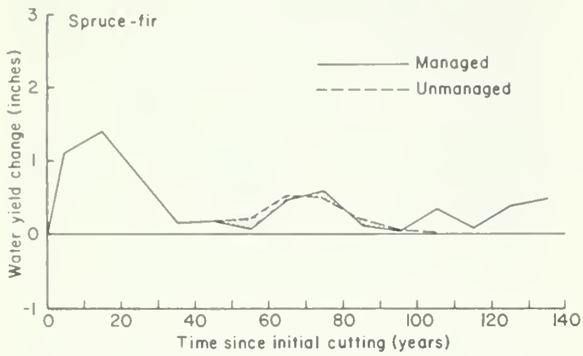


Figure 9. Projected water yield changes for managed (all options) and unmanaged spruce-fir following initial patch-cutting on one response unit. Cutting cycle 30 years (50 years initial cut); site index 80 feet; all initial and subsequent stocking levels likely to be timber management goals.

Table 10.--Watershed management strategy for spruce-fir, Deadhorse Creek planning unit, Fraser Experimental Forest, Colorado[1]

Management strategy		Response unit 1	2	3
Treatment I				
Patch[2]	1st yr.	X		
Treatment II				
Patch[2]	51st yr.		X	
Thin[3]		X		
Treatment III				
Thin[3]	81st yr.	X		
Treatment IV				
Patch[2]	101st yr.			X
Thin[3]			X	
Treatment V				
Thin[3]	111th yr.	X		
Treatment VI				
Thin[3]	131st yr.		X	
Treatment VII				
Harvest[2]	141st yr.	X		

[1]Aspect: NE
Elevation: 10,200 ft. msl
Slope: 35 percent

[2]33 percent of the area cut in openings 5 to 8 times tree height.

[3]Thin to growing stock levels specified under section on Timber Management Alternatives. Yield tables for spruce-fir are based on breast height age. On a 30-year cutting cycle a minimum of 20 additional years will be required foı trees to reach breast height.

Table 11.--Projected changes in water yield resulting from timber harvesting in spruce-fir, Deadhorse Creek planning unit, Fraser Experimental Forest, Colorado

Interval (years)	Water yield increase, by treatment I	II	III	IV
	- - - - - *Inches* - - - - -			
0-10	0.91			
11-20	1.20			
21-30	.64			
31-40	.10			
41-50	.10			
51-60		1.26		
61-70		1.49		
71-80		1.21		
81-90			0.71	
91-100			.42	
101-110			1.22	
111-120				2.06
121-130				1.54
131-140				1.09

Summary

The following paragraphs highlight the practical aspects of this work, and summarize important principles which should be considered in land use planning.

• Highest water yields result when old-growth subalpine forests are harvested in small patches. When forest openings are: (1) less than 8 tree-heights in diameter; (2) protected from wind, and (3) interspersed so that they are 5 to 8 tree-heights apart, an optimum pattern of snow accumulation results. More snow is deposited in the openings, and less snow accumulates in the uncut forest so that total snow on headwater basins is not significantly increased.

• Snowmelt in the small openings on all aspects is more rapid than in the uncut forest. This accelerated melt causes streamflow to be higher on the rising limb of the hydrograph than before harvest cutting. When there is considerable natural regulation in the form of deep porous soils, recession flows should not be changed appreciably and annual flood peaks are not significantly increased provided that the forest cover on no more than 50 percent of the watershed is removed in a system of small openings.

• Simulation analyses indicate that under a patch-cut alternative, water yield increases on south slopes are at least as large as corresponding increases from north aspects. Hence, there is no reason to favor areas with the highest natural water yield if the objective is to maximize water yield from old-growth subalpine forests.

• Due to the considerable length of time that it takes for subalpine coniferous forests to regenerate, increased water yields from patch-cutting can go undiminished for 30 years and longer. Even after this period of time, it is conceivable that 30 additional years will be required before runoff increases from the initial timber harvest are completely erased.

• It should be emphasized that the *pattern* in which trees are harvested determines whether or not runoff will be increased. For example, when the forest cover is removed in large clearcut blocks or by selective cutting of individual trees, increased water yields will be far less than that attained if the same volume of timber is harvested in a system of small dispersed forest openings. Under some conditions, streamflow may actually be decreased when timber is selectively harvested or clearcut in large blocks.

• In much of the Rocky Mountain Region, timber harvesting which produces the most additional water is ecologically sound. If done properly, it does not reduce water quality; it is a silviculturally acceptable procedure and compatible with the guidelines recently developed from research in old-growth subalpine forests (Alexander 1972, 1973, 1974). The strategies selected for optimum water production are compatible with the conversion of old-growth to stands managed from the regeneration period to final harvest for timber production.

• Procedures are available for projecting long-term yields of both wood and water resulting from a broad array of management alternatives. This capability provides the manager with the opportunity to examine the probable results of his operations within the context of multi-resource management.

Conclusion

One of the major shortcomings of the models described in this paper is the lack of sufficient data for validation, particularly with respect to man's long-term impacts on the timber and water resources. Nevertheless, the models produce expected results based on experience and the state-of-the-art. It is believed that the output from the examples above contain the type of information which hydrologists, silviculturalists, and land use planners need to know in order to make difficult management decisions. The ability of the models described in this paper and other similar models to integrate complex forest and water systems make them unique and powerful tools for evaluating a broad array of land management alternatives.

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Appendix A
Typical Yield Tables Produced by LPMIST

YIELDS PER ACRE OF EVEN-AGED STANDS OF LODGEPOLE PINE
SITE INDEX 60
THINNING INTENSITY- INITIAL- 80. SUBSEQUENT- 80.

	ENTIRE STAND BEFORE AND AFTER THINNING							PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	1000	110	4.5	24	1270	170	0					
30	325	50	5.3	26	630	170	0	675	60	640	0	0
40	322	72	6.4	32	1160	720	0					
50	321	93	7.3	36	1670	1340	0					
60	321	115	8.1	42	2420	2120	8700					
60	185	76	8.7	43	1650	1490	6100	136	39	770	630	2600
70	182	91	9.6	48	2220	2050	8600					
80	179	106	10.4	52	2790	2620	11100					
90	179	122	11.2	56	3480	3280	14200					
90	104	80	11.9	57	2280	2160	9600	75	42	1200	1120	4600
100	104	93	12.8	60	2740	2600	11800					
110	104	106	13.7	63	3240	3090	14300					
120	104	119	14.5	65	3730	3560	16800					

DWARF MISTLETOE INFECTION DID NOT OCCUR DURING THE ROTATION OF 120. YEARS.

MERCH. CU. FT. - TREES 6.0 INCHES D.B.H. AND LARGER TO 4-INCH TOP.

BD. FT. - TREES 6.5 INCHES D.B.H. AND LARGER TO 6-INCH TOP.

YIELDS PER ACRE OF EVEN-AGED STANDS OF LODGEPOLE PINE
SITE INDEX 60
THINNING INTENSITY- INITIAL- 120. SUBSEQUENT- 120.

	ENTIRE STAND BEFORE AND AFTER THINNING							PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	1000	110	4.5	24	1270	180	0					
30	505	72	5.1	25	880	180	0	495	38	390	0	0
40	502	99	6.0	32	1540	760	0					
50	500	122	6.7	35	2140	1540	0					
60	498	145	7.3	41	2990	2410	0					
60	322	107	7.8	42	2250	1920	0	176	38	740	490	0
70	322	127	8.5	47	3010	2700	11100					
80	322	145	9.1	52	3770	3470	14300					
90	321	165	9.7	55	4580	4240	17900					
90	207	120	10.3	56	3370	3170	13300	114	45	1210	1070	4600
100	207	137	11.0	59	4070	3840	16500					
110	207	152	11.6	62	4670	4410	19400					
120	207	168	12.2	64	5300	5020	22400					

DWARF MISTLETOE INFECTION DID NOT OCCUR DURING THE ROTATION OF 120. YEARS.

MERCH. CU. FT. - TREES 6.0 INCHES D.B.H. AND LARGER TO 4-INCH TOP.

BD. FT. - TREES 6.5 INCHES D.B.H. AND LARGER TO 6-INCH TOP.

Appendix B
Typical Yield Tables Produced by SPRYLD

YIELDS PER ACRE OF MANAGED, EVEN-AGED STANDS OF ENGELMANN SPRUCE AND SUBALPINE FIR

SITE INDEX 80, 30-YEAR CUTTING CYCLE

THINNING LEVELS= INITIAL - 80., SUBSEQUENT - 80.

ENTIRE STAND BEFORE AND AFTER THINNING								PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANTABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANTABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	850	94	4.5	28	1010	340	0					
30	314	52	5.5	29	680	340	0	536	42	330	0	0
40	311	78	6.8	38	1260	900	0					
50	305	106	8.0	45	2030	1650	4200					
60	295	133	9.1	53	2920	2530	8300					
60	149	80	9.9	53	1810	1610	5700	146	53	1110	920	2600
70	145	99	11.2	59	2510	2310	9200					
80	145	122	12.4	65	3370	3150	13600					
90	145	146	13.6	70	4350	4120	18700					
90	55	80	16.3	71	2440	2340	11100	90	66	1910	1780	7600
100	55	95	17.8	75	3000	2910	14500					
110	55	112	19.3	79	3610	3520	18300					
120	55	130	20.8	82	4290	4200	22500					
						TOTAL YIELDS				7640	6900	32700

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 400. CUBIC FEET AND 2000. BOARD FEET

MERCH. CU. FT. - TREES 5.0 INCHES D.B.H. AND LARGER TO 4-INCH TOP.

BD. FT. - TREES 8.0 INCHES D.B.H. AND LARGER TO 6-INCH TOP.

YIELDS PER ACRE OF MANAGED, EVEN-AGED STANDS OF ENGELMANN SPRUCE AND SUBALPINE FIR

SITE INDEX 80, 30-YEAR CUTTING CYCLE

THINNING LEVELS= INITIAL - 120., SUBSEQUENT - 120.

ENTIRE STAND BEFORE AND AFTER THINNING								PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANTABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANTABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	850	94	4.5	28	1010	340	0					
30	505	72	5.1	29	870	340	0	345	22	140	0	0
40	498	108	6.3	37	1620	1050	0					
50	485	141	7.3	45	2540	1940	0					
60	466	175	8.3	52	3660	3040	8700					
60	259	117	9.1	52	2570	2230	7300	207	58	1090	810	1400
70	249	141	10.2	59	3480	3130	11800					
80	249	173	11.3	64	4680	4300	17800					
90	249	205	12.3	69	5960	5570	24400					
90	103	120	14.6	70	3600	3430	15900	146	85	2360	2140	8500
100	103	142	15.9	75	4540	4360	20900					
110	103	166	17.2	78	5410	5220	26300					
120	103	190	18.4	82	6310	6120	31900					
						TOTAL YIELDS				9900	9070	40400

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 400. CUBIC FEET AND 2000. BOARD FEET

MERCH. CU. FT. - TREES 5.0 INCHES D.B.H. AND LARGER TO 4-INCH TOP.

BD. FT. - TREES 8.0 INCHES D.B.H. AND LARGER TO 6-INCH TOP.

Leaf, Charles F., and Robert R. Alexander.
1975. Simulating timber yields and hydrologic impacts resulting from timber harvest on subalpine watersheds. USDA For. Serv. Res. Pap. RM-133, 20 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

A dynamic simulation model determines the hydrologic changes resulting from timber harvesting, and correlary models simulate timber yields. Emphasis is placed on the "planning unit" which is defined by environmental characteristics, including combinations of slope, aspect, elevation, and forest cover. The models are intended for use on subalpine watersheds where the primary source of streamflow is melting snow. The hydrologic model simulates winter snow accumulation, short- and longwave radiation balance, snowpack condition, snowmelt, and subsequent runoff in time and space. The timber models simulate projected timber yields in response to changes in cultural treatments and/or variations in original stand and site conditions.

Keywords: Computer models, forest management, simulation analysis, hydrology, watershed management.

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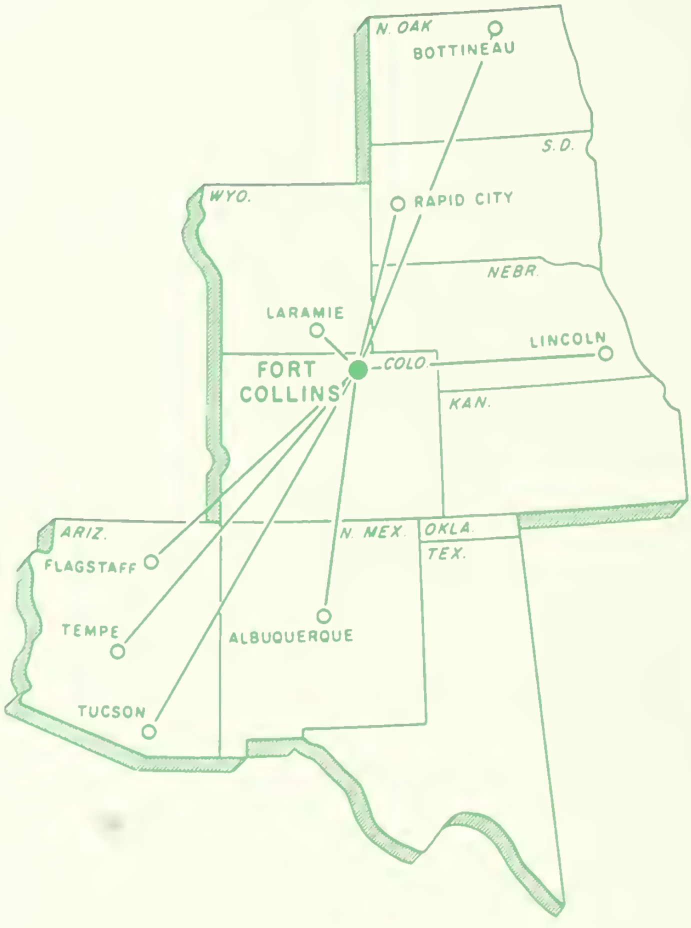
N. DAK
BOTTINEAU
S. D.
RAPID CITY
WYO.
NEBR.
LARAMIE
LINCOLN
FORT COLLINS
COLO.
KAN.
ARIZ.
N. MEX.
OKLA.
TEX.
FLAGSTAFF
TEMPE
ALBUQUERQUE
TUCSON

YIELD TABLES FOR MANAGED EVEN-AGED STANDS OF SPRUCE-FIR IN THE CENTRAL ROCKY MOUNTAINS

by Robert R. Alexander,
Wayne D. Shepperd and
Carleton B. Edminster

USDA Forest Service
Research Paper RM-134

February 1975

Rocky Mountain Forest and
Range Experiment Station

Forest Service
U.S. Department of Agriculture
Fort Collins, Colorado

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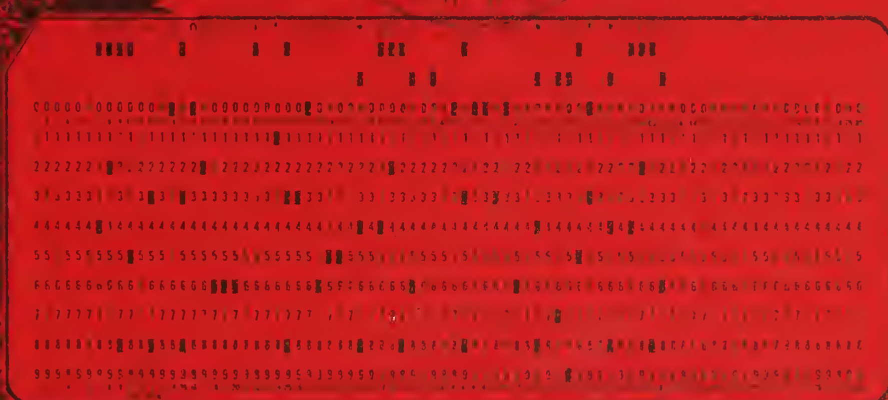

Abstract

Presents procedures for deriving yield tables for managed stands of spruce-fir from data obtained on temporary plots, and the computer programs developed by Myers (1971). Oxford: 566 (083.5) 6

Keywords: Engelmann spruce, subalpine fir, stand yield tables, timber management, managed stands, simulation.

Authors' Preface

The procedures for computing yield tables for managed even-aged stands of spruce-fir presented in this Paper were adapted from the field and computer procedures for managed stand yield tables developed by Myers (1971). We replaced the species-specific statements for ponderosa pine with functions applicable to spruce-fir, and made a few minor changes in the way the program operates. Much of Myers' original text is repeated here so that readers will not have to refer to two publications.

USDA Forest Service
Research Paper RM-134

February 1975

Yield Tables for Managed Even-Aged Stands of Spruce-Fir in the Central Rocky Mountains

by

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

Contents

Yield Tables for Managed Even-Aged Stands of Spruce-Fir in the Central Rocky Mountains

Robert R. Alexander, Wayne D. Shepperd, and Carleton B. Edminster

Timber management in the Engelmann spruce (*Picea engelmannii*)-subalpine fir (*Abies lasiocarpa*) type in the central and southern Rocky Mountains is in a period of transition to more intensive and varied management practices. Large areas of old-growth forests are rapidly being converted to stands that must be managed from the regeneration period to harvesting. Yield tables that predict probable yields of wood that will result from specified combinations of site quality, frequency and intensity of thinning, and utilization standards provide goals toward which conversion can be directed. They also provide part of the information needed to determine the influence of timber management practices on other forest resources (Myers 1971). Land managers can examine alternatives and make decisions through computerized evaluation (Program TEVAP2) of forestry activities, a procedure that uses yield-table computation in a set of mathematical operations (Myers 1974).

Procedures for the computation of yield tables for managed even-aged stands of spruce-fir presented in this Paper were adapted from the field and computer procedures for managed stand yield tables (Program PONYLD) developed by Myers (1971). Included are (1) identification of the field measurements that provide the basic data needed to produce the yield tables, (2) the relationships that replace the species-specific statements in Myers' Program PONYLD, (3) the computer program (SPRYLD) written in FORTRAN IV that computes and prints yield tables for spruce-fir, and (4) an example of what program SPRYLD can produce. The computer program SPRYLD has the capacity of producing a series of yield tables which show how projected outcomes will vary in response to changes in cultural treatments and/or variations in original stand and site conditions. Large numbers of tables, each based on a specific set of alternatives, can be computed and printed for a few cents each. They provide the manager with the opportunity to examine the probable results of his operations, make necessary changes in management goals, and study the effect of these changes before money is spent on them (Myers 1971).

General Description of Methods

The nine items of information (working tools) described later are species-specific statements in Myers' (1971) computer program. All but the first item, the desired residual stand after each cutting which is based on available information from thinned stands, were replaced to compute yield tables for even-aged managed stands of spruce-fir. Data for these eight items of information were based on temporary growth prediction plots measured in detail. Tree volume equations (Myers and Edminster 1972) and site index curves (Alexander 1967) applicable to spruce-fir stands in the central Rocky Mountains were used in the analyses of data described in the following sections.

There are no thinned stands of spruce-fir in the central Rocky Mountains, and partially cut stands were unsuitable for sampling; therefore, the growth prediction plots were placed in 69 undisturbed even-aged stands throughout the spruce-fir type in Colorado and Wyoming. These plots, chosen to approximate what a managed stand might look like, conformed to the usual requirements as to uniformity of site quality, range in tree sizes, and stand density across the plot. The trees were also free of diseases or insect infestations that would affect growth. The plots covered a range of site quality (SI 40 to

110) and stand density (30 to 1,600 stems per acre). Age classes varied from 20 to 160 years.

Measurements made on each growth prediction plot included the following:

1. Plot area.
2. Heights and ages of 6 to 10 dominant trees suitable for site index determination (Alexander 1967).
3. Diameter at breast height (d.b.h.) of each tree to the nearest 0.1 inch.
4. Total height of each tree to the nearest 1.0 foot, or a sufficient sample in each diameter class to construct a height/diameter curve where a large number of trees were measured. Heights of all dominants and codominants were measured except where tops were dead, defective, or deformed.
5. Crown class of each tree.
6. Total ages of a sample of dominant and codominant trees to validate even-age status of the main stand.
7. Radial wood growth during the past 10 years from increment borings at breast height along an average radius.
8. D.b.h. outside bark of all trees that appeared to have died during the last 10 years.
9. On 12 plots, a number of cut or leave codes for each tree based on trial marking to simulate several intensities of thinning. This information was used to provide some of the input needed to determine diameter and height increases due to thinning, stand volumes, and volume conversion factors. Additional simulated data were generated using Program SPRCHK, a modification of Program PONCHK (Myers 1971). The 12 plots were also used to verify the SPRCHK output.

Plot and tree data computed initially from the field measurements included:

1. Site index (Alexander 1967).
2. A height-diameter curve for each plot to provide a height for each tree for which actual height was not measured.

Measured and computed items that describe the present stand were used to compute the following values for each plot:

1. Number of trees per acre.
2. Number of dominants and codominants per acre.
3. Basal area per acre.
4. Average d.b.h., computed as the tree of average basal area.
5. Average height of dominant and codominant trees.
6. Average height of all trees.
7. Average main stand age.
8. Total cubic feet from ground to tip for all trees, per acre.
9. Merchantable cubic feet to a 4-inch top in trees 5 inches d.b.h. and larger, per acre.
10. Board feet (Scribner Rule) to a 6-inch top in trees 8 inches d.b.h. and larger, per acre.

All except item 7 were generated as part of the output of Program SPRCHK.

Diameters of live trees, diameters of the tallied dead trees, and present stand age on each plot provide the following items that described the stands 10 years ago at the beginning of the prediction period.

1. Number of trees, per acre.
2. Basal area, per acre.
3. Past d.b.h. of each tree from present d.b.h., radial wood growth, and periodic bark growth (Myers and Alexander 1972).
4. Average stand diameter (tree of average basal area).
5. Average main stand age (present main stand age minus 10 years).

Development of Items to Replace Species-Specific Statements and Other Modifications Needed to Adapt Myers' (1971) Program PONYLD to SPRYLD

After plot measurements were obtained and summarized, the items described below were computed as one or more relationships to convert the species-specific statements in Program PONYLD to spruce-fir. Most of the nine items that appear as FORTRAN statements in Program SPRYLD and its associated subroutines SPRCUT and SPRVOL were obtained by regression analysis of plot values described above.

1. Stocking After Cutting

Stand density to be left after each cutting is expressed as the relationship between basal area and average stand diameter. Data on spruce-fir from thinning studies or temporary plots were not available to construct a graph of desired basal area over stand diameter for local average diameter. Data for this item were taken directly from Myers' (1971) Program PONYLD. When sufficient information for spruce-fir becomes available, this item will be examined and necessary adjustments made.

The following, taken from Myers (1971), is repeated here for continuity.

"In table 1, basal area increases with diameter until 10.0 inches diameter is reached, and remains constant thereafter. The designation 'growing stock level 80' indicates that basal area is 80.0 ft² when diameter is 10.0 inches or larger, regardless of what basal area may be at lower average diameters.

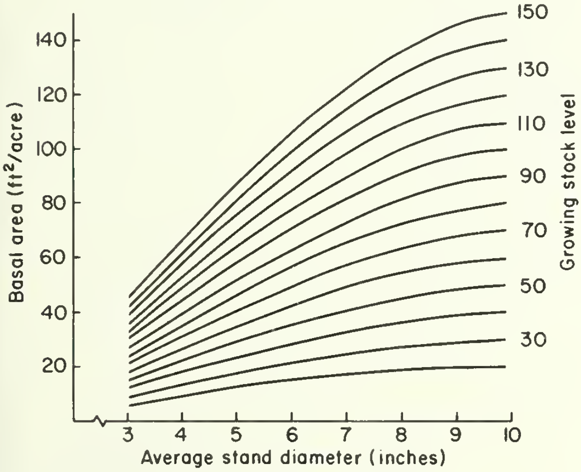

Figure 1. — Basal area after thinning in relation to average stand diameter for standard levels of growing stock (from Myers 1971).

"Desired stand density will vary with the objectives of management, and a family of basal area-diameter relationships is needed (fig. 1). The original single curve or function of basal area on diameter is treated as a guide curve from which other curves can be produced. Basal areas for any growing stock level can be computed by multiplying the guiding values for level 80 in table 1 by the ratio level/80."

The level designations that are the variables THIN, REST, and DSTY in SPRYLD are the same as appear in PONYLD.

The curves of figure 1 define growing stock goals for many possible management objectives. Any desired form of the guide curve may be used if the appropriate statements of subroutine SPRCUT are modified properly.

Relationships shown in table 1 appear as functions for level 80 in program SPRYLD.

Table 1.--Basal areas after intermediate cutting in relation to average stand diameter growing stock level 80 (from Myers 1971)

Average stand d.b.h. after cutting (Inches)	Basal area per acre	Average stand d.b.h. after cutting (Inches)	Basal area per acre
	ft^2		ft^2
2.0	12.1	6.0	56.6
2.1	13.2	6.1	57.6
2.2	14.4	6.2	58.5
2.3	15.5	6.3	59.4
2.4	16.7	6.4	60.3
2.5	17.9	6.5	61.2
2.6	19.0	6.6	62.1
2.7	20.2	6.7	62.9
2.8	21.3	6.8	63.8
2.9	22.5	6.9	64.6
3.0	23.7	7.0	65.4
3.1	24.8	7.1	66.2
3.2	26.0	7.2	67.0
3.3	27.1	7.3	67.7
3.4	28.3	7.4	68.5
3.5	29.5	7.5	69.2
3.6	30.6	7.6	69.9
3.7	31.8	7.7	70.6
3.8	32.9	7.8	71.2
3.9	34.1	7.9	71.9
4.0	35.2	8.0	72.5
4.1	36.4	8.1	73.1
4.2	37.6	8.2	73.7
4.3	38.7	8.3	74.3
4.4	39.9	8.4	74.8
4.5	41.0	8.5	75.3
4.6	42.2	8.6	75.8
4.7	43.4	8.7	76.3
4.8	44.5	8.8	76.7
4.9	45.7	8.9	77.1
5.0	46.8	9.0	77.5
5.1	47.8	9.1	77.9
5.2	48.8	9.2	78.2
5.3	49.8	9.3	78.5
5.4	50.8	9.4	78.8
5.5	51.8	9.5	79.1
5.6	52.8	9.6	79.3
5.7	53.8	9.7	79.5
5.8	54.7	9.8	79.7
5.9	55.7	9.9	79.8
		10.0+	80.0

Basal areas computed from these functions are multiplied by terms that include the desired growing stock level (THIN) to obtain values for other growing stock levels. Variables for which FORTRAN statements were taken from PONYLD and their use, were:

"a. DBHP — to find a d.b.h. less than 10.0 inches when basal area is known. Three equations for DBHP are used to simplify representation of the nonlinear relationship between d.b.h. and basal area.

b. BREAK and BUST — to compute values of basal area that are the upper limits of applicability of the first two equations for DBHP.

c. SQFT — to find basal area when d.b.h. is known. Two equations represent the nonlinear relationship for d.b.h. less than 10.0 inches."

2. Description of Unthinned, Young Stands

Values in the first line of each yield table describe stand conditions just prior to initial thinning. They are entered directly from data cards or are computed from the data. Users of SPRYLD must, therefore, be able to describe the stands that do or should exist at time of initial thinning. In a yield table for managed stands, the stand density and related average diameter given in the first line result when stand regeneration and subsequent growth and mortality progress as planned.

Only a few unthinned young spruce-fir stands were found that represented possible regeneration goals for various management objectives. Furthermore, no usable data were available from yield studies made elsewhere. It was not possible, therefore, to determine average diameter for each site class for various combinations of age and number of trees per acre. Instead, an average diameter in relation to number of trees per acre was determined for an average site index at age 30 years, the youngest age appearing in the yield tables. It was then necessary to make a judgment decision as to the average diameters and number of trees that appeared reasonable for managed stands at the time of first thinning for each site class. These values range from 800 stems per acre with an average diameter of 4.7 inches for site index classes 100 and greater to 950 stems per acre with an average diameter of 4.4 inches for site index classes 40 and 50. As more young stands with reasonable spacing reach 30 years of age, additional data will become available to evaluate this first approximation, and make necessary adjustments.

3. Diameter Increase from Growth

Regression analysis of data from growth prediction plots provided an equation for predicting future average stand diameter of spruce-fir. Present average stand diameter is estimated from past average stand diameter, site index, and past basal area per acre. The following equation for a 10-year prediction period appears in SPRYLD as the FORTRAN statement for DBHO:

$$DBHO = 1.62917 + 1.03371\ (DBHT)$$

$$+\ 0.01304\ (SITE) - 0.90669\ (\log_{10} BAST)$$

$$S_{yx} = 0.2469 \quad R^2 = 0.9948$$

where DBHO = present average stand diameter.
DBHT = past average stand diameter.
SITE = site index.
BAST = past basal area per acre.

4. Diameter Increase from Thinning

The change in average stand diameter resulting from intermediate cuttings was estimated from data obtained by trial marking of growth prediction plots, and the supplemental procedure developed by Myers (1971) and generated by Program SPRCHK. This later procedure provided simulated data on combinations of initial stand diameters, stocking level, and stand density not available from the trial markings.

In subroutine SPRCUT, diameter after thinning is estimated from diameter before thinning and the percentage of trees to be retained. Regression analysis of data from simulated thinnings provides two functions — DBHE and PDBHE — that represent the same variable, diameter after thinning.

DBHE is computed directly in subroutine SPRCUT from the following equation if at least 50 percent of the trees are retained:

$$DBHE = 0.02666 + 1.30655\ (DBHO) - 0.00306\ (DBHO \times PRET)$$

$S_{yx} = 0.1413$, $R^2 = 0.9985$

where DBHE = average diameter after thinning.
DBHO = average stand diameter before thinning.
PRET = percentage of trees retained after thinning.

With fewer trees retained, the relationship is nonlinear, so PDBHE is computed in subroutine SPRCUT from the following equation and its antilogarithm becomes DBHE:

$$PDBHE = 0.33206 + 0.98346\ (\log_{10} DBHO) - 0.14170\ (\log_{10} PRET)$$

$S_{yx} = 0.0187$, $R^2 = 0.9898$

5. Heights of Dominants and Codominants

Average heights of dominant and codominant trees were computed from data from the growth prediction plots and from Alexander's (1967) site index curves adjusted from dominant height to dominant and codominant height (table 2). Regression analysis provided two equations that appear as statements for HTSO in SPRYLD, for estimating height for various combinations of age and site index:

The equations are shown below:

$$HTSO\ (AGEO < 100) = -13.71751 + 0.15087\ (SITE) + 0.00126\ (AGEO^2) + 0.01371\ (AGEO \times SITE) - 0.00006\ (AGEO^2 \times SITE)$$

$S_{yx} = 2.0074$, $R^2 = 0.9920$

$$\log_{10} HTSO\ (AGEO \geq 100) = 0.91859 - \frac{100.43601}{AGEO} + 0.62318\ (\log_{10} SITE) + 40.08154\ \frac{\log_{10} SITE}{AGEO}$$

Table 2.--Average height (feet) of dominant and codominant trees at various ages and site indexes for Engelmann spruce (as computed by statements for HTSO)

Main stand age (years)	Site index (Based on dominant trees)						
	40	50	60	70	80	90	100
20	3	7	11	15	19	23	27
30	8	13	18	23	28	33	38
40	12	18	25	31	37	43	49
50	17	24	31	37	44	51	58
60	21	29	36	44	51	59	67
70	25	33	41	50	58	66	74
80	29	37	46	55	63	72	81
90	33	41	50	60	68	77	87
100	36	45	54	64	73	82	92
110	39	48	58	67	77	86	96
120	41	51	61	70	80	89	99
130	43	54	63	73	83	92	102
140	45	56	66	76	86	95	105
150	47	58	68	78	88	98	107
160	49	60	70	80	90	100	109
170	51	61	72	82	92	101	111
180	53	63	73	83	93	103	113

$S_{yx} = 0.0101$, $R^2 = 0.9938$

where HTSO = average height of dominant and codominant trees before thinning.
SITE = site index.
AGEO = main stand age.

6. Height Increase from Thinning

Changes in the average height of dominant and codominant trees due to intermediate cuttings were estimated from data provided by trial markings of growth prediction plots, and simulated thinnings generated by Program SPRCHK for various additional combinations of stocking level, initial stand diameter, and initial stand density. In SPRYLD, the variable ADDHT is the computed amount of change estimated from the percentage of trees retained (PRET) by the equation below:

$$ADDHT = -1.81392 + 17.77922 \sqrt{\frac{1}{PRET}}$$

$S_{yx} = 0.0864$, $R^2 = 0.9958$

At each cutting, the current value of ADDHT is added to height before thinning, HTSO, to obtain height after thinning, HTST. It is also added to a cumulative sum of changes, HTCUM, so that computed heights before thinning will show the effects of past treatments as well as of age. Values for ADDHT are small because changes in height are for dominant and codominant trees only.

7. Noncatastrophic Mortality

Mortality in unthinned stands is usually more important than in thinned stands. Since the only data available were from growth prediction plots, and they were located in unthinned stands with spacings that appeared desirable for managed stands, estimates of mortality in managed stands are only approximate. Furthermore, we did not compute a prediction equation for mortality for spruce-fir stands with an average diameter of 10.0 inches or larger because of the wide variability in mortality in those stands.

The prediction equation in SPRYLD for stands with an average diameter of less than 10.0 inches, shown below for the percentage of mortality expressed as a decimal (DIED), contains average stand diameter and basal area at the beginning of the period as independent variables:

$$\text{DIED} = -0.0003967 + 0.0000382\ (\text{DBHT} \times \text{BAST})$$

$$S_{yx} = 0.0055, \quad R^2 = 0.9677$$

where DIED = percentage of trees that have died during measurement period (10 years).
DBHT = average stand diameter at the beginning of the measurement period.
BAST = basal area per acre at the beginning of the measurement period.

8. Stand Volume Equation

Plot tallies of tree diameters and heights from growth prediction plots, the result of simulated thinnings, and trial markings were converted to total cubic foot, merchantable cubic foot, and board foot volumes per acre with appropriate tree volume equations (Myers and Edminster 1972). In subroutine SPRVOL, only total cubic foot volumes per acre are computed directly, and therefore are the only unit of measure for which a stand volume equation is needed.

Stand volume equations appear as statements to compute CUFT in subroutine SPRVOL. Two statements were used because the relationship was not linear over the range of D^2H that can appear in the yield tables:

$$\text{CUFT}\ (D^2H < 22{,}500) = (0.34480 - 0.00524\text{BA} + 0.0023575D^2H) \times N$$

$$S_{yx} = 0.4982, \quad R^2 = 0.9936$$

$$\text{CUFT}\ (D^2H \geq 22{,}500) = (7.60196 - 0.01052\text{BA} + 0.0020103D^2H) \times N$$

$$S_{yx} = 1.9210, \quad R^2 = 0.9940$$

where CUFT = total cubic foot volume per acre.
D = average stand diameter.
BA = basal area per acre.
H = average height of dominant and codominant trees.
N = number of trees per acre.

The standard errors of estimate quoted above result from the prediction of cubic foot volume of a tree of average d.b.h. and height, before multiplying by number of trees per acre.

9. Volume Conversion Factors

Subroutine SPRVOL computes volumes in merchantable cubic feet and board feet from total cubic volume per acre and appropriate conversion factors. Data from growth prediction plots, trial markings, and simulated thinnings that produced the stand volume equations also provided conversion factors. The quantity of each unit per total cubic foot was determined separately for each data point. A stand diameter of 5.0 inches and top diameter of 4.0 inches for merchantable cubic feet, and a stand diameter of 8.0 inches and top diameter of 6.0 inches for board feet, were selected as appropriate minimums. Regression analysis provided the function to compute the conversion from total cubic volume to merchantable cubic volume and board foot volumes that appear as statements FCTR and PROD in SPRVOL. FCTR can be estimated by the following equation from average stand diameter:

$$FCTR = 0.82375 + \frac{3.45569}{D}$$

$$+ 0.00013(D^2) - \frac{28.86783}{D_2}$$

$$S_{yx} = 0.0273, \quad R^2 = 0.9572$$

Estimates of PROD for spruce-fir can be improved if basal area is included with diameter in the equations. Two equations shown below appear in SPRVOL so the relationships can be expressed in simpler terms over a wide range of diameters:

$$PROD\ (D < 16.5\ \text{inches}) = 4.59159 -$$

$$\frac{214.06370}{D^2} + 0.39782\ (\log_{10} BA)$$

$$S_{yx} = 0.1567, \quad R^2 = 0.9561$$

$$PROD\ (D \geq 16.5\ \text{inches}) = 8.59422 -$$

$$\frac{19.54507}{\sqrt{D}} + 0.44432\ (\log_{10} BA)$$

$$S_{yx} = 0.1191, \quad R^2 = 0.8575$$

Description of Program SPRYLD

Program SPRYLD consists of a main program and two subroutine subprograms written in standard FORTRAN IV. The main program reads the data cards, performs most computations, and writes the yield tables. Subroutine SPRCUT determines the new average stand diameter and percentage of trees retained after cutting to the specified growing stock level. Subroutine SPRVOL computes volumes in total cubic feet per acre, and factors to convert these volumes to other units. Operations performed by each routine are indicated by comment statements in the source listing (Appendix 1).

As mentioned earlier, program SPRYLD computes and prints sets of yield tables. The variable NTSTS, read from data card type 1, controls the number of sets of tables. The number of yield tables within a set is controlled by variable MIX, read from data card type 3. The first yield table of each set is computed from initial conditions and controls on operations specified on data cards type 3, 4, and 5. Subsequent yield tables within a set are computed from the same conditions and controls, with the exception of the growing stock level for intermediate cuts after initial thinning. This growing stock level is increased by the value of DSTINC (read from data card type 3) over the level of the previous yield table. Operations performed for each yield table are:

1. Computation of basal area, height, and volumes just prior to initial thinning.
2. Partial cutting to the growing stock level specified for initial thinning or subsequent cutting. Cutting will not be simulated if the stand is already below the growing stock level specified.
3. Computation of post-cutting density, basal area, height, and volumes.
4. Printing of table headings once for each yield table and printing of values appropriate for the stand age.
5. Projection of diameter, height, and stand density for one or more periods until the next intermediate cut is scheduled. Stand volumes and other values are computed and printed at ages when no cutting is scheduled.
6. Repetition of steps 2 to 5 until stand age at time of initial regeneration cutting is reached.
7. Redefinition of the growing stock to be left after cutting and the interval between regeneration cuttings if shelterwood cuttings are specified. Table computations will be terminated if clearcutting is specified.
8. Repetition of steps 2 to 7 to accomplish regeneration cuts until the age of the final cut is reached.
9. Printing of totals for volumes removed. Volumes less than COMCU or COMBF (read from data card type 2) will not be included in the totals so that total commercial yields may be compared, if desired. Actual totals may be obtained by entering values of 1.0 for COMCU and COMBF on data card type 2.

Subroutine SPRCUT computes average stand diameter after cutting from diameter before cutting and the percentage of trees retained. The percentage of trees retained is needed as an independent variable, but is itself an unknown. Successive percentages of trees retained are tested until d.b.h. after thinning, number of trees retained, and residual basal area agree with the diameter and basal area combination specified by the growing stock level of the cut. These combinations are shown in table 1 for growing stock level 80.0.

Subroutine SPRVOL computes total cubic feet per acre and factors to convert this volume to other units. Conversions to merchantable cubic feet and to board feet are shown in Appendix 1. Utilization standards for these units are given in subsection 9 of the previous section and in the comment statements of SPRVOL. Conversions to other units or utilization standards may supplement or replace those already in SPRVOL.

Program SPRYLD should run with little or no modification on any computer that accepts FORTRAN IV, has a minimum of 32K words of storage, and has two input/output devices (unit 5 for program and data deck input and unit 6 for printed output). Changes to adapt the program to other utilization standards and for additional computations are described by Myers (1971) in his section headed Modifications of PONYLD, and are not repeated here.

Description of the Data Deck for Program SPRYLD

The data deck for program SPRYLD consists of five types of data cards. These cards are numbered by their order of appearance in the data deck except that cards type 3, 4, and 5 may be repeated in sets as specified by variable NTSTS from card type 1. The first two cards of the data deck (types 1 and 2) enter values which do not change during a computer run. Cards type 3, 4, and 5 enter values used in the computation of a set of yield tables which may change between sets of tables. The contents of each data card are described in the following tabulation of the order and contents of the data deck.

An Application of SPRYLD

The problem described below demonstrates the computations made by SPRYLD and the printed results obtained. It illustrates some of the questions that may be asked and the information that will be provided. The example also serves as a test problem for use in adapting the source program to locally available computing facilities.

A forest manager wishes to determine the intensity of thinning that will maximize volume production in board feet in stands of site index 80 (SITE). Length of the cutting cycle (JCYCL) has not been standardized, but will be 30 years for this test. He also wants to compare yields from two-cut and three-cut shelterwood, both with the final removal cut scheduled for stand age 150 years (REGN(2) for two-cut shelterwood, REGN(3) for three-cut shelterwood) and considering the current crop only. Alternatives calling for more than one precommercial thinning are unacceptable. Minimum commercial volumes per acre are 400 cubic feet (COMCU) and 2000 board feet (COMBF). The manager expects that his procedure for regeneration cuts will result in a new stand that contains 850 trees per acre (DENO) by age 30 (AGEO), with an average diameter of 4.6 inches (DBHO). (The data deck consisting of 32 cards is shown in fig. 2.)

```
                          COLUMN NUMBERS

                    11111111112222222222333333333344444444445
          12345678901234567890123456789012345678901234567890

CARD TYPE

    1        6  80  10

    2       400    2000

    3       30   3   20
    4        30       45    850      80      80      80
    5       120        80   150

    3       30   3   20
    4        30       45    850      80      80     100
    5       120        80   150

    3       30   3   20
    4        30       45    850      80      80     120
    5       120        80   150

    3       30   3   20
    4        30       45    850      80      80      80
    5        90        80   120        80   150

    3       30   3   20
    4        30       45    950      80      80     100
    5        90        80   120        80   150

    3       30   3   20
    4        30       45    850      80      80     120
    5        90        80   120        80   150
```

Figure 2. — Data deck for test problem.

Yield tables produced by SPRYLD, a few of which are reproduced in Appendix 2, can assist in decision-making in many ways. Money yields and rates earned can be com-

Order and Contents of the Data Deck for Program SPRYLD

Card type	Number of cards	Variable name	Columns	Format	Description of variable
1	1	NTSTS	1-4	I4	Number of tests or sets of yield tables to be produced (greater than or equal to 1).
		GIDE	5-8	F4.0	Base level of set of growing stock levels (equal to 80.0 for the listing in Appendix 1).
		RINT	9-12	F4.0	Number of years for which a growth equation makes one projection (equal to 10.0 for the listing in Appendix 1).
2	1	COMCU	1-8	F8.3	Minimum cut in merchantable cubic feet per acre to be included in total yields (greater than or equal to 1.0).
		COMBF	9-16	F8.3	Minimum cut in board feet per acre to be included in total yields (greater than or equal to 1.0).
3	1 per test	JCYCL	1-4	I4	Interval between intermediate cuts. A multiple of RINT.
		MIX	5-8	I4	Number of stocking levels for intermediate cuts to be examined in one test. Equivalent to number of yield tables produced per test (greater than or equal to 1).
		DSTINC	9-16	F8.3	Amount growing stock level (for intermediate cuts after initial thinning) will be increased over level of previous yield table in a test if MIX is greater than 1. Leave blank if MIX equals 1.
4	1 per test	AGEO	1-8	F8.3	Initial age in years to be shown in a yield table. Stand age when first thinning occurs (greater than 0.0).
		DBHO	9-16	F8.3	Average stand d.b.h. in inches just prior to initial thinning at stand age AGEO (greater than 0.0).
		DENO	17-24	F8.3	Number of trees per acre just prior to initial thinning at stand age AGEO (greater than 0.0).
		DSTY	25-32	F8.3	Lowest growing stock level for intermediate cuts after initial thinning in a test. Level will increase by DSTINC on the second and subsequent yield tables in a test if MIX is greater than 1. Value of DSTY must be greater than 0.0.
		SITE	33-40	F8.3	Site index for the stand (greater than 0.0).
		THIN	41-48	F8.3	Growing stock level for initial thinning at age AGEO (greater than 0.0).
5	1 per test	REGN(1)[1]	1-8	F8.3	Stand age at which first regeneration cut will occur. Must be greater than 0.0 as REGN(1) is rotation age for clearcutting.
		VLLV(1)	9-16	F8.3	Percentage, as a decimal, of growing stock level for intermediate cuts to be left at age REGN(1). Leave this and next 3 variables blank for clearcutting.

Card type	Number of cards	Variable name	Columns	Format	Description of variable
		REGN(2)[1]	17-24	F8.3	Stand age at which second regeneration cut, if any, will occur. Final cut of 2-cut shelterwood or second cut of 3-cut shelterwood.
		VLLV(2)	25-32	F8.3	Percentage, as a decimal, of growing stock level left after first regeneration cut to be left at age REGN(2). Leave this and next variable blank for 2-cut shelterwood.
		REGN(3)[1]	33-40	F8.3	Stand age at which third regeneration cut, if any, will occur. Final cut of 3-cut shelterwood.

[1] *Values for ages for regeneration cuts must equal the value of AGEO plus a multiple of the value of RINT.*

puted by applying thinning costs and stumpage values to the volumes given in the tables. Stand ages at culmination of mean annual increment, and rates earned assist in the selection of rotations.

For the situation described above, yields and numbers of precommercial thinnings are of greatest immediate interest. These items are summarized in tables 3 and 4 for the 18 yield tables produced. Combinations of high initial and intermediate subsequent growing stock levels produce the greatest volumes with one precommercial thinning. Additional comparisons should be made to include such factors as probable thinning costs, cubic yields from thinnings not commercial for board feet, and the average size of tree produced. As expected, the current crop produces more board feet in 150 years if cut by two-cut shelterwood than if by three-cut shelterwood. The latter treatment may, however, get the next crop off to an earlier start.

Modifications of SPRYLD

SPRYLD can be modified to study actual stands, especially to determine if treatment in unthinned stands is justified, and to add other measures and variability as described for PONYLD by Myers (1971).

Table 3.--Yields in board feet, including commercial thinnings, of the 18 combinations of initial and subsequent growing stock levels[1]

Initial growing stock level	Subsequent growing stock level		
	80	100	120
	mbd ft		
	Two-cut Shelterwood		
80	40.9	46.3	53.4
100	41.8	47.5	52.8
120	42.1	47.9	52.2
	Three-cut Shelterwood		
80	37.2	42.2	48.2
100	38.4	43.6	48.2
120	39.0	44.5	48.0

[1]See text p.3 for description of growing stock levels.

Table 4.--Number of precommercial thinnings if each of the 18 combinations of initial and subsequent growing stock levels[1] is established as specified by the data deck. (Both types of cutting gave the same results)

Initial growing stock level	Subsequent growing stock level		
	80	100	120
80	1	2	2
100	1	1	2
120	1	1	2

[1]See text p.3 for description of growing stock levels.

Description of Program SPRCHK

Program SPRCHK — used to calculate volumes, volume conversion factors, and diameters and heights for different combinations of stand variables not available from growth prediction plots — is the same as Myers (1971) Program PONCHK, except that the equations used to compute volumes are for spruce (Myers and Edminster 1972).

Modifications Needed to Use Spruce-Fir in Myers' (1974) Program TEVAP2

Subroutine WORKGP in Myers (1974) TEVAP2 permits the program to be used with other species. To use spruce-fir, replace the dummy continue statement number 4 with a CALL statement that will call subroutine ESSF, the species-specific statements for spruce-fir to be used with TEVAP2. SPNUM (I) equal to 4 will then designate subroutine ESSF. The subroutine organization is shown in Appendix 3.

Basic information used in ESSF has been described earlier, with the exception of one equation (ADD) which is included to estimate merchantable cubic volume obtained as a byproduct of saw-log cuts. ADD is computed from stand diameter as follows:

$$ADD = 1.54375 + \frac{11.43324}{D}$$

$$S_{yx} = 0.1168, \quad R^2 = 0.8517$$

where ADD = cubic foot volume of saw logs (hundreds of cubic feet per m board feet).
D = average stand diameter.

Literature Cited

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1972. Bark thickness and past diameters of Engelmann spruce in Colorado and Wyoming. USDA For. Serv. Res. Note RM- 217, 2 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

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Appendix I: Listing of Program SPRYLD

```
      PROGRAM SPRYLD
     1(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C TO COMPUTE AND PRINT YIELD TABLES FOR MANAGED EVEN-AGED STANDS OF
C ENGELMANN SPRUCE AND SUBALPINE FIR.
C
C DEFINITIONS OF VARIABLES.
C
C     ADDHT = INCREASE OR DECREASE IN AVERAGE STAND HEIGHT BY THINNING.
C     AGED = INITIAL AGE IN YIELD TABLE.
C     BASC = BASAL AREA CUT PER ACRE.
C     BASD = BASAL AREA PER ACRE BEFORE THINNING.
C     BAST = BASAL AREA PER ACRE AFTER THINNING.
C     BDFC = BOARD FEET CUT PER ACRE.
C     BDFD = BOARD FEET PER ACRE BEFORE THINNING.
C     BDFT = BOARD FEET PER ACRE AFTER THINNING.
C     CFMC = MERCHANTABLE CU. FT. CUT PER ACRE.
C     CFMD = MERCH. CU. FT. PER ACRE BEFORE THINNING.
C     CFMT = MERCH. CU. FT. PER ACRE AFTER THINNING.
C     COMBF = MINIMUM COMMERCIAL CUT, BOARD FEET.
C     COMCU = MINIMUM COMMERCIAL CUT, CU. FT.
C     DBHD = AVERAGE STAND D.B.H. BEFORE THINNING.
C     DBHT = AVERAGE STAND D.B.H. AFTER THINNING.
C     DENC = TREES CUT PER ACRE.
C     DEND = TREES PER ACRE BEFORE THINNING.
C     DENT = TREES PER ACRE AFTER THINNING.
C     DIED = PERCENTAGE, AS A DECIMAL, OF TREES THAT DIE DURING PERIOD
C           RINT.
C     OLEV = GROWING STOCK LEVEL FOR INTERMEDIATE CUTS AFTER FIRST.
C     OSTINC = AMOUNT GROWING STOCK LEVEL FOR INTERMEDIATE CUTS WILL BE
C           INCREASED OVER LEVEL OF PREVIOUS YIELD TABLE IN A TEST.
C     OSTY = LOWEST VALUE OF OLEV USED IN A TEST.
C     GIDE = BASE FOR GROWING STOCK LEVELS, 80.0 IN EXAMPLE SHOWN.
C     HTSD = TREE HEIGHT BEFORE THINNING.
C     HTST = TREE HEIGHT AFTER THINNING.
C     JCYCL = INTERVAL BETWEEN INTERMEDIATE CUTS.
C     JSBD = SUM OF BOARD FEET FROM ALL CUTS WITH YIELD OF COMBF OR
C           LARGER.
C     JSMC = SUM OF MERCH. CU. FT. FROM ALL CUTS WITH YIELD OF COMCU OR
C           LARGER.
C     JSTF = SUM OF TOTAL CU. FT. FROM ALL CUTS.
C     MIX = NUMBER OF STOCKING LEVELS EXAMINED PER TEST.
C     NTSTS = NUMBER OF TESTS PER BATCH.
C     PRET = PERCENTAGE OF TREES RETAINED AFTER THINNING.
C     REGN(I) = STAND AGE WHEN REGENERATION CUT I OCCURS.
C     RINT = NUMBER OF YEARS FOR WHICH PROJECTION IS MADE.
C     ROTA = FINAL AGE IN YIELD TABLE.
C     SITE = SITE INDEX.
C     THIN = GROWING STOCK LEVEL FOR INITIAL THINNING.
C     TOTC = TOTAL CUBIC FEET CUT PER ACRE.
C     TOTD = TOTAL CUBIC FEET PER ACRE BEFORE THINNING.
C     TOTT = TOTAL CUBIC FEET PER ACRE AFTER THINNING.
C     VLLV(I) = PERCENT OF PREVIOUS OLEV TO BE LEFT AT REGN(I), ENTERED
C           AS A DECIMAL.
C
      COMMON BA,BAST,CUFT,DBHD,DBHT,DEND,FCTR,HITE,GIDE,PRET,PROD,REST,S
     1TAND,VDM
      DIMENSION REGN(3),VAR(10),VLLV(2)

      DO 1 J=1,10
    1 VAR(J) = 0.0

C READ NUMBER OF TESTS, BASE OF GROWING STOCK LEVELS, AND LENGTH OF
C PROJECTION PERIOD FROM CARD TYPE ONE.

      READ (5,5) NTSTS,GIDE,RINT
    5 FORMAT (I4,2F4.0)
      IF(NTSTS .LE. 0) GO TO 170
      IF(GIDE .LE. 0.0) GO TO 170
      VAR(5) = RINT

C READ MINIMUM COMMERCIAL CUTS FOR COMPUTATION OF COLUMN TOTALS FROM
C CARD TYPE TWO.

      READ (5,10) COMCU,COMBF
   10 FORMAT (10F8.3)
      VAR(8) = COMCU
      VAR(9) = COMBF

C EXECUTE PROGRAM ONCE FOR EACH SET OF INITIAL VALUES OF INTEREST.

      DO 160 I=1,NTSTS
      JTEM = 0

C READ CUTTING INTERVAL AND LEVELS PER TEST FROM CARD TYPE THREE.

      READ (5,15) JCYCL,MIX,OSTINC
   15 FORMAT (2I4,F8.3)
      IF(JCYCL .LE. 0 .OR. MIX .LE. 0) GO TO 170
      JTEM = JCYCL

C READ INITIAL STAND VALUES FROM CARD TYPE FOUR.
C
      READ (5,10) AGED,DBHD,DEND,OSTY,SITE,THIN
      VAR(1) = AGED
      VAR(2) = DBHD
      VAR(3) = DEND
      VAR(4) = OSTY
      VAR(6) = SITE
      VAR(7) = THIN
C
C READ SILVICULTURAL CONTROLS FROM CARD TYPE FIVE.
C
      READ (5,10) REGN(1),VLLV(1),REGN(2),VLLV(2),REGN(3)
      VAR(10) = REGN(1)
      DO 20 L=1,10
      IF(VAR(L) .LE. 0.0) GO TO 170
   20 CONTINUE
      OLEV = 0.0
      DO 25 NA=1,3

      L = 4 - NA
      IF(REGN(L) .EQ. 0.0) GO TO 25
      ROTA = REGN(L)
      GO TO 30
   25 CONTINUE
C
C PROVIDE FOR SEVERAL GROWING STOCK LEVELS PER TEST.
C
   30 DO 160 M=1,MIX
      ADDHT = 0.0
      BDFD = 0.0
      BDFT = 0.0
      CFMD = 0.0
      CFMT = 0.0
      HTCUM = 0.0
      JSBD = 0
      JSMC = 0
      JSTF = 0
      TEM = M
      OLEV = OSTY + (TEM - 1.0) * OSTINC
      BASD = DEND * 0.0054542 * DBHD * DBHD
C
C OBTAIN AVERAGE HEIGHT AND VOLUMES PER ACRE.
C
C-----STATEMENTS FOR HTSD AND IF STATEMENT ARE SPECIES-SPECIFIC.
C
      IF(AGED .GE. 100.0) GO TO 35
      HTSD = -13.71751 + 0.15087 * SITE + 0.00126 * AGED * AGED +
     1 0.01371 * AGED * SITE - 0.00006 * AGED * AGED * SITE
      GO TO 40
   35 HTSD = 0.91859 - 100.43601 / AGED + 0.62318 * ALOG10(SITE) +
     1 40.08154 * ALOG10(SITE) / AGED
      HTSD = 10.0 ** HTSD
   40 HITE = HTSD
      BA = BASD
      STAND = DEND
      VDM = DBHD
      CALL SPRVOL
      TOTD = CUFT
      BDFD = CUFT * PROD
      CFMD = CUFT * FCTR
      REST = THIN
C
C ENTER LOOP FOR REMAINING COMPUTATIONS AND PRINTOUT.
C
      DO 130 K=1,100
C
C CHANGE STANDARDS IF A REGENERATION CUT IS DUE.
C
   43 IF(AGED .GE. ROTA) GO TO 60
      IF(AGED .LT. REGN(1)) GO TO 55
      IF(AGED .NE. REGN(1)) GO TO 45
      OLEV = OLEV * VLLV(1)
      REST = OLEV
      JCYCL = REGN(2) - REGN(1) + 0.5


      GO TO 55
   45 OLEV = OLEV * VLLV(2)
      REST = OLEV
      JCYCL = REGN(3) - REGN(2) + 0.5
C
C INCREASE D.B.H. BY THINNING AND COMPUTE POST-THINNING VALUES.
C
   55 CALL SPRCUT
      IF(PRET .GE. 100.0) GO TO 56
      JDENT = (BAST / (0.0054542 * DBHT * DBHT)) + 0.5
      DENT = JDENT
      BAST = 0.0054542 * DBHT * DBHT * DENT
      IF(BAST .LT. BASD) GO TO 58
   56 BAST = BASD
      HTST = HTSD
      DENT = DEND
      JDENT = DEND + 0.5
      DBHT = DBHD
      TOTT = TOTD
      BDFT = BDFD
      CFMT = CFMD
      GO TO 60
C
```

```
TATEMENT FOR AOOHT IS SPECIES-SPECIFIC.

OOHT = - 1.B1392 + 17.77922 * SQRT(1.0 / PRET)
TCUM = HTCUM + AOOHT
TST = HTSO + AOOHT
TANO = OENT
OM = OBHT
ITE = HTST
A = BAST
ALL SPRVOL
OTT = CUFT
OFT = CUFT * PROO
FMT = CUFT * FCTR

E MOOE ANO ROUNO OFF FOR PRINTING.

AGEO = AGEO
SITE = SITE
OENO = OENO + 0.5
HTSO = HTSO + 0.5
TOTO = (TOTO * 0.1) + 0.5
TOTO = JTOTO * 10
BASO = BASO + 0.5
CFMO = (CFMO * 0.1) + 0.5
CFMO = JCFMO * 10
BOFO = (BOFO * 0.01) + 0.5
BOFO = JBOFO * 100
HTST = HTST + 0.5
TOTT = (TOTT * 0.1) + 0.5
TOTT = JTOTT * 10
CFMT = (CFMT * 0.1) + 0.5
CFMT = JCFMT * 10
F(JCFMT .GT. JCFMO) JCFMO = JCFMT
BOFT = (BOFT * 0.01) + 0.5
BOFT = JBOFT * 100
F(JBOFT .GT. JBOFO) JBOFO = JBOFT
BAST = BAST + 0.5
OENC = JOENO - JOENT
BASC = JBASO - JBAST
TOTC = JTOTO - JTOTT
CFMC = JCFMO - JCFMT
F(JCFMC .LE. 0) JCFMC = 0
BOFC = JBOFO - JBOFT
F(JBOFC .LE. 0) JBOFC = 0

ERIOOIC CUTS FOR LAST LINE OF YIELO TABLE.

F(AGEO .GE. ROTA) GO TO 70
STF = JSTF + JTOTC
FMC = JCFMC
F(CFMC .LT. COMCU) GO TO 65
SMC = JSMC + JCFMC
OFC = JBOFC
F(BOFC .LT. COMBF) GO TO 70
SBO = JSBO + JBOFC

 HEAOINGS FOR YIELO TABLE.

F(K .GE. 2) GO TO 92

HANGE TABLE HEAOING FOR OTHER SPECIES.

RITE (6,BO) JSITE,JCYCL
ORMAT (1H1,//,27X,B2HYIELOS PER ACRE OF MANAGEO, EVEN-AGED STANOS
OF ENGELMANN SPRUCE ANO SUBALPINE FIR/1HO,48X,11HSITE INDEX ,I3,1
,,I4,19H-YEAR CUTTING CYCLE)
RITE (6,B2) THIN,OLEV
ORMAT (1HO,41X,26HTHINNING LEVELS= INITIAL -,F6.0,14H, SUBSEQUENT
-,F6.0)
RITE (6,B4)
ORMAT (1HO,25X,3BHENTIRE STANO BEFORE AND AFTER THINNING,2Bx,26HP
RIOOIC INTERMEOIATE CUTS)
RITE (6,B6)
ORMAT (1HO,9X,5HSTANO,10X,5HBASAL,3X,7HAVERAGE,2X,7HAVERAGE,3X,5H
OTAL,3X,9HMERCHANT-,3X,9HSAWTIMBER,9X,5HBASAL,4X,5HTOTAL,3X,9HMER
HANT-,3X,9HSAWTIMBER)
RITE (6,BB)
ORMAT (1H ,10X,3HAGE,4X,5HTREES,3X,4HAREA,4X,6HO.B.H.,3X,6HHEIGHT
2X,6HVOLUME,2X,11HABLE VOLUME,4X,6HVOLUME,3X,5HTREES,3X,4HAREA,3X
6HVOLUME,2X,11HABLE VOLUME,4X,6HVOLUME)
RITE (6,90)
ORMAT (1H ,BX,7H(YEARS),3X,3HNO.,3X,6HSQ.FT.,4X,3HIN.,6X,3HFT.,4X
6HCU.FT.,5X,6HCU.FT.,6X,6HBO.FT.,4X,3HNO.,3X,6HSQ.FT.,2X,6HCU.FT.
5X,6HCU.FT.,6X,6HBO.FT.)

 TABLE ENTRIES OF OIAMETER, VOLUMES, ETC.

RITE (6,94) JAGEO,JOENO,JBASO,OBHO,JHTSO,JTOTO,JCFMO,JBOFO
ORMAT (1HO,9X,I4,4X,I5,2X,I4,5X,F5.1,5X,I3,4X,I5,6X,I5,6x,I6)
F(AGEO .GE. ROTA) GO TO 135
RITE (6,96) JAGEO,JOENT,JBAST,OBHT,JHTST,JTOTT,JCFMT,JBOFT,JOENC,
BASC,JTOTC,JCFMC,JBOFC
ORMAT (1H ,9X,I4,4X,I5,2X,I4,5X,F5.1,5X,I3,4X,I5,6X,I5,6X,I6,4X,(
,3X,I3,5X,I4,6X,I4,BX,I5)

TE VALUES FOR EACH PERIOO. THIN AS SPECIFIED.

RINT = RINT
K = JCYCL / IRINT
O 120 L=1,IK
GEO = AGEO + RINT
F(AGEO .GT. ROTA) GO TO 135

TE NEW O.B.H. BEFORE THINNING ANO ROUNO OFF TO 0.1 INCH.
```

```
C
C-----STATEMENT FOR OBHO IS SPECIES-SPECIFIC.
C
      OBHO = 1.62917 + 1.03371 * OBHT + 0.01304 * SITE - 0.90669 *
     1 ALOG10(BAST)
      IOBHO = OBHO * 10.0 + 0.5
      OBHO = IOBHO
      OBHO = OBHO * 0.1
C
C-----STATEMENT FOR OIEO IS SPECIES-SPECIFIC. CHANGE 10.0 IN IF
C-----STATEMENT IF OIEO STATEMENT APPLIES TO LARGER TREES.
C
      IF(OBHT .GE. 10.0) GO TO 100
      DIEO = (-0.03967 + 0.003B2 * OBHT * BAST) * 0.01
      IF(OIEO .LT. 0.0) OIEO = 0.0
      OENO = OENT * (1.0 - OIEO)
      MNK = OENO + 0.5
      OENO = MNK
      GO TO 105
  100 OENO = OENT
  105 BASO = OENO * (0.0054542 * DBHO * OBHO)
C
C OBTAIN AVERAGE HEIGHT ANO VOLUMES PER ACRE.
C
C-----STATEMENTS FOR HTSO ANO IF STATEMENT ARE SPECIES-SPECIFIC.
C
      IF(AGEO .GE. 100.0) GO TO 110
      HTSO = -13.71751 + 0.150B7 * SITE + 0.00126 * AGEO * AGEO +
     1 0.01371 * AGEO * SITE - 0.00006 * AGEO * AGEO * SITE
      GO TO 115
  110 HTSO = 0.91B59 - 100.43601 / AGEO + 0.6231B * ALOG10(SITE) +
     1 40.08154 * ALOG10(SITE) / AGEO
      HTSO = 10.0 ** HTSO
  115 HTSO = HTSO + HTCUM
      STANO = OENO
      VOM = OBHO
      HITE = HTSO
      BA = BASO
      CALL SPRVOL
      TOTO = CUFT
      BOFO = CUFT * PROO
      CFMO = CUFT * FCTR
C
C TEST IF REGENERATION CUT IS OUE.
C
      OO 11B KU=1,3
      IF(AGEO .EO. REGN(KU)) GO TO 43
  118 CONTINUE
C
C CHANGE MOOE AND ROUNO OFF FOR PRINTING.
C
      IF(L .EQ. IK) GO TO 125
      KOENO = DENO + 0.5
      KAGEO = AGEO
      KHTSO = HTSO + 0.5
      KBASO = BASO + 0.5
      KTOTO = (TOTO * 0.1) + 0.5
      KTOTO = KTOTO * 10
      KCFMO = (CFMO * 0.1) + 0.5
      KCFMO = KCFMO * 10
      KBOFO = (BOFO * 0.01) + 0.5
      KBOFO = KBOFO * 100
C
C WRITE VALUES FOR THE PERIOO IF THINNING IS NOT OUE.
C
      WRITE (6,94) KAGEO,KOENO,KBASO,OBHO,KHTSO,KTOTO,KCFMO,KBOFO
      OBHT = OBHO
      BAST = BASO
      OENT = OENO
  120 CONTINUE
  125 REST = OLEV
  130 CONTINUE
C
C AOO FINAL CUTS TO TOTAL YIELOS ANO WRITE TOTAL YIELOS.
C
  135 JSTF = JSTF + JTOTO
      CFMO = JCFMO
      IF(CFMO .LT. COMCU) GO TO 140
      JSMC = JSMC + JCFMO
  140 BOFO = JBOFO
      IF(BOFO .LT. COMBF) GO TO 145
      JSBO = JSBO + JBOFO
  145 WRITE (6,150) JSTF,JSMC,JSBO
  150 FORMAT (1HO,/,67X,12HTOTAL YIELOS,1BX,I6,4X,I6,6X,I7)
      WRITE (6,155) COMCU,COMBF
  155 FORMAT (1HO,//,11X,44HMINIMUM CUTS FOR INCLUSION IN TOTAL YIELOS--
     1,F6.0,15H CUBIC FEET ANO,F7.0,11H BOARO FEET)
      WRITE (6,156)
  156 FORMAT (1HO,10X,66HMERCH. CU. FT. - TREES 5.0 INCHES O.B.H. ANO LA
     1RGER TO 4-INCH TOP.)
      WRITE (6,157)
  157 FORMAT (1HO,10X,59HBO. FT. - TREES B.0 INCHES O.B.H. ANO LARGER TO
     1 6-INCH TOP.)
C
C PREPARE FOR NEXT TABLE OF THE TEST.
C
      AGEO = VAR(1)
      OBHO = VAR(2)
      DENO = VAR(3)
      JCYCL = JTEM
  160 CONTINUE
      GO TO 200
  170 WRITE (6,175)
  175 FORMAT (1H1,///,10X,66HEXECUTION STOPPEO BECAUSE OF NEGATIVE OR ZE
     1RO ITEM ON A OATA CARO.)
  200 CALL EXIT
      ENO
```

```
      SUBROUTINE SPRCUT

 TO ESTIMATE INCREASE IN AVERAGE D.B.H. DUE TO THINNING.

      COMMON BA,BAST,CUFT,DBHO,DBHT,DENO,FCTR,HITE,GIDE,PRET,PROD,REST,S
     1TAND,VDM

      IF(DBHO .LT. 9.4) GO TO 30

 COMPUTE D.B.H. IF DBHO IS LARGE ENOUGH FOR BASAL AREA TO REMAIN CONSTANT.

      PRET = 100.0
      DO 21 KJ=1,100

-----STATEMENTS FOR DBHE AND PDBHE ARE SPECIES-SPECIFIC.

      IF(PRET .LT. 50.0) GO TO 5
      DBHE = 0.02666 + 1.30655 * DBHO - 0.00306 * PRET * DBHO
      GO TO 11
    5 PDBHE = 0.33206 + 0.98346 * ALOG10(DBHO) - 0.14710 * ALOG10(PRET)
      DBHE = 10.0 ** PDBHE
   11 IDBHE = DBHE  * 10.0 + 0.5
      DBHE = IDBHE
      DBHE = DBHE * 0.1
      DENE = DENO * PRET * 0.01
      NDENE = DENE + 0.5
      DENE = NDENE
      BASE = 0.0054542 * DBHE * DBHE * DENE
      NBASE = BASE * 10.0 + 0.5
      BASE = NBASE
      BASE = BASE * 0.1
      TMPY = 0.0054542 * DBHE * DBHE
      TEM = BASE - REST
      IF(KJ .EQ. 1 .AND. TEM .LT. 0.0) GO TO 90
      IF(TEM .LE. TMPY) GO TO 70
      IF(TEM .LT. 4.0) GO TO 20
      PRET = PRET - 1.0
      GO TO 21
   20 PRET = PRET - 0.3
   21 CONTINUE
      GO TO 70

 COMPUTE D.B.H. IF BASAL AREA INCREASES WITH D.B.H.

   30 PRET = 40.0
      IF(DBHO .GT. 7.0) PRET = 70.0
      DO 65 J=1,100

-----STATEMENTS FOR DBHE AND PDBHE ARE SPECIES-SPECIFIC.

      IF(PRET .GE. 50.0) GO TO 40
      PDBHE = 0.33206 + 0.98346 * ALOG10(DBHO) - 0.14710 * ALOG10(PRET)
      DBHE = 10.0 ** PDBHE
      GO TO 45
   40 DBHE = 0.02666 + 1.30655 * DBHO - 0.00306 * PRET * DBHO
   45 IDBHE = DBHE * 10.0 + 0.5
      DBHE = IDBHE
      DBHE = DBHE * 0.1
      DENE = DENO * (PRET * 0.01)
      NDENE = DENE + 0.5
      DENE = NDENE
      BASE = 0.0054542 * DBHE * DBHE * DENE
      NBASE = BASE * 10.0 + 0.5
      BASE = NBASE
      BASE = BASE * 0.1

-----CHANGE STATEMENTS FOR BREAK, BUST AND FIRST 3 STATEMENTS FOR DBHP
-----IF OTHER GROWING STOCK LEVEL BASE THAN TABLE 1 IS USED.

      BREAK = 49.9 * REST / GIDE
      IF(BASE .GT. BREAK) GO TO 50
      DBHP = (GIDE / REST) * (0.08682 * BASE) + 0.94636
      GO TO 52
   50 BUST = 66.2 * (REST / GIDE)
      IF(BASE .GT. BUST) GO TO 51
      DBHP = (GIDE / REST) * (0.10938 * BASE) - 0.17858
      GO TO 52
   51 TMPY = BASE * (GIDE / REST)
      TEM = TMPY * TMPY
      DBHP = 19.04740 * TMPY - 0.26673 * TEM + 0.0012539 * TEM * TMPY
     1 - 448.76833
      IF(TMPY .GT. GIDE) DBHP = DBHO + 0.8
   52 IDBHP = DBHP * 10.0 + 0.5
      DBHP = IDBHP
      DBHP = DBHP * 0.1
      IF(IDBHP - DBHE) 60,70,61
   60 PRET = PRET * 1.02
      IF(PRET .GT. 100.0) GO TO 90
      GO TO 65
   61 PRET = PRET * 0.98
   65 CONTINUE
   70 DBHT = DBHE

 COMPUTE POST-THINNING BASAL AREA.

-----CHANGE TWO IF STATEMENTS AND STATEMENTS FOR SOFT IF DIFFERENT
-----GROWING STOCK LEVEL BASE IS USED.

      IF(DBHT .GT. 5.0) GO TO 75
      SOFT = 11.58495 * DBHT - 11.09724
      GO TO 76
   75 IF(DBHT .GE. 10.0) GO TO 77
      TEM = DBHT * DBHT
      SOFT = 7.76226 * DBHT +0.85289 * TEM -0.07952 * TEM * DBHT-3.45624
   76 BAST = (REST / GIDE) * SOFT
      GO TO 80
   77 BAST = REST
   80 RETURN
   90 PRET = 100.0
      RETURN

      END
```

```
      SUBROUTINE SPRVOL
C
C TO COMPUTE VOLUMES PER ACRE IN VARIOUS UNITS.
C
      COMMON BA,BAST,CUFT,DBHO,DBHT,DENO,FCTR,HITE,GIDE,PRET,PROD,R
     1TAND,VDM
C
      FCTR = 0.0
      PROD = 0.0
C
C COMPUTE TOTAL CUBIC FEET PER ACRE.
C
      D2H = VDM * VDM * HITE
C
C-----STATEMENTS FOR CUFT AND IF STATEMENT ARE SPECIES-SPECIFIC.
C
      IF(D2H .GE. 22500.0) GO TO 5
      CUFT = (0.0023575 * D2H - 0.00524 * BA + 0.34480) * STAND
      GO TO 10
    5 CUFT = (0.0020103 * D2H - 0.01052 * BA + 7.60196) * STAND
   10 IF(VDM .LT. 5.0) GO TO 40
C
C OBTAIN CONVERSION FACTORS FOR MERCH. CU. FT. - VOLUMES TO 4.0-INC
C IN TREES 5.0 INCHES D.B.H. AND LARGER.
C
C-----STATEMENT FOR FCTR AND IF STATEMENT ARE SPECIES-SPECIFIC.
C
      FCTR = 0.82375 + 3.45569 / VDM + 0.00013 * VDM * VDM - 28.R67
     1 (VDM * VDM)
      IF(FCTR .GT. 0.99) FCTR = 0.99
   25 IF(VDM .LT. 8.0) GO TO 40
C
C OBTAIN CONVERSION FACTORS FOR BD. FT. - VOLUMES TO 6.0-INCH TOP I
C TREES 8.0 INCHES D.B.H. AND LARGER.
C
C-----STATEMENTS FOR PROD AND IF STATEMENT ARE SPECIES-SPECIFIC.
C
      IF(VDM .GE. 16.5) GO TO 30
      PROD = 4.59159 - 214.06370 / (VDM * VDM) + 0.39782 * ALOG10(B
      GO TO 40
   30 PROD = 8.59422 - 19.54507 / SQRT(VDM) + 0.44432 * ALOG10(BA)
   40 RETURN
      END
```

Appendix II: Output of SPRYLD

Two-Cut Shelterwood

YIELOS PER ACRE OF MANAGEO, EVEN-AGEO STANOS OF ENGELMANN SPRUCE ANO SUBALPINE FIR

SITE INOEX 80, 30-YEAR CUTTING CYCLE

THINNING LEVELS= INITIAL - 80., SUBSEOUENT - 80.

ENTIRE STAND 8EFORE ANO AFTER THINNING								PERIODIC INTERMEOIATE CUTS				
STANO AGE (YEARS)	TREES NO.	8ASAL AREA SO.FT.	AVERAGE O.8.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME 80.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME 80.FT.
30	850	94	4.5	28	1010	340	0					
30	314	52	5.5	29	680	340	0	536	42	330	0	0
40	311	78	6.8	38	1260	900	0					
50	305	106	8.0	45	2030	1650	4200					
60	295	133	9.1	53	2920	2530	8300					
60	149	80	9.9	53	1810	1610	5700	146	53	1110	920	2600
70	145	99	11.2	59	2510	2310	9200					
80	145	122	12.4	65	3370	3150	13600					
90	145	146	13.6	70	4350	4120	18700					
90	55	80	16.3	71	2440	2340	11100	90	66	1910	1780	7600
100	55	95	17.8	75	3000	2910	14500					
110	55	112	19.3	79	3610	3520	18300					
120	55	130	20.8	82	4290	4200	22500					
120	18	62	25.2	84	2050	2030	11300	37	68	2240	2170	11200
130	18	72	27.1	87	2420	2400	13700					
140	18	83	29.0	89	2830	2810	16500					
150	18	94	30.9	91	3280	3250	19500					
							TOTAL YIELOS			8870	8120	40900

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 400. CUBIC FEET ANO 2000. 80ARO FEET

MERCH. CU. FT. - TREES 5.0 INCHES O.B.H. ANO LARGER TO 4-INCH TOP.

80. FT. - TREES 8.0 INCHES O.8.H. AND LARGER TO 6-INCH TOP.

YIELDS PER ACRE OF MANAGEO, EVEN-AGED STANOS OF ENGELMANN SPRUCE ANO SUBALPINE FIR

SITE INOEX 80, 30-YEAR CUTTING CYCLE

THINNING LEVELS= INITIAL - 80., SUBSEOUENT - 120.

ENTIRE STAND 8EFORE ANO AFTER THINNING								PERIODIC INTERMEOIATE CUTS				
STANO AGE (YEARS)	TREES NO.	8ASAL AREA SO.FT.	AVERAGE O.8.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME 80.FT.	TREES NO.	8ASAL AREA SO.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME 80.FT.
30	850	94	4.5	28	1010	340	0					
30	314	52	5.5	29	680	340	0	536	42	330	0	0
40	311	78	6.8	38	1260	900	0					
50	305	106	8.0	45	2030	1650	4200					
60	295	133	9.1	53	2920	2530	8500					
60	228	119	9.8	53	2660	2360	8500	67	14	260	170	0
70	218	141	10.9	59	3520	3220	12800					
80	218	171	12.0	65	4670	4350	18700					
90	218	204	13.1	70	5990	5640	25500					
90	92	121	15.5	71	3650	3500	16500	126	83	2340	2140	9000
100	92	142	16.8	75	4570	4400	21800					
110	92	164	18.1	79	5320	5160	26500					
120	92	189	19.4	82	6240	6080	32300					
120	32	96	23.4	83	3150	3120	17100	60	93	3090	2960	15200
130	32	110	25.1	86	3700	3670	20700					
140	32	125	26.8	89	4310	4270	24800					
150	32	142	28.5	91	4960	4910	29200					
							TOTAL YIELOS			10980	10010	53400

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELOS-- 400. CUBIC FEET ANO 2000. 80ARO FEET

MERCH. CU. FT. - TREES 5.0 INCHES D.8.H. ANO LARGER TO 4-INCH TOP.

80. FT. - TREES 8.0 INCHES O.8.H. AND LARGER TO 6-INCH TOP.

YIELDS PER ACRE OF MANAGED, EVEN-AGED STANDS OF ENGELMANN SPRUCE AND SUBALPINE FIR

SITE INDEX 80, 30-YEAR CUTTING CYCLE

THINNING LEVELS= INITIAL - 120., SUBSEQUENT - 80.

	ENTIRE STAND BEFORE AND AFTER THINNING							PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	850	94	4.5	28	1010	340	0					
30	505	72	5.1	29	870	340	0	345	22	140	0	0
40	498	108	6.3	37	1620	1050	0					
50	485	141	7.3	45	2540	1940	0					
60	466	175	8.3	52	3660	3040	8700					
60	172	78	9.1	52	1740	1510	4800	294	97	1920	1530	3900
70	167	99	10.4	59	2470	2230	8400					
80	167	123	11.6	64	3350	3100	12800					
90	167	149	12.8	69	4390	4120	18200					
90	61	80	15.5	70	2420	2320	10800	106	69	1970	1800	7400
100	61	96	17.0	75	3100	2990	14700					
110	61	113	18.4	79	3660	3550	18100					
120	61	130	19.8	82	4320	4210	22200					
120	20	63	24.0	83	2060	2040	11200	41	67	2260	2170	11000
130	20	73	25.9	86	2460	2430	13700					
140	20	84	27.8	89	2890	2860	16600					
150	20	96	29.7	91	3360	3320	19800					
							TOTAL YIELDS			9650	8820	42100

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 400. CUBIC FEET AND 2000. BOARD FEET

MERCH. CU. FT. - TREES 5.0 INCHES D.B.H. AND LARGER TO 4-INCH TOP.

BD. FT. - TREES 8.0 INCHES D.B.H. AND LARGER TO 6-INCH TOP.

YIELDS PER ACRE OF MANAGED, EVEN-AGED STANDS OF ENGELMANN SPRUCE AND SUBALPINE FIR

SITE INDEX 80, 30-YEAR CUTTING CYCLE

THINNING LEVELS= INITIAL - 120., SUBSEQUENT - 120.

	ENTIRE STAND BEFORE AND AFTER THINNING							PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	850	94	4.5	28	1010	340	0					
30	505	72	5.1	29	870	340	0	345	22	140	0	0
40	498	108	6.3	37	1620	1050	0					
50	485	141	7.3	45	2540	1940	0					
60	466	175	8.3	52	3660	3040	8700					
60	259	117	9.1	52	2570	2230	7300	207	58	1090	810	1400
70	249	141	10.2	59	3480	3130	11800					
80	249	173	11.3	64	4680	4300	17800					
90	249	205	12.3	69	5960	5570	24400					
90	103	120	14.6	70	3600	3430	15900	146	85	2360	2140	8500
100	103	142	15.9	75	4540	4360	20900					
110	103	166	17.2	78	5410	5220	26300					
120	103	190	18.4	82	6310	6120	31900					
120	35	96	22.4	83	3160	3120	16900	68	94	3150	3000	15000
130	35	110	24.0	86	3710	3670	20400					
140	35	125	25.6	88	4300	4260	24300					
150	35	141	27.2	91	4940	4890	28700					
							TOTAL YIELDS			11680	10840	52200

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 400. CUBIC FEET AND 2000. BOARD FEET

MERCH. CU. FT. - TREES 5.0 INCHES D.B.H. AND LARGER TO 4-INCH TOP.

BD. FT. - TREES 8.0 INCHES D.B.H. AND LARGER TO 6-INCH TOP.

Three-Cut Shelterwood

YIELDS PER ACRE OF MANAGED, EVEN-AGED STANDS OF ENGELMANN SPRUCE AND SUBALPINE FIR

SITE INDEX 80, 30-YEAR CUTTING CYCLE

THINNING LEVELS= INITIAL - 80., SUBSEQUENT - 80.

ENTIRE STAND BEFORE AND AFTER THINNING								PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	850	94	4.5	28	1010	340	0					
30	314	52	5.5	29	680	340	0	536	42	330	0	0
40	311	78	6.8	38	1260	900	0					
50	305	106	8.0	45	2030	1650	4200					
60	295	133	9.1	53	2920	2530	8300					
60	149	80	9.9	53	1810	1610	5700	146	53	1110	920	2600
70	145	99	11.2	59	2510	2310	9200					
80	145	122	12.4	65	3370	3150	13600					
90	145	146	13.6	70	4350	4120	18700					
90	40	64	17.1	71	1970	1900	9200	105	82	2380	2220	9500
100	40	76	18.7	76	2410	2340	11800					
110	40	90	20.3	80	2910	2840	14900					
120	40	105	21.9	83	3460	3400	18400					
120	13	49	26.4	84	1620	1610	9000	27	56	1840	1790	9400
130	13	57	28.4	87	1930	1910	11000					
140	13	66	30.4	90	2250	2230	13200					
150	13	75	32.5	92	2620	2600	15700					
						TOTAL YIELDS				8280	7530	37200

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 400. CUBIC FEET AND 2000. BOARD FEET

MERCH. CU. FT. - TREES 5.0 INCHES D.B.H. AND LARGER TO 4-INCH TOP.

BD. FT. - TREES 8.0 INCHES D.B.H. AND LARGER TO 6-INCH TOP.

YIELDS PER ACRE OF MANAGED, EVEN-AGED STANDS OF ENGELMANN SPRUCE AND SUBALPINE FIR

SITE INDEX 80, 30-YEAR CUTTING CYCLE

THINNING LEVELS= INITIAL - 80., SUBSEQUENT - 120.

ENTIRE STAND BEFORE AND AFTER THINNING								PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	850	94	4.5	28	1010	340	0					
30	314	52	5.5	29	680	340	0	536	42	330	0	0
40	311	78	6.8	38	1260	900	0					
50	305	106	8.0	45	2030	1650	4200					
60	295	133	9.1	53	2920	2530	8500					
60	228	119	9.8	53	2660	2360	8500	67	14	260	170	0
70	218	141	10.9	59	3520	3220	12800					
80	218	171	12.0	65	4670	4350	18700					
90	218	204	13.1	70	5990	5640	25500					
90	66	96	16.3	71	2930	2820	13400	152	108	3060	2820	12100
100	66	113	17.7	76	3570	3450	17300					
110	66	131	19.1	79	4260	4140	21500					
120	66	151	20.5	83	5010	4900	26300					
120	23	76	24.6	84	2500	2480	13700	43	75	2510	2420	12600
130	23	87	26.4	87	2950	2920	16700					
140	23	100	28.2	89	3440	3400	19900					
150	23	113	30.0	92	3960	3920	23500					
						TOTAL YIELDS				10120	9160	48200

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 400. CUBIC FEET AND 2000. BOARD FEET

MERCH. CU. FT. - TREES 5.0 INCHES D.B.H. AND LARGER TO 4-INCH TOP.

BD. FT. - TREES 8.0 INCHES D.B.H. AND LARGER TO 6-INCH TOP.

YIELOS PER ACRE OF MANAGEO, EVEN-AGEO STANOS OF ENGELMANN SPRUCE ANO SUBALPINE FIR

SITE INOEX 80, 30-YEAR CUTTING CYCLE

THINNING LEVELS= INITIAL - 120., SUBSEQUENT - 80.

	ENTIRE STANO BEFORE ANO AFTER THINNING							PERIOOIC INTERMEOIATE CUTS				
STANO AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE O.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BO.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BO.FT.
30	850	94	4.5	28	1010	340	0					
30	505	72	5.1	29	870	340	0	345	22	140	0	0
40	498	108	6.3	37	1620	1050	0					
50	485	141	7.3	45	2540	1940	0					
60	466	175	8.3	52	3660	3040	8700					
60	172	78	9.1	52	1740	1510	4800	294	97	1920	1530	3900
70	167	99	10.4	59	2470	2230	8400					
80	167	123	11.6	64	3350	3100	12800					
90	167	149	12.8	69	4390	4120	18200					
90	45	64	16.2	71	1970	1890	8900	122	85	2420	2230	9300
100	45	78	17.8	75	2460	2390	11800					
110	45	92	19.4	79	2990	2910	15100					
120	45	107	20.9	82	3550	3480	18500					
120	15	53	25.4	84	1730	1720	9500	30	54	1820	1760	9000
130	15	61	27.4	87	2060	2040	11700					
140	15	71	29.4	89	2430	2400	14100					
150	15	81	31.4	91	2820	2790	16800					
						TOTAL	YIELOS			9120	8310	39000

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELOS-- 400. CUBIC FEET ANO 2000. BOARO FEET

MERCH. CU. FT. - TREES 5.0 INCHES O.B.H. ANO LARGER TO 4-INCH TOP.

BO. FT. - TREES 8.0 INCHES O.B.H. ANO LARGER TO 6-INCH TOP.

YIELOS PER ACRE OF MANAGEO, EVEN-AGEO STANOS OF ENGELMANN SPRUCE ANO SUBALPINE FIR

SITE INOEX 80, 30-YEAR CUTTING CYCLE

THINNING LEVELS= INITIAL - 120., SUBSEQUENT - 120.

	ENTIRE STANO BEFORE ANO AFTER THINNING							PERIOOIC INTERMEOIATE CUTS				
STANO AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE O.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BO.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BO.FT.
30	850	94	4.5	28	1010	340	0					
30	505	72	5.1	29	870	340	0	345	22	140	0	0
40	498	108	6.3	37	1620	1050	0					
50	485	141	7.3	45	2540	1940	0					
60	466	175	8.3	52	3660	3040	8700					
60	259	117	9.1	52	2570	2230	7300	207	58	1090	810	1400
70	249	141	10.2	59	3480	3130	11800					
80	249	173	11.3	64	4680	4300	17800					
90	249	205	12.3	69	5960	5570	24400					
90	75	96	15.3	71	2910	2780	13000	174	109	3050	2790	11400
100	75	114	16.7	75	3690	3550	17400					
110	75	134	18.1	79	4360	4230	21600					
120	75	156	19.5	82	5160	5030	26500					
120	25	76	23.6	83	2510	2480	13500	50	80	2650	2550	13000
130	25	88	25.4	86	2970	2940	16500					
140	25	101	27.2	89	3470	3430	19900					
150	25	115	29.0	91	4010	3970	23600					
						TOTAL	YIELOS			10940	10120	48000

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELOS-- 400. CUBIC FEET ANO 2000. BOARO FEET

MERCH. CU. FT. - TREES 5.0 INCHES O.B.H. ANO LARGER TO 4-INCH TOP.

BO. FT. - TREES 8.0 INCHES O.B.H. AND LARGER TO 6-INCH TOP.

Appendix III: Listing of Subroutine ESSF

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SUBROUTINE ESSF

TION FOR ALL SPECIES - SPECIFIC STATEMENTS APPLICABLE TO ENGELMANN
CE - SUBALPINE FIR IN COLORADO ANO WYOMING.

CDMMDN ADD,AGE(2),AGEO,BA(2),BAS(2),BASO,BAST,BAUS,BFMRCH,BFVDL,
CFVOL,OATE(6),DBH(2),DBHE,DBHO,DBHT,DEN(2),DEND,DENT,OMUS,FBA(2),
FCTR(2),FOM(2),FON(2),FHT(2),FORET(19),FVL(2),HT(2),HTCUM,HTSD,
HTST,KAK,KNO,MIN,MNK,NBK,NCMP,NSUB,NWGP,PD8HE,PRET,PROO(2),REST,
SAVE,SBARB,SBARE,SBARG,SBAS,SITE,SLAND,TBA(2),TOM(2),TEM,TIME,TMBR
,TMPD,TOT(2),TOTD,TDTT,TVL(2),VDM(2),VLUS,OMR(2)
COMMDN ABFAG(5,15),ACINT(5),ADJ(5),AGETH(5,14),ALLCF(5,14),ALDWC(5
),ALW8F(5),AMCAG(5,15),ANCUT(5,14),AREA(5,14),8DMAI(5),BFAGE(5,15)
,BFINT(5),CFAGE(5,15),CFBF(5,14),COMBF(5),COMCU(5),CUCY(5),CUINT(5
),CUMAI(5),OBHTH(5,14),DELAY(5),DENTH(5,14),OLEV(5),FN8O(5),
FNCU(5),GROWB(5,2,14),GROWC(5,2,14),GVLBF(5),GVLCU(5),INVL(5,3,14)
,NSI(5),OPBD(5),OPCU(5),PAI8D(5),PAICU(5),POOR(5),REGN(5,3,14),
RINT(5),SARSP(5),SBF(5),SHELT(5,2,14),SHWO(5,2,14),SMC(5),SMSP(5),
SUBBF(5,14),SUBCF(5,14),SUMCF(5),SYST(5),THIN(5),VLLV(5,3,14),
WGNUM(5),WGPDES(5,20),WGPNM(5,3),SPNUM(5),TPB(5,7),PASP(5,7)
COMMDN ACBAR(7),ARBK(7),BARSI(7,14),BFTH(7,27),CMTH(7,27),CUTA(7,2
7),CUTB(7,27),HELP(7,27),NSBK(7),OPEN(7,27),PBRSI(7,14),PDCFN(7,27
),PDCFR(7,27),PSPLT(7,27),PUNC(7,27),SARETY(7,35),SLVG(7,27),SPLT(
7,27),TMTY(7),UNCML(7,27),PABR(7),PARTY(7,35)
CDMMON ACFNL(5,7,15),ACRGN(5,7,15),ACSI(5,7,14),ACSP(5,7),GR8D(5,7
CDMMON ACFNL(5,7,15),ACRGN(5,7,15),ACSI(5,7,14),ACSP(5,7),GRBD(5,7
,15),GRMC(5,7,15),PS(5,7,14),STYP(35),TYPNM(35,5),PASI(5,7,14)

COMMON /BLKO/ IJ,IK,KI,VDL,TVDL

GD TD (10,20,30,40,50,60,70,80,90,1C0,110,120), IJ

ION 1 - FIND TDTAL CUBIC FDOT VOLUME.

D2H = DBH(IK) * DBH(IK) * HT(IK)
IF(D2H .GE. 22500.0) GO TD 11
TOT(IK) = (0.0023575 * D2H - 0.00524 * BAS(IK) + 0.34480) *DEN(IK)
GO TO 12
TGT(IK) = (0.0020103 * 02H - 0.01052 * BAS(IK) + 7.60196)* OEN(IK)
RETURN

ION 2 - VDLUME CDNVERSION FACTORS.
H. CU. FT. - TREES 6.0 INCHES D.B.H. AND LARGER TD 4-INCH TDP.
FT. - TREES 10.0 INCHES O.B.H. AND LARGER TO 8-INCH TOP.

DO 21 J=1,2
FCTR(J) = 0.0
PRDD(J) = 0.0
DO 26 I=1,KNO
IF(VOM(I) .LE. 4.99) GO TD 26
FCTR(I) = 0.82375 + 3.45569 / VOM(I) + 0.G0013 * VDM(I) * VDM(I)
 - 28.86783 / (VDM(I) * VDM(I))
IF(FCTR(I) .GT. 0.99) FCTR(I) = 0.99
IF(VDM(I) .LE. 7.99) GO TO 26
IF(VDM(I) .GE. 16.5) GO TO 25
PRDD(I) = 4.59159 - 214.06370 / (VDM(I) * VDM(I)) + 0.39782 *

 ALDG10(BA(I))
GD TD 26
PRDO(I) = 8.59422 - 19.54507 / SQRT(VDM(I)) + 0.44432 * ALOG10(8A(
I))
CONTINUE
RETURN

ION 3 - GROWTH FOR NEXT PERICO.

DD 35 I=1,2
TMOY = AGE(I) + TIME
IF(TMDY .LT. TEM) GD TO 35
FDM(I) = 1.62917 + 1.G3371 * DBH(I) + 0.01304 * SITE - 0.90669 *
 ALOG10(SBAS)
IF(DBH(I) .GE. 10.0) GD TD 32
FDN(I) = (-0.03967 + 0.G0382 * DBH(I) * SBAS) * 0.01
IF(FON(I) .LT. 0.0) FDN(I) = 0.0
FDN(I) = DEN(I) * (1.0 - FDN(I))
MNK = FDN(I) + 0.5
FDN(I) = MNK
GD TO 33
FON(I) = DEN(I)
FBA(I) = 0.0054542 * FDM(I) * FDM(I) * FDN(I)
IF(AGE(I) .GE. 100.0) GD TD 37
FHT(I) = -13.71751 + 0.15087 * SITE + 0.00126 * AGE(I) * AGE(I) +
 0.G1371 * AGE(I) * SITE - 0.00006 * AGE(I) * AGE(I) * SITE
GO TO 38
FHT(I) = 0.91859 - 100.43601 / AGE(I) + 0.62318 * ALOG10(SITE) +
 40.08154 * ALOG10(SITE) / AGE(I)
FHT(I) = 10.0 ** FHT(I)
D2H = FDM(I) * FOM(I) * FHT(I)
IF(D2H .GE. 22500.0) GO TO 34
FVL(I) = (0.0023575 * D2H - 0.00524 * FBA(I) + 0.34480) * FDN(I)
GD TO 35
FVL(I) = (0.0020103 *D2H - 0.01052 * FBA(I) + 7.60196) * FDN(I)
CONTINUE
RETURN

ION 4 - FUTURE UNTHINNED UNDERSTORY IF DVERSTORY REOUCEO NOW.

DMUS = 1.62917 + 1.03371 * OBH(2) + 0.01304 * SITE - 0.90669 *
 ALDG10(BAS(2))
```

```
      IF(OBH(2) .GE. 10.0) GD TO 41
      DNUS = (-G.03967 + 0.00382 * DBH(2) * BAS(2)) * 0.01
      IF(ONUS .LT. 0.0) DNUS = 0.0
      DNUS = DEN(2) * (1.0 - ONUS)
      MNK = DNUS + 0.5
      DNUS = MNK
      GO TO 42
   41 DNUS = DEN(2)
   42 8AUS = 0.0054542 * DMUS * DMUS * DNUS
      IF(AGE(2) .GE. 100.0) GO TO 47
      HTUS = -13.71751 + 0.15087 * SITE + 0.00126 * AGE(2) * AGE(2) +
     1 0.01371 * AGE(2) * SITE - 0.00006 * AGE(2) * AGE(2) * SITE
      GD TO 48
   47 HTUS = 0.91859 - 100.43601 / AGE(2) + 0.62318 * ALOG10(SITE) +
     1 40.08154 * ALDG10(SITE) / AGE(2)
      HTUS = 10.0 ** HTUS
   48 D2H = DMUS * DMUS * HTUS
      IF(D2H .GE. 22500.0) GO TD 43
      VLUS = (0.0023575 * D2H - 0.00524 * 8AUS + 0.34480) * DNUS
      GO TO 44
   43 VLUS = (0.G020103 * 02H - 0.01052 * BAUS + 7.60196) * DNUS
   44 RETURN
C
C SECTION 5 - NEW D.B.H. AFTER THINNING.
C
   50 IF(PRET .LT. 50.0) GD TD 51
      DBHE = 0.02666 + 1.30655 * OBHO - 0.00306 * PRFT * DBHO
      GO TC 52
   51 PDBHE = 0.33206 + 0.98346 * ALOG10(DBHO) - 0.14710 * ALOG10(PRET)
      DBHE = 10.0 ** POBHE
   52 RETURN
C
C SECTION 6 - CUBIC FEET AS BYPRODUCT OF SAWLOG CUT.
C
   60 ADD = VCL * (1.54375 + 11.43324 / DBH(KI))
      AOD = TVGL - ADD
      IF(ADO .LT. COMCU(KAK)) ADD = 0.0
      RETURN
C
C SECTION 7 - VOLUME IF THINNED NOW AND IF THINNEO IN TIME YEARS.
C
   70 HT(KI) = HT(KI) - 1.81392 + 17.77922 * SQRT(1.0 / PRET)
      TEM = TBA(IK) / (0.0054542 * TDM(IK) * TDM(IK))
      D2H = TDM(IK) * TOM(IK)* HT(KI)
      IF(D2H .GE. 22500.0) GO TO 71
      TVL(IK) = (0.0023575 * D2H - 0.00524 * TBA(IK) + 0.34480) * TEM
      GO TC 72
   71 TVL(IK) = (0.0020103 * 02H - 0.01052 * TBA(IK) + 7.60196) * TEM
   72 RETURN
C
C SECTION 8 - STATUS AT END OF PERIOD IF THINNEO AT START OF PERIOD.
C
   80 J = TIME / RINT(KAK)
      DO 83 I=1,J
      IF(TBA(1) .LE. 0.0) GO TO 83
      HT(1) = HT(1) - 1.81392 + 17.77922 * SORT(1.0 / SAVE)
      FDM(1) = 1.62917 + 1.03371 * TDM(1) + 0.01304 * SITE - 0.90669 *
     1 ALOG10(T8A(1))
      IF(AGE(KI) .GE. 100.0) GD TO 87
      FHT(1) = -13.71751 + 0.15087 * SITE + 0.00126 * AGE(KI) * AGE(KI)
     1 + 0.01371 * AGE(KI) * SITE - 0.00006 * ACE(KI) * AGE(KI) * SITE
      GO TC 88
   87 FHT(1) = 0.91859 - 100.43601 / AGE(KI) + 0.6231B * ALDG10(SITE) +
     1 40.08154 * ALDG10(SITE) / AGE(KI)
      FHT(1) = 10.0 ** FHT(1)
   88 MNK = (TBA(1) / (0.0054542 * TDM(1) * TDM(1))) + 0.5
      IF(TDM(1) .LT. 10.0) GO TD 81
      FDN(1) = MNK
      GO TO 82
   81 FON(1) = (-0.03967 + 0.00382 * TDM(1) * TBA(1)) * 0.01
      IF(FDN(1) .LT. 0.0) FDN(1) = 0.0
      TEM = MNK
      NKM = TEM * (1.0 - FDN(1)) + 0.5
      FON(1) = NKM
   82 FBA(1) = FDN(1) * 0.0054542 * FOM(I) * FDM(1)
      TDM(1) = FDM(1)
      TBA(1) = FBA(1)
      HT(1) = FHT(1)
      AGE(KI) = AGE(KI) + RINT(KAK)
   83 CONTINUE
      D2H = FDM(1) * FOM(1) * FHT(1)
      IF(D2H .GE. 22500.0) GO TO 84
      FVL(1) = (0.0023575 * D2H - 0.00524 * FBA(1) + 0.34480) * FDN(1)
      GO TO 85
   84 FVL(1) = (0.0020103 * D2H - 0.01C52 * F8A(1) + 7.6G196) * FDN(1)
   85 RETURN
C
C SECTION 9 - HEIGHT ANO VOLUME BEFORE THINNING.
C
   90 IF(AGEO .GE. 100.0) GO TO 91
      HTSO = -13.71751 + 0.15087 * SITE + 0.00126 * AGEO * AGEO +
     1 0.01371 * AGED * SITE - 0.00006 * AGED * AGEO * SITE
      GO TO 92
   91 HTSO = 0.91859 - 100.43601 / AGEO + 0.62318 * ALOG10(SITE) +
     1 40.08154 * ALDG10(SITE) / AGEO
      HTSO = 10.0 ** HTSO
   92 HTSO = HTSO + HTCUM
      D2H = DBHO * D8HD * HTSO
```

```
      IF(02H .GE. 22500.0) GO TO 93
      TOTO = (0.0023575 * D2H - 0.00524 * BASO + 0.34480) * OENO
      GO TO 94
   93 TOTO = (0.0020103 * 02H - 0.01052 * BASO + 7.60196) * OENO
   94 RETURN
C
C SECTION 10 - HEIGHT ANO TOTAL CUBIC FEET PER ACRE AFTER THINNING.
C
  100 AOOHT = - 1.81392 + 17.77922 * SQRT(1.0 / PRET)
      HTCUM = HTCUM + AODHT
      HTST = HTSO + AOOHT
      02H = OBHT * OBHT * HTST
      IF(02H .GE. 22500.0) GO TO 101
      TOTT = (0.0023575 * 02H - 0.00524 * BAST + 0.34480) * OENT
      GO TO 102
  101 TOTT = (0.0020103 * 02H - 0.01052 * BAST + 7.60196) * DENT
  102 RETURN
C
C SECTION 11 - O.B.H. AT END OF PROJECTION PERIOO.
C
  110 OBHO = 1.62917 + 1.03371 * DBHT + 0.01304 * SITE - 0.90669 *
     1 ALOG10(BAST)
      RETURN
C
C SECTION 12 - MORTALITY AS A PERCENTAGE OF INITIAL OENSITY.
C
  120 DENO = (-0.03967 + 0.00382 * OBHT * BAST) * 0.01
      RETURN
      ENO
```

Alexander, Robert R., Wayne D. Shepperd, and Carleton B. Edminster.
1975. Yield tables for managed stands of spruce-fir in the central Rocky Mountains. USDA For. Serv. Res. Pap. RM-134, 20 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

Presents procedures for deriving yield tables for managed stands of spruce-fir from data obtained on temporary plots, and the computer programs developed by Myers (1971).

Keywords: *Picea engelmannii, Abies lasiocarpa*, stand yield tables, timber management, managed stands, simulation.

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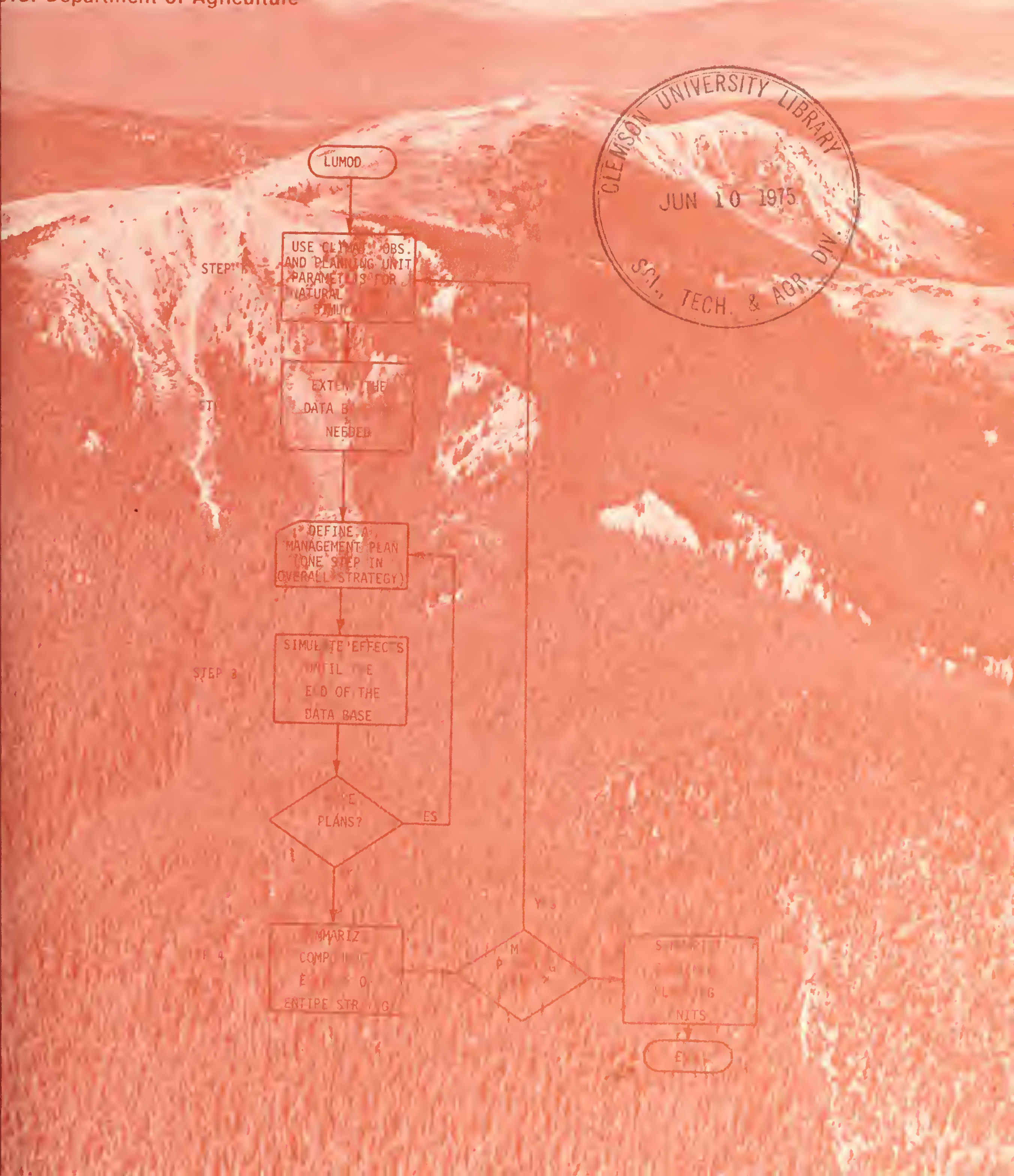
Land Use Simulation Model of the Subalpine Coniferous Forest Zone

Charles F. Leaf and Glen E. Brink

Rocky Mountain Forest and
Range Experiment Station

Forest Service
U.S. Department of Agriculture



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Abstract

A dynamic model simulates the short- and long-term hydrologic impacts of combinations of timber harvesting and weather modification to develop management strategies for planning intervals which can vary from a few years to the rotation age of subalpine forests (120 years and longer). Management strategies may subdivide a given "planning unit," defined by environmental characteristics, into as many as eight distinct "response units," which may be managed independently. Different cutting practices may be imposed on the response units, and any number of cuttings can be made at specified years during the planning interval. All interactions between the various response units are accounted for in both time and space. Moreover, the model contains time trend functions which compute changes in evapotranspiration, soil water, forest cover density, reflectivity, interception, snow redistribution, and sediment yield as the forest stands respond to timber harvesting.

Keywords: Computer models, coniferous forest, forest management, land use planning, simulation analysis, subalpine hydrology, watershed management.

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Land Use Simulation Model of the Subalpine Coniferous Forest Zone

by
Charles F. Leaf, Hydraulic Engineer
and
Glen E. Brink, Computer Programer

Rocky Mountain Forest and Range Experiment Station[1]

[1]Central headquarters maintained at Fort Collins in cooperation with Colorado State University. Leaf is now a consulting engineer in Fort Collins.

CONTENTS

Land Use Simulation Model of the Subalpine Coniferous Forest Zone

Charles F. Leaf and Glen E. Brink

Introduction

Conflicts between interest groups over land-use impacts on the environment in the subalpine zone cannot be resolved without objective multi-resource analyses. These analyses must account for both primary resource responses and their interactions. Dynamic simulation models are one way of providing the framework for comprehensive land-use planning in ecologically complex forests. The output from such models should help planners to better understand how various land-use practices influence productivity and environmental quality. Moreover, multi-resource simulation models should help to achieve the most desirable balance of uses and products from the subalpine coniferous forest zone.

Some progress has been made in the development of simulation models that predict the short-term effects of timber harvesting on snowmelt and water yield (Leaf and Brink 1972, 1973a, 1973b, Leaf 1975). This work has been expanded to determine the long-term interactions between the water and timber resources in old-growth subalpine forests subjected to partial cutting and regeneration practices. The effects of logging and road construction on erosion and sediment yields are also considered.

The objective has been to design a model that: (1) is formulated in terms of the diverse form, structure, and arrangement of natural forest stands; and (2) at least qualitatively accounts for the response of these stands to management, based on the best information available.

Theory

Comparison of Subalpine Water Balance Model and Land Use Model

Leaf and Brink (1973a,b) have previously described a water balance model for simulating runoff from subalpine watersheds. This model is now being used in representative areas throughout the Rocky Mountain region for simulating watershed management practices and their resultant effects on hydrologic system behavior.

The Land Use Model has greatly expanded capabilities in that it utilizes the output from the Subalpine Water Balance Model (Leaf and Brink 1973b) to simulate both immediate and long-term effects of forest and watershed management on the water resource. Considerable flexibility is provided for simulating alternative silvicultural systems.

All but two of the subroutines in the core of the Subalpine Water Balance Model are used by the Land Use Model without significant changes; they are not discussed here, therefore, but are listed in Appendix II. Complete descriptions of the unrevised routines are also given in Leaf and Brink (1973a,b). Two subroutines, EVTRAN and CANVAP, were extensively revised as discussed later in this report. A "time-trend package" has been developed which simulates the long-term changes in the primary hydrologic variables. These variables are expressed in terms of accepted silvicultural concepts as described in this report.

In developing the Land Use Model, it was necessary to restructure the Subalpine Water Balance Model to make it the core system of a more versatile planning tool. The analytical framework of the Water Balance Model is a watershed divided into subunits defined by homogeneous environmental characteristics (slope, aspect, elevation, and forest cover composition and density). Hydrologic responses are computed for each subunit, then weighted according to their respective areas and combined to produce an overview of hydrologic system behavior on a watershed basis.

In the Land Use Model, the emphasis is shifted from the watershed to a "planning unit" of any size, which has all of the inherent characteristics of the hydrologic subunits discussed above, but which also accommodates the objectives of management. The Land Use Model is designed to simulate the effects of combinations of timber harvesting and weather modification in order to develop management strategies for planning intervals. These planning intervals can vary from a few years to the rotation age of subalpine forests (120 years and longer).

Management strategies may subdivide a given planning unit into as many as eight distinct areas or "response units" of any size, which may be managed independently at varying points in time during the planning interval. Provision is also made so that different cutting practices may be imposed on the response units, and finally, any number of cuttings may be made on a given response unit at specified years during the planning interval.

Hydrologic integrity is maintained as management strategies are formulated, since all interactions between the various response units are accounted for in both time and space. Moreover, the overall hydrologic effects resulting from each management decision on the planning unit are projected to the end of the planning interval as though that decision were the final one in the strategy. Thus, the singular effects of each decision can be evaluated.

Table 1 compares the capabilities of the Subalpine Water Balance Model described by Leaf and Brink (1973a,b) and the Land Use Model described in this report.

Table 1.—Comparison of Subalpine Water Balance Model with Land Use Model

Factor	WBMODEL	LUMOD
Desired output	Watershed	Planning Unit
Secondary output	Subunit	Region
Method of computation	Subunits combined to yield watershed response	Response units combined to yield response for planning unit
Time trends	None	Yes
Erosion and sediment yield	None	Yes
Multiple treatments	Limited	Full range

Detailed flow chart descriptions and pertinent theory follow.

Land Use Model Configuration (Program LUMOD)

Program LUMOD is the controlling routine for a series of five relatively independent steps in the Land Use Model. The Control Data Corporation's 6400 FΦRTRAN Extended[2] provides Overlay capabilities which are ideally suited to the operation of the model. If such capabilities are not available, however, the five steps could be performed in a series of computer runs with communication among them through the use of magnetic tape files.

Procedural Differences from Subalpine Water Balance Model (fig. 1)

Step 1 (and to some extent, step 3) corresponds to the Water Balance Model described by Leaf and Brink (1973b). Both models utilize the Water Balance routines as their core.

Since climatological observations are rarely available for the long periods of time simulated by the Land Use Model, step 2 extends the data base by a randomized selection of water years until the planning interval is completed.

Both models contain peripheral routines which handle input/output and supply the continuous and static conditions to the core. It is the peripheral routines which embody the different objectives of each model.

The Water Balance Model was designed to simulate the effects of management strategies on an entire watershed over relatively short periods of time. Thus, computer memory was used extensively

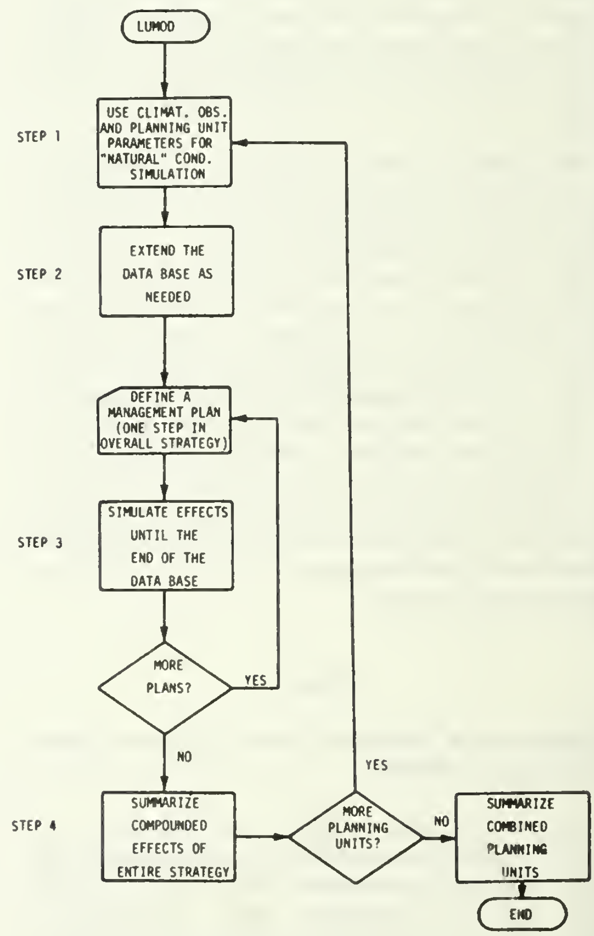

Figure 1.—General flow of Land Use Model.

for retaining simulated results until a composite overview was produced. Little use was made of online storage. In the Land Use Model, however, the objective has been to extend the capabilities of the Water Balance Model across a much longer time frame, with the added ability of introducing new management decisions at various points during the planning interval. Not only did we want the capacity to simulate each management decision independently, but we wanted to be able to view the interactive effects of a new decision on ones previously implemented. Moreover, an added objective was to simulate the effects of time, as demonstrated through reforestation, on each response unit at each point in the planning interval. It was therefore necessary to develop peripheral routines which were concerned with only one planning unit at one time. Use of computer memory was diminished as use of online storage increased to facilitate retention of: (1) input data for "multiple-passes"; and (2) voluminous output data which are summarized for the planning unit, watershed, and perhaps for a region comprising several watersheds.

Time Trends.—With the Water Balance routines collectively defined as the "core system" of the Land Use Model, it is useful to identify the time trends routines as "satellite" to the model, since they are accessed only once each water year as opposed to daily utilization of the "core system." Imposition of time trends on the simulation also required one additional means of communication (common block/TIME/) between routines.

Response Units

A planning unit of any desired size is subdivided in the management strategy into as many as eight distinct management areas, called "response units", seven of which may be subjected to timber harvesting practices during a planning interval. It should be emphasized that a response unit need not be made up of a single forest area, but represents a percentage of the area of the entire planning unit. For example, consider a response unit that is 40 percent of the planning unit and subjected to patch-cutting. Such a unit is not considered as one very large forest opening, but rather as an array of small openings distributed over the entire planning unit and occupying 40 percent of its area. One response unit out of the eight is retained in the "natural" state to aid in simulating the redistribution of precipitation or weather modification. If the entire planning unit is managed, however, the area-weighting factor for the "natural" response unit is set to zero and it no longer affects the results. It is retained in the simulation, regardless of its weight, since the time trend functions cause the managed response unit to approach the same state as the natural response unit. All of the time functions are defined for each managed response unit, and are totally independent of the functions for other response units.

Model Subroutines

The routines discussed below are time trend routines that compute changes in evapotranspiration, soil water, forest cover density, reflectivity, interception, snow redistribution, and erosion and sediment yield. Peripheral routines, which are meaningful only in implementing the hydrologic and silvicultural concepts on a computer, are not discussed in detail here, but can be found in the FORTRAN listings in Appendix II. The remainder of the Water Balance routines that comprise the core system of the Land Use Model are also described in Leaf and Brink (1973b).

Evapotranspiration.—Subroutines EVTRAN and CANVAP, as described by Leaf and Brink (1973b), have been extensively revised to account for the regrowth of forest stands after harvest cutting. In computing evapotranspiration, there is some evidence that water use during the growing season proceeds at rates limited only by available energy until the soil water is depleted to 50 percent of the maximum "available" for transpiration (field capacity index). Thereafter, transpiration is decreased in proportion to the amount of soil water below one-half of the field capacity index. In open or cutover areas, it was reasoned that the absence of dense vegetation and a highly developed root system reduces evapotranspiration below maximum rates unless the soil mantle is completely recharged. Thereafter, evapotranspiration is linearly decreased to zero at three-fourths of the field capacity index (fig. 2a). As forest vegetation is established on cutover areas and consumptive use increases, the relationship in fig. 2a changes until ultimately, as the forest cover is reestablished, it approaches the old-growth forest curve (fig. 2b). It is this phenomenon which is primarily responsible for diminishing water yield increases from timber harvesting. The rate at which this transition takes place depends upon forest species, climate, stand conditions, and the objectives of management.

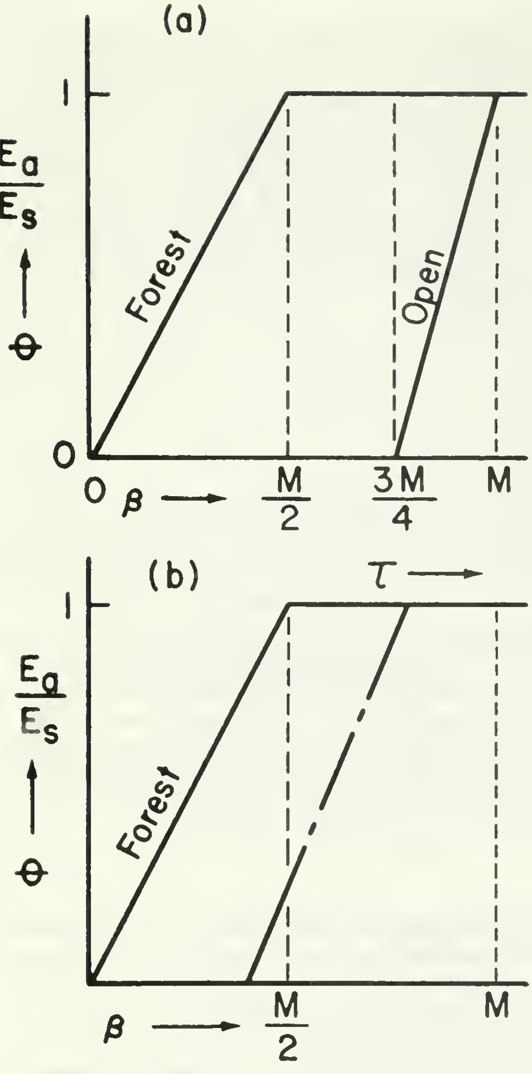

Figure 2.—Relationships showing evapotranspiration as a function of available soil water for: (a) old-growth forest and open conditions, and (b) old-growth forest and some intermediate forest cover condition several years after timber harvesting.

A general expression for the relations shown in figure 2 can be written as follows:

$$\Theta = \Delta\left[\beta - \left(\tau - \frac{1}{\Delta}\right)\right] = \Delta(\beta - \tau) + 1$$

$$\beta \geqslant \tau, \Theta = 1$$

$$\tau - \frac{1}{\Delta} < \beta < \tau \qquad [1]$$

$$\beta < \tau - \frac{1}{\Delta}, \Theta = 0$$

where θ = the ratio, $\frac{E_a}{E_s}$. E_a is the actual evapotranspiration rate and E_s is computed in this model by a modified version of the Hamon equation (Leaf and Brink 1973b).

β = the available soil water at any time. can vary between O and M, where M is the "field capacity index."

τ = the critical point at which available soil water begins to limit evapotranspiration. can vary between M/2 and M.

Δ = the slope of the relationship between E_a/E_s = 0 and 1.

In addition to complex factors such as ecological habitat and stand condition, the rate at which a forest reestablishes itself varies according to species. Discussions and background literature for the three major forest types of the subalpine zone are summarized by Alexander (1974). Of the three types, spruce-fir forests are the most difficult to regenerate, and therefore require the longest time for regrowth. Due to its seed production and growth habits, lodgepole pine does not require as much time to reestablish itself. Finally, since aspen normally regenerates from root suckers, a new stand promptly occupies the site, and on many sites growth exceeds that of associated conifers for decades.

Hydrologic changes resulting from timber harvest in the subalpine zone persist for many years. The Fool Creek watershed study in central Colorado (Hoover and Leaf 1967, Leaf 1975) resulted in water yield increases which did not show a significant decline more than 15 years after treatment. These results and results from timber management research were used to develop the time-trend relationships discussed below.

The procedure used in deriving the assumed time-trend equations was to: (1) establish plateaus, and maximum and minimum values for each hydrologic parameter; (2) establish critical values at which a transition takes place (that is, "when things begin to happen"); and (3) assume a functional relationship for each process which determines all intermediate values with respect to time.

Although the time-trend relationships may not be inherently correct, they are certainly plausible in light of our present understanding of long-term hydrologic phenomena. The validity of the equation should be determined by additional research.

Soil Water.—The critical point at which available soil water begins to limit evapotranspiration (τ) was assumed to vary with time and species (fig. 3):

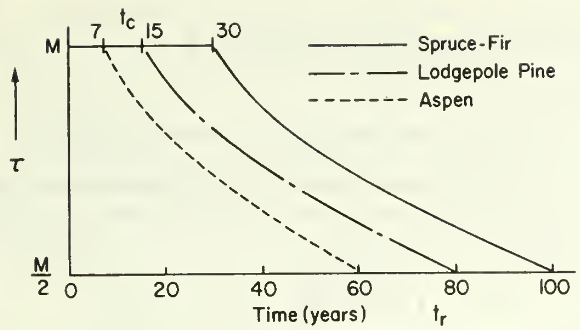

Figure 3.—Variation of τ with time and vegetation type.

$$\tau = Me^{-k(t - t_{c_1})} \qquad \begin{array}{l} \tau = M, t < t_{c_1} \\ \tau = M/2, t > t_r \end{array} \qquad [2]$$

where k = an index of the rate of decline of τ.
t_{c_1} = the time at which available soil water begins to limit evapotranspiration in years.
t_r = the time at which the hydrologic effect of timber harvesting becomes insignificant.

The parameters, k and t_{c_1}, vary according to forest species. When $t \leq t_{c_1}$, no adjustments are made in the soil water correction, since watershed experiments indicate that a correction is not warranted for a number of years after timber harvest. Assumed values of t_{c_1}, t_r, and k for the three species are:

Forest type	t_{c_1}	t_r	k
aspen	7 years	60 years	0.01
lodgepole pine	15 years	80 years	.01
spruce-fir	30 years	100 years	.01

The assumed relationship between Δ and τ is given by:

$$\Delta = \frac{4\tau}{M^2} \qquad [3]$$

Substituting equation [2] and [3] into equation [1] yields

$$\Theta = 4e^{-k(t - t_{c_1})} \left[\beta/M - e^{-k(t - t_{c_1})}\right] + 1 \qquad [4]$$

which is a general equation for θ as a function of forest cover type, field capacity index, and time.

Forest Cover Density.—Forest cover density plays an important role in the simulation model. It is the major descriptive parameter of the form, structure, and arrangement of forest stands, and therefore controls the energy balance, interception, and evapotranspiration. Forest cover density as used in the Land Use Model is not defined as "canopy" or "crown closure," but rather as a parameter that describes the net effects of the vegetation on the transmission of solar radiation to the forest floor. Forest cover density varies according to crown closure, the vertical foliage distribution, species, season, and stocking (Reifsnyder and Lull 1965). Empirical relationships between various timber stand variables and percent radiation beneath the forest canopy (transmissivity coefficient) have been determined from field measurements (Miller 1959, Muller 1971). A similar relationship was derived for the three major subalpine forest species in the process of calibrating the model against observed snowmelt rates (Leaf and Brink 1973a) and from solar radiation transmission studies in central Colorado. The resulting equation from this work is given by

$$T = 0.19\, C_{dmx}^{-0.6} \qquad [5]$$

where T = the transmissivity of the forest canopy expressed as a decimal fraction of the amount of solar radiation available above the forest canopy.
C_{dmx} = the natural old-growth forest cover density (expressed as a decimal).

Combinations of C_{dmx} and T that were found acceptable during calibration of the model for lodgepole pine, aspen, and spruce-fir in central Colorado are summarized below:

Forest type	C_{dmx}	T
lodgepole pine	0.25-0.45	0.40-0.30
spruce-fir	0.50-0.65	0.30-0.25
aspen		
foliated	0.35	0.35
defoliated	0.20	0.50

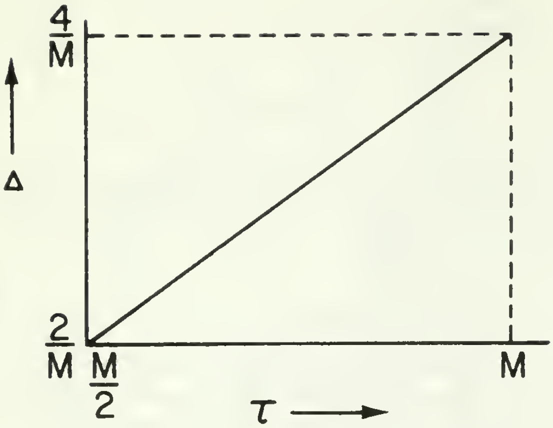

Figure 4.—Assumed variation of **Δ** *as a function of* τ.

As vegetation reoccupies cutover areas, forest cover density (C_d) increases with time until it reaches a maximum. Research has shown that the rate at which canopy development reaches this plateau depends on environmental conditions, stocking levels, and species. In coniferous forests, it can vary from 30 to more than 80 years; in aspen, growth and resultant canopy development is normally much more rapid due to the presence of an extensive root system at the time of stand regeneration (Pollard 1972). Accordingly, the following assumed relationship for C_d as a function of time was developed:

$$C_d = \frac{C_{dmx}}{\Phi^2}(t - t_{c_2})^2 \qquad t_{c_2} \leq t \leq \Phi \qquad [6]$$

where C_d = intermediate forest cover density expressed as a decimal.

Φ = the time in years from t_{c_2} at which maximum forest cover density is reached. This parameter was assumed to vary according to vegetation type as follows:

Forest type	Φ
lodgepole pine	40 years
spruce-fir	80 years
aspen	20 years and

t_{c_2} = critical time at which regeneration is sufficient to reestablish the stand when $t < t_{c_2}$, $C_d = 0$.

Reflectivity.—The relationship between reflectivity and forest cover density derived by Leaf and Brink (1973b) was modified as follows:

$$R_f = R_{fo}\exp\left[\frac{\omega C_{dmx}(t - t_{c_2})^2}{\Phi^2}\right] \qquad [7]$$

R_f = the reflectivity of the forest stand.

R_{fo} = the reflectivity of a forest opening (assumed herein as 0.5). When $t < t_{c_2}$, $R_f = 0.5$.

$\omega = 1.609\, C_{dmx}^{-1}$

Subroutine EVTRAN as used in the Land Use Model incorporates the effects of natural regeneration discussed above. As explained in the discussion for Subroutine TRENDS, the final computations of the adjustment factor for available soil water (equation 4) are performed in Subroutine EVTRAN, since they are dependent on the dynamic state of the soil mantle storage. The simulated potential evapotranspiration E_s is then adjusted for both available soil water and canopy reflectivity (equation 7) to produce the actual evapotranspiration E_a. It should be noted that equation 7 is constant over a water year and is recomputed after each growing season. Subroutine EVTRAN also alters the soil mantle storage according to the calculated evapotranspiration.

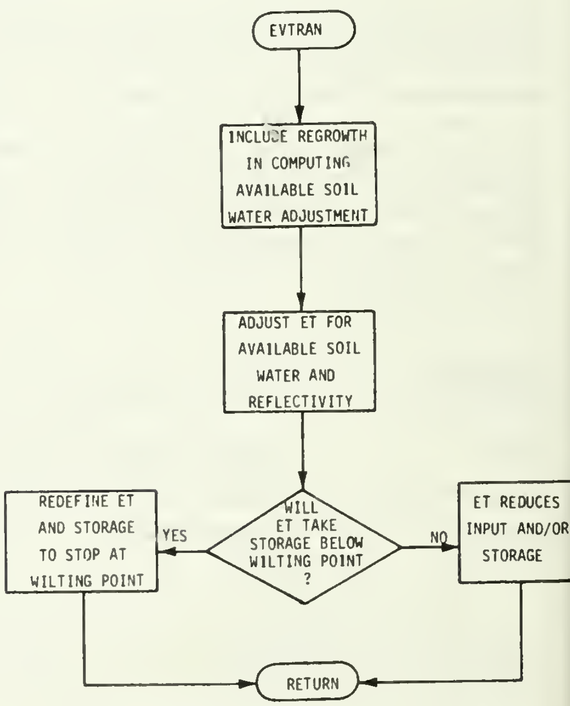

Figure 5.—Subroutine EVTRAN.

Interception.—Subroutine CANVAP (Leaf and Brink 1973b) is essentially unchanged except that allowance is made for snow interception as the forest regrows after harvest cutting, by weighting the effects of both snow evaporation from areas not occupied by trees (SNOWVAP in Leaf and Brink 1973b) and evaporation from intercepted snow. In the Land Use Model, evaporation from the snow surface and from intercepted snow is computed by the following rational relationships:

$$V_s = (1 - C_d)E_s \text{ and} \quad [8]$$

$$V_c = (1/C_d)E_s \quad [9]$$

where V_S = evaporation from the snow surface.

V_c = intercepted snow evaporation.

C_d = intermediate forest cover density expressed as a decimal, where $C_d < C_{dmx}$.

E_s = potential evapotranspiration as defined in equation [1].

When $C_d \geq \frac{C_{dmx}}{2}$, and snow rests on the canopy, evaporation is computed by equation [9]; when the canopy is free of snow, evaporation takes place according to equation [8]. However, when $0 < C_d < \frac{C_{dmx}}{2}$, both equations [8] and [9] are used as follows:

$$V_t = E_s \left[\frac{2}{C_{dmx}} + \left(1 - \frac{2C_d}{C_{dmx}}\right)\left(1 - C_d\right)\right] \quad [10]$$

V_t = combined evaporation from snow surface and intercepted snow in cutover areas.

We believe that equation [10] more realistically represents the evaporation from cutover areas that are not completely occupied by forest vegetation. When $C_d = 0$, $V_t = V_S$. By substituting equation [6] into equation [10], the following relationship is obtained:

$$V_t = E_s \left[\frac{2}{C_{dmx}} + \left(1 - \frac{2(t - t_c)^2}{\Phi^2}\right)\left(1 - \frac{C_{dmx}}{\Phi^2}\left\{t - t_c\right\}^2\right)\right] \quad [11]$$

which expresses V_t as a function of C_{dmx} and time.

Snow Redistribution.—Redistribution of snow as a result of patch-cutting is a significant factor influencing runoff. In lodgepole pine, this phenomenon is not diminished more than 30 years after timber harvest in spite of regrowth of trees and increased forest cover density (Hoover and Leaf 1967). Changes in natural snow accumulation patterns produced by patch-cutting will likely persist until the new crop of trees approaches the height of the surrounding forest. Accordingly, the following relationships were developed for simulating snow redistribution effects with time and forest species:

$$\rho = \rho_{mx} \exp\left[-k_1(t - t_{c_3})\right] \qquad t \leq t_{c_3}, \rho = \rho_{mx}; \quad t \leq t_{r_1}, \rho = 1 \quad [12]$$

where ρ = snow redistribution factor in the cutover area, which varies according to the silvicultural system used. For example, when 40 percent of the area is occupied by small openings 5 tree-heights in diameter, the winter snowpack is increased by 30 percent in the open and decreased 20 percent in the uncut forest.

ρ_{mx} = the redistribution factor immediately after timber harvesting.

k_1 = an index of the rate of decline of ρ.

t_{c_3} = the time at which forest regrowth begins to reduce snow redistribution in years.

t_{r_1} = the time at which forest regrowth causes snow redistribution to become insignificant.

The parameters k, t_{r_1}, and t_{c_3} vary according to forest species. When $t \leq t_{c_3}$, no adjustments are made in the redistribution, since field studies indicate that a correction is not warranted for several years after harvest cutting. Assumed values of t_{c_3}, t_{r_1}, and k_1 for the three subalpine types are summarized below:

Forest type	t_{c_3}	t_{r_1}	k_1
aspen	20 years	80 years	0.57
lodgepole pine	40 years	120 years	.04
spruce-fir	80 years	160 years	.04

It should be emphasized that redistribution is optimum only when timber is harvested in small patches (5-8 tree heights in diameter) that occupy less than 50 percent of a given planning unit. For other combinations of opening size and area, the redistribution factor should be reduced in proportion to the size of openings above and below 5 to 8 tree heights.

Individual-tree Selection Cutting.—In the Land Use Model, selection cutting corresponds to a reduction of the forest cover density (C_d). The degree that C_d is reduced depends on the characteristics of the stand and the volume of timber removed. If C_d is reduced by 50 percent or less from C_{dmx}, it is assumed that forest canopy density does not increase subsequent to cutting. However, if C_d is reduced more than 50 percent from C_{dmx}, equation [6] is used to simulate redevelopment of the canopy with time. Solving equation [6] for time yields:

$$t_\eta = \left(\frac{\Phi^2 C_d}{C_{dmx}}\right)^{1/2} + t_{c_2} \qquad [13]$$

If the degree to which thinning reduces C_{dmx} is given by η, then C_d is given by

$$C_d = C_{dmx}(1 - \eta)$$

Hence, equation [13] can be written as:

$$t_\eta = \Phi\left[(1 - \eta)\right]^{1/2} + t_{c_2} \qquad [14]$$

t = the time required to reach the reduced forest cover density as if the stand were initially patch-cut.

η = the degree that C_d is reduced from C_{dmx} (expressed as a decimal).

All of the time trend relationships are then initialized at t_η to simulate the hydrologic effects of selection cutting.

Subroutine TRENDS (Fig. 6).—This routine initially defines the time functions discussed above in terms of the boundary conditions supplied by Subroutine GBROUND. After each growing season, Subroutine TRENDS redefines the functions whenever necessary to incorporate the effects of time.

Subroutine GBOUND (Fig. 7).—Subroutine GBOUND is used to initialize the basic functions which comprise the time trends concept. These functions are expressed in terms of a wide variety

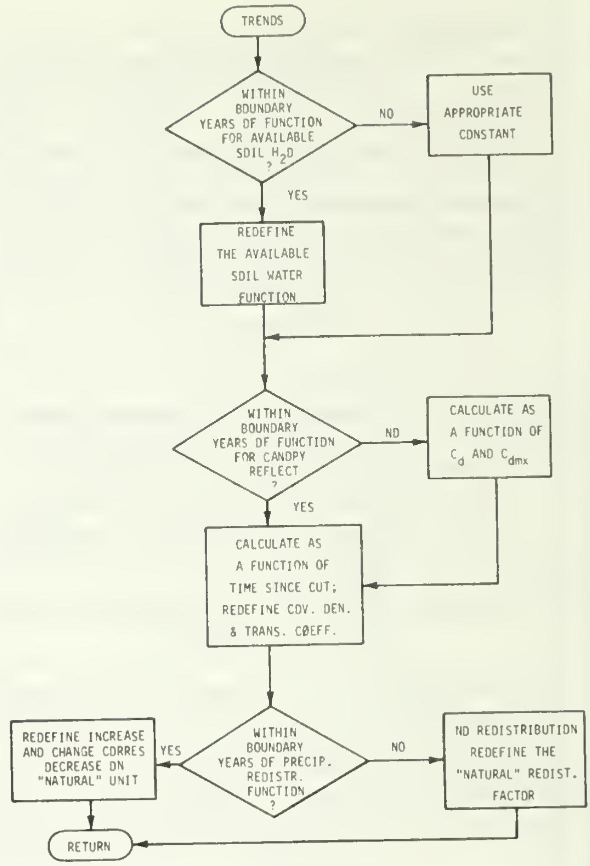

Figure 6.—Subroutine TRENDS.

of management practices. As trees regrow after cutting, the impact of the original removal is diminished until the hydrologic changes are no longer significant. Therefore, all parameters are specified in terms of the number of years following treatment (t_{cn}) when the effect of timber harvesting begins to diminish, and in terms of the number of years following treatment when hydrologic changes become negligible. If the parameters are not specified, the model assumes the values indicated in table 2, which vary according to vegetation type.

Subroutine GBOUND converts the boundary years into "real time" based on the year of treatment, and calculates the required parameters that are dependent solely on the boundary conditions.

Erosion and Sediment Yield

One of the environmental impacts associated with land use in the subalpine zone is erosion resulting from road construction. Accordingly, indices of onsite erosion and sediment yield downstream are

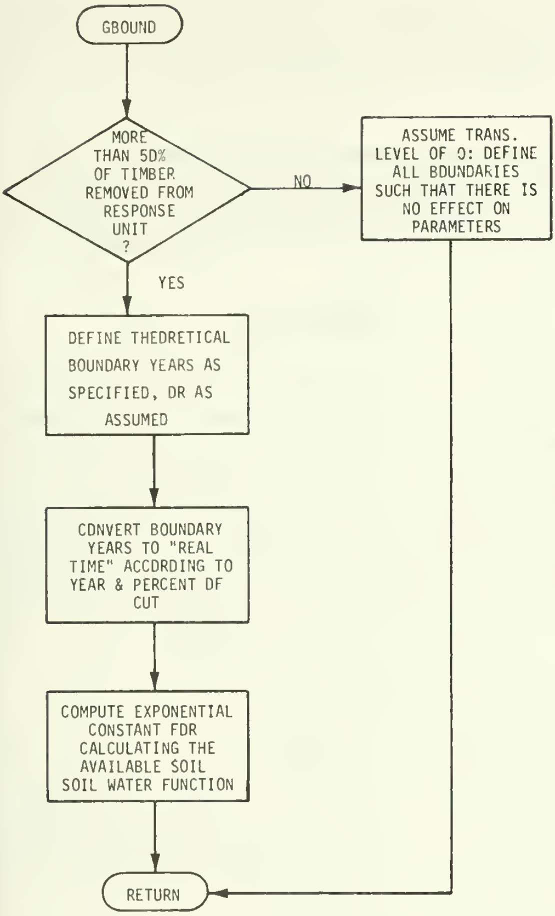

Figure 7.—Subroutine GBOUND.

computed by the Land Use Model. The erosion indices are computed from a system of empirical equations developed by Leaf (1974), based on field measurements of sediment yields in central Colorado (Leaf 1966, 1970, 1971), and a time trend equation proposed by Megahan (1974).

The model is based on measurements of accumulated sediment below a 1-square-mile experimental watershed. The sediment contained enough leaf litter and related organic debris so that the dry volumes of mineral soil occupied approximately 75 percent of the total volume of debris (dry unit weight approximately 85 lb/ft^3). Moreover, the data were obtained from a stable watershed (26 percent average slope) and a road system that was carefully constructed with a high standard of followup maintenance. Thus, although the equations may not be generally applicable throughout the Rocky Mountain Region, we believe they will serve as good first approximations of total sediment yield until more data become available.

Table 2.—Assumed boundary years for the time trend functions

Factor	Years before effect begins to diminish	Years until effect becomes negligible
Lodgepole pine		
Available soil water	15	80
Canopy reflectivity	0	40
Precipitation redistribution	40	120
Spruce-fir		
Available soil water	30	100
Canopy reflectivity	0	80
Precipitation redistribution	80	160
Aspen		
Available soil water	7	60
Canopy reflectivity	0	20
Precipitation redistribution	20	80

Sediment yields are expressed in terms of watershed characteristics, engineering design variables, and time. The equation for predicting cumulative onsite erosion is:

$$S = 0.12\ DEn \qquad [15]$$

where S = the total cumulative onsite erosion at time (t) after disturbance in ft^3.
D = the projected length of the disturbed area perpendicular to the road centerline in ft.
E = the unit cumulative onsite erosion at time (t) after disturbance in ft^3/acre.
n = the number of miles of road system.
$0.12 = 5{,}280 \frac{ft}{mi} \div 43{,}560 \frac{ft^2}{acre}$.

The projected length (D) is given by the equation

$$D = W \frac{W/2 \tan \nu}{\tan \Theta - \tan \nu} \qquad [16]$$

where W = the "effective" width of road in ft.
ν = steepness of the watershed sidelope in degrees.
$\Theta = \Theta_C = \Theta_F$ = the average angle of the cut and fill slopes in degrees.

The unit cumulative erosion (E) describes the erosion time trend, and can be expressed as

$$E = \epsilon_n t - S_o\ (e^{-k_2 t} - 1) \qquad [17]$$

where ϵ_n = an estimate of the long-term "normal" erosion rate on the undisturbed area in ft^3/acre. For central Colorado, (ϵ_n) is equal to 0.28 ft^3/acre based on 15 years of data collected from undisturbed watersheds.

S_0 = an index of the amount of soil available for erosion. This index is 201.3, based on statistical fitting to field measurements.

k_2 = an index of the rate of decline of erosion following disturbance, defined to be 0.085 by statistical fitting methods.

Sediment yields downstream expressed on a watershed basis are given by the equation

$$Q_s = \frac{S}{A} \qquad [18]$$

Equation [16] assumes balanced cut and fill (i.e., that the centerline bisects the road width). This is not usually the case, since the cross-section can vary from total cut to total fill in actual practice. However, we believe that a sufficiently accurate index of the total area disturbed can be obtained by estimating an "effective" width and average cut and fill slopes for the proposed road system. Such estimates require considerable judgment and a knowledge of the topography.

Three additional assumptions are behind equations [15] - [17]. First, it was assumed that the equations provide a better index of erosion than equations based on rainfall-derived erodibility indices. Such equations may be grossly in error, since they do not predict time trends, nor do they account for the effects of melting snow, which is responsible for much of the sediment yield from the subalpine zone in central Colorado. The second assumption was that onsite erosion is proportional to the area disturbed. Finally, it was assumed that the delivery ratio is constant for a given watershed size, regardless of the amount of area disturbed. These assumptions involve complex interactions between the hydrology, geology, and soil, which need to be verified by additional study.

Equation [18] is valid provided that the upstream drainage area does not exceed 1 square mile. Sediment yields at downstream points would be less, since delivery ratios are inversely related to watershed area. It should be noted that the model has not been programmed to compute delivery ratios for upstream areas greater than 1 square mile.

Because equations [15] - [18] describe sediment yields in terms of watershed slope and engineering design parameters, the land use planner has at least some latitude, subject to the limitations discussed above, in evaluating the potential short- and long-term impacts of alternative road systems required for various timber harvesting practices.

Subroutine SEDMOD (Fig. 8).—Equations [15] - [18] are appended to the Land Use Model as Subroutine SEDMOD. Program LUMOD provides the road design and sediment model parameters.

Applications

We have used the Land Use Model to simulate the long-term effects of forest and watershed management on the South Tongue River in the Bighorn National Forest (fig. 9). Elevations on the timbered portions of this drainage basin vary from approximately 8,000 to 8,900 ft. msl. Soils are derived from granitic rocks; virtually all of the forest cover is lodgepole pine. To illustrate how the model has been used, results from the analysis of

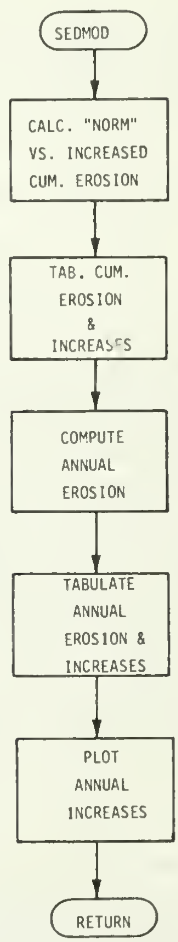

Figure 8.—Subroutine SEDMOD.

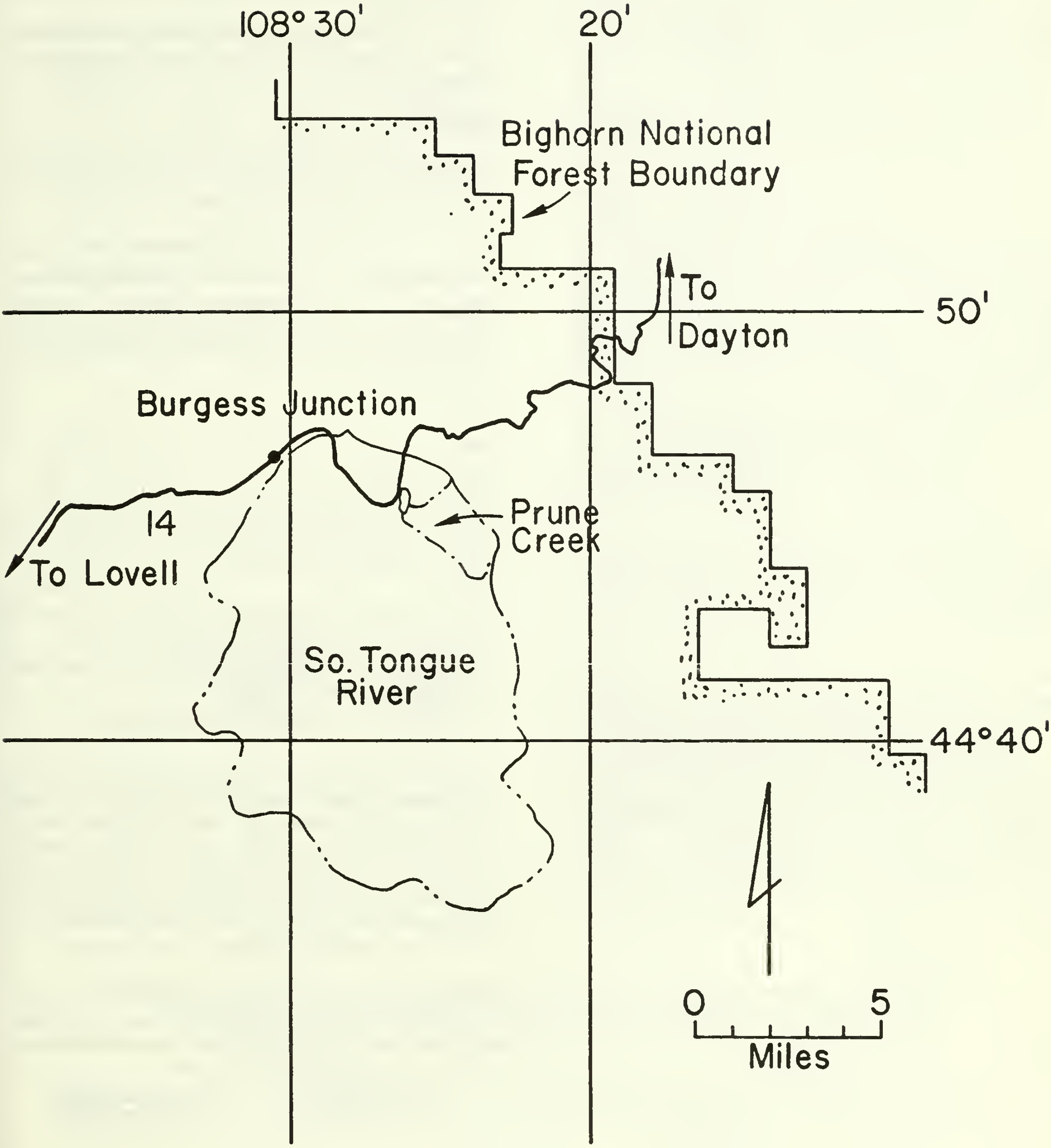

Figure 9.—Location map for South Tongue River, Bighorn National Forest.

one planning unit will be summarized here. Average values for pertinent geographic and hydrologic characteristics of a typical forested watershed in the South Tongue River drainage basin are:[3] area, 640 acres; elevation, 8,480 ft.; aspect, WSW; slope, 17%; C_{dmx}, 40%; peak snowpack water equivalent, 15.5 in.; annual precipitation, 29.6 in.; evapotranspiration, 15.8 in.; annual runoff, 13.8 in.

In addition to improving water yield, the management strategy selected for this example is compatible with wildlife habitat improvement and timber production. Under this strategy, the old-growth timber would be harvested so that approximately 40 percent of the planning unit area would be occupied by small openings — five to eight times tree height. Forest openings would be constructed in a balanced and unified pattern that is visually compatible with the natural landscape. The openings would be permanently maintained by clearing the natural reproduction at 30-year intervals after the initial patch-cut.

The remaining 60 percent of the planning unit area would be retained in continuous forest cover. However, trees would also be removed from this area on an individual tree basis at 30-year intervals so that the old-growth is gradually converted into a broad-aged stand.

[3]*Based on hydrologic simulation analyses of the effects of timber harvesting on Prune Creek, a 2,461-acre tributary of the South Tongue River (see fig. 9.).*

Table 3.—Projected changes in water yield resulting from timber harvesting, South Tongue River Planning Unit, Bighorn National Forest

Interval (Years)	Water yield increase, by treatment I	II	III	IV
	Inches			
0-10	+1.58			
11-20	+1.87			
21-30	+1.15			
31-40	+ .85	+1.59		
41-50	+ .71	+1.78		
51-60	+ .60	+1.54		
61-70	+ .38		+2.97	
71-80	+ .10		+2.41	
81-90	+ .04		+1.93	
91-100	- .05			+2.92
101-110	- .02			+2.75
111-120	- .01			+1.79

The simulated management strategy essentially follows the recommendations published by Alexander (1972), which are keyed to stand descriptions, insect and disease problems, and windfall risk situations.

The management strategy would maintain a vigorous and productive forest cover throughout the planning interval.

Runoff Increases

The diagram below illustrates the management strategy selected for this example:

Management strategy	Response unit (percent of planning unit area) 1 (40%)	2 (30%)	3 (30%)
Patch 1st yr.[1]	X		
Select 31st yr.[2]		X	
Clear[3]	X		
Select 61st yr.[2]		X	X
Clear[3]	X		
Clear 91st yr.[3]	X		
Select[2]			X

[1]*Forty percent of planning unit area occupied by openings 5 to 8 tree-heights in diameter.*
[2]*Individual-tree selection cut so that forest cover density (C_d) is reduced 50 percent.*
[3]*Clear regrowth from permanent openings.*

Projected 10-year mean runoff increases under this management strategy are summarized in table 3. The increases above the heavy diagonal line at any given time represent the overall response resulting from preceding management decisions. The data below the line reflect the singular effects of the initial patch-cut on 40 percent of the planning unit, as if it were the final decision in the strategy.

Water yields are improved throughout the planning interval, with the highest increases occuring after Treatment III. The projected runoff increases during each treatment interval are:

Treatment	Runoff increase
	Percent
I	11.1
II	11.9
III	17.7
IV	18.0

Apparently, the effect of the intial patch-cut persists for at least 60 and perhaps 70 years. Thereafter, the effect on water yield becomes negligible for all practical purposes.

Seasonal Distribution of Water Yields

The projected effects of the management strategy on distribution of water available for streamflow are summarized in table 4. These values represent increments of generated runoff, not routed streamflow. Hence, the effects of watershed storage must be considered in interpreting the data.

As seen in table 4, inputs from snowmelt are significantly increased during the April 16-30 and May 1-15 intervals, and decreased in June. Minor inputs to streamflow also occur in July, as compared to no input in the natural state, due to the less favorable hydrologic condition of the watershed.

Peak Flows

The hydrologic analysis in this example indicates that peak flows will be changed little if at all under the proposed management strategy. However, seasonal peaks would occur approximately 9 days earlier:

Treatment	Change in peak 7-day generated runoff	Change in timing
	Inches	*Days*
I	-0.2	-9
II	0	-9
III	+ .3	-9
IV	+ .4	-10

The projected overall effect of the proposed management strategy on runoff timing and peak flows would be to increase snowmelt and resultant streamflow in April and May. This accelerated input would enlarge early spring flows and cause the hydrograph to peak approximately 1 week earlier throughout the planning interval. Annual peak flows would not be increased, however, and runoff on the recession side of the hydrograph during the summer months may be slightly diminished.

Erosion and Sediment Yield

It is assumed that the proposed logging operation on the planning unit would require the equivalent of approximately 12 miles of road system, including all spur roads and landings. Because most of the disturbed area would be occupied by roads, it can be described in terms of road design variables, which have the following characteristics based on watershed side slopes averaging 17 percent:

"effective width" = 14 feet
average cut and fill slopes = 1½:1
width of disturbed area = 19 feet (from equation [16])
area disturbed per mile = 2.3 acres

The total area disturbed on the 1-square-mile planning unit is approximately 28 acres. For the purposes of this example, it is assumed that the entire road system would be constructed before logging operations on the planning unit. Thus most of the impact from road construction would take place during the first 30-year treatment interval.

The projected 10-year mean erosion increases produced by the proposed road system are summarized in table 5. Erosion on the 28 acres disturbed would increase 631 ft^3 above the untreated norm of 3.8 ft^3 immediately after the road construction, then decrease to less than 1 ft^3 above the norm after

Table 4.—Projected changes in distribution of water available for streamflow resulting from timber harvesting. South Tongue River Planning Unit, Bighorn National Forest

Runoff interval	Natural generated runoff	Average change in generated runoff, by treatment I	II	III	IV
		Inches			
April 16-30	0.1	+0.9	+0.7	+1.2	+0.5
May 1-15	1.7	+2.1	+2.5	+2.2	+3.1
May 16-31	5.9	+ .6	+ .3	+ .5	+1.3
June 1-15	5.6	-3.0	-2.7	-2.5	-3.1
June 16-30	.7	- .4	- .3	- .5	- .5
July 1-15	0	+ .1	+ .1	+ .1	+ .1

90 years. It is expected that after the first 30 years, increased erosion would be one-fifth of that immediately after road construction. By 60 years, it would be one-seventieth. Ratios of increased erosion on the disturbed area to the norm before road construction for each 30-year treatment interval are tabulated below.

Treatment	Ratio
	(Increase/undisturbed norm)
I	43.4
II	3.4
III	.3
IV	.1

Although a 40-fold increase in on-site erosion appears high at first, it must be weighed against the typically minimal erosion on subalpine watersheds. Whether or not the increased erosion and sediment yield are excessive would depend on local requirements for water quality and fisheries. On Fool Creek, in central Colorado, no detrimental effects on the land resource or water quality were observed in spite of the fact that on-site erosion was increased by approximately a factor of 60 immediately after road construction. This empirical model is based on data obtained from a carefully constructed road system and a high standard of followup maintenance, however. Any application of the model in its present form should presume similar standards of construction and maintenance.

Conclusion

Validation of the Subalpine Land Use Model will require additional data on long-term responses. In the meantime, we believe that the output from the model will produce the type of information land use planners need in order to make difficult management decisions. The ability of the Subalpine Land Use Model and other similar models to integrate complex forest and water systems makes them unique and powerful tools for evaluating the hydrologic effects of a broad array of land-use schemes in the subalpine zone. A user's guide for the model follows in Appendix I. A complete listing of the model is summarized in Appendix II.

Table 5.—Projected increases[1] in on-site erosion resulting from road construction. South Tongue River Planning Unit, Bighorn National Forest

Interval (years)	Average erosion increase,[2] by treatment I	II	III	IV
	Cubic feet			
1-10	631			
11-20	270			
21-30	115			
31-40		49		
41-50		21		
51-60		9		
61-70			4	
71-80			2	
81-90			1	
91-100				<1
101-110				
111-120				

[1]*Assumptions:*
1. *Area disturbed by road system = 28 acres.*
2. *Approximate unit weight of sediment = 85 lb/ft.³.*

[2]*Untreated norm = 3.8 ft³.*

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APPENDIX I: USER'S GUIDE FOR SUBALPINE LAND USE MODEL

INTRODUCTION

This brief user's guide describes the input parameters necessary for the operation of the Subalpine Land Use Model (LUMOD). The parameter cards are discussed in the same order as that of the parameter card deck; thus, by preparing the cards in this step-by-step method, the deck will be in the proper order. The guide provides the card columns in which the parameter value is to be punched, as well as the format by which it is read. This guide is intended for use by those primarily concerned with application of the model; it does not provide any computer systems information and, therefore, is of limited value to programers or others who are computer-oriented.

The general flow of the model is as follows:

Step 1. Proofread the parameter card deck.

Step 2. Simulate the natural conditions from the climatological data (original data base.)

Step 3. Extend the original data base by randomly selecting years until the desired planning interval is reached.

Step 4. Simulate the management strategy from the extended data base.

Step 5. Repeat steps 2-4 for all planning units.

Step 6. Combine the planning units into a regional summary.

The following optional recovery procedures are provided:

1. The extended data base may be saved on a magnetic tape named "SAVNEW."
2. The results of the management strategy which are used in the regional summary are punched on cards in the event of abnormal termination. Thus, if one planning unit simulation had been successfully completed and the job aborted during the next planning unit, the RECOVERY DECK could replace the planning unit deck for the completed unit on the next run. This avoids recomputing an entire planning unit, but still provides results for use in the regional summary.

REGION CARDS

REGIONAL PARAMETERS

Card		Columns	Contents	Format
1	Identified by the word REGION.	1-6	"REGION"	A6
	The number of years to be simulated is generally the rotation cycle for a species; the original data base will be extended to the specified number by randomly selecting and repeating original years.	11-15	Number of years ($1 \leq n \leq 165$)	I5
	Initialize the random number generator with a positive number.	16-20	Seed for random number generator	I5
	If a magnetic tape is provided under the name SAVNEW, the extended data base is captured and saved for either recovery purposes or for use with other management strategies.	21-25	Save the extended data base? (0 = NO, 1 = YES, 2 = copy SAVOLD to SAVNEW before adding new files)	I5
	As the management strategy for a planning unit is completed, the information for the composite regional output is stored on the recovery deck in case the run terminates abnormally. Under normal termination, the recovery deck is not punched, but if specified, it may be punched regardless of the mode of termination.	26-30	Punch the recovery deck even under normal termination? (0 = NO, 1 = YES)	I5
	The five principal hydrologic components may be independently selected for regional summary output.	31	Print generated runoff? (0 = NO, 1 = YES)	I1
		32	" precipitation? " "	"
		33	" evapotranspiration? " "	"
		34	" change in storage? " "	"
		35	" change in W. E.? " "	"
2	The region ID may contain 80 characters of information.	1-80	Region identification	8A10

PLANNING UNIT DECK

PLANNING UNIT ID

Card		Columns	Contents	Format
3	The planning unit ID may contain 60 characters of descriptive information.	1-60	Planning unit identification	6A10
	A two-digit number may be included to identify the recovery files. (It is always appended to the year as a decimal on the files.)	61-62	Optional identification number	I2
	If the driving variable data are on magnetic tape SAVOLD (saved on a previous run), specify 14. Otherwise, specify 10. (Note: if a tape of card images is used rather than a DATA DECK, the tape ID must be UNEDIT). With a 14, the remaining cards for NATURAL CONDITIONS must be omitted, since only the management strategy simulation is to be done.	64-65	Input file (10 or 14)	I2
	Indicate the percent of the total region area represented by this planning unit. (.15 = 15%)	66-68	Area Weight	F3.2
	If results are wanted at the planning unit level, specify the types of output. The codes are as follows (note 1,2&3 are available only as indicated):	69	Print detailed natural conditions? (0,1)	I1
		70	" list of years in extended data base? (0,1)	"
		71	" detailed managed conditions? (0,1)	"
		72	" list of time variant conditions? (0,1)	"
	0 - Not wanted	73	" generated runoff? (0,1,2,3)	"
	1 - Print the results	74	" precipitation? "	"
	2 - Print and plot only the differences	75	" evapotranspiration? "	"
	attributable to the management	76	" change in storage? "	"
	strategy	77	" change in W. E. "	"
	3 - Both 1 and 2.	78	" Bimonthly generated runoff? (0,2)	"
		79	" Peak W. E. and date? (0,2)	"
		80	" 7-day peak R.O. and starting date? (0,2)	"

NATURAL CONDITIONS

Card		Columns	Contents	Format
4	Identified by the words: SUBSTATION CONSTANTS	1-20	"SUBSTATION CONSTANTS"	2A10
	Transmissivity Coefficient: (If left blank, the model will supply a value as a function of the forest canopy density.)	21-25	Transmissivity Coefficient	F5.2

Estimate the decimal percent of the solar radiation reaching the canopy which is transmitted (allowed to pass through) to the snowpack and/or understory. The following table summarizes combinations of cover densities and transmissivity coefficients which were found acceptable during the calibration of the model in lodgepole pine and spruce-fir forest in central Colorado:

COVER DENSITY	TRANSMISSIVITY COEFF
0.00 (open)	1.00
.25	.45
.30, .35	.40
.40	.35
.45	.30
.55, .65	.25

	Columns	Contents	Format
Cover Density: Using the above table as a guide, estimate the forest canopy density as a decimal percent. (In the table, the values below 50 were for lodgepole pine, with those above 50 for spruce-fir.)	26-30	Cover Density	F5.2
Maximum Cover Density: Normally, this value is the same as number 5. But if a reduction in cover density is desired, this variable will allow adjustments to be made in the evapotranspiration and energy balance to compensate for that reduction.	31-35	Maximum Cover Density	F5.2
Vegetation Type - Indicate the forest canopy composition as lodgepole pine, spruce-fir, or deciduous.	40	1 = lodgepole, 2 = spruce-fir, 3 = deciduous	I1
Reflectivity Threshold Temperature: The model assumes that fresh snowfall increases the snowpack reflectivity according to internally controlled functions. However, field experience has shown that it is not necessarily increased during snow events where the daily maximum temperature varies according to aspect and elevation. The table below indicates some station characteristics and corresponding reflectivity threshold temperatures.	41-45	Reflectivity Threshold	F5.0

Card		Columns	Contents	Format
4	Relative Elevation / Aspect / °F. High / North, East / 32 Low-Middle / East / 40 Low-Middle / North / 45 All ranges / West / 45 Low / South / 60 Middle-High / South / 70			
	Melt Threshold Temperature - During initial snowpack accumulation, the model relies on a base temperature to stop melt when the mean daily temperature is below that base. A knowledge of the typical pattern of fall snow accumulation will guide the user in selecting a threshold temperature. Areas where the snowpack accumulates and melts frequently might indicate a low threshold (32°F.). High thresholds (40°-45°F.) may be assumed where the snowpack may yield some melt, but generally continues to build once started.	46-50	Melt Threshold	F5.0
	Available Soil Water - Estimate the soil mantle recharge requirement at which water is no longer available for transpiration. Examplea: -5.3; -7.8; -10.6 inches.	51-55	Available Soil Water	F5.2
	Deciduous Winter Values - The values defined in items 4, 5, and 6 represent the foliated conditions of a deciduous forest. Corresponding values must be supplied for the defoliated state and must represent the reduction in cover density between the seasons. The values used most frequently for cover density and maximum cover density on aspen stands in the central Rockies were .35 and .20 for the foliated and defoliated states, respectively. The model was allowed to generate the transmissivity coefficients as a function of those cover densities.	56-60 61-65 66-70	Deciduous Winter trans. coeff " " cov. den. " " max. cov. den.	F5.2 F5.2 F5.2
	Latitude - Select 38°, 40°, 42°, or 44°	72-73	Latitude (38,40,42, or 44)	I2
	Aspect - Leave blank for a horizontal surface, or select N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, OR NNW	75-77	Aspect (Left-justified)	A3
	Slope - Leave blank for a horizontal surface, or select 10%, 20%, 30%, or 40%	79-80	Slope (10,20,30, or 40)	I2
5	Identified by the words INITIAL CONDITIONS, this card provides these conditions on Oct 1 of the first water year:	1-20	"INITIAL CONDITIONS"	2A10
	Initial Snowpack Tempersture, °C.	21-25	Snowpack Temperature	F5.2
	Initial Snowpack Water Equivalent, inches	26-30	Snowpack Water Equivalent	F5.2
	Initial Recharge Requirement, inches	31-35	Recharge Requirement	F5.2
6	Identified by the words: DAILY ET	1-10	"DAILY ET"	A10
	Average Daily Evapotranspiration - Obtain estimates of the average daily potential evapotranspiration in inches for each month.	21-25 26-30 31-35 ° ° ° 76-80	Average daily ET for Jan " " " " Feb " " " " Mar " " " " Dec	F5.2 " " "
7	Identified by the words AIR TEMP COEFF + ADJ	1-20	"AIR TEMP COEFF + ADJ"	2A10
	Air Temperature Correlation Coefficients - Supply the correlation coefficients for predicting the daily extreme temperatures in °F. from a base station, where the coefficients A and B are of the form,	21-25 26-30 31-35	A_{MAX} B_{MAX} A_{MIN}	F5.3 " "
	$T_{subunit} = A + B(T_{base})$	36-40	B_{MIN}	"
	If the entire basin is being considered as a unit with observed extremes available, the coefficients would be 0.0 and 1.0, respectively. Examples: Maximum A = 4.779 B = 0.907 Minimum A = 0.698 B = 1.023			
	Specify a post-peak precip adjustment, if desired. Example 1.15 = 15% increase.	41-45	Post-peak precip adjustment	F5.3

Card		Columns	Contents	Format
8	Identified by the word: FORMAT	1-6	"FORMAT"	A6
	Specify the format for reading a data card. All six input items (month, day, year, max temp, min temp, and precip.) must be read by F formats. Read the date variables by F2.0	7-70	Variable Format (include parenthesis)	6A10,A4
	Specify the file number (or data deck number) if more than one set of data is included.	72-73	File number on "UNEDIT"	I2
	Specify the relative order on the card for the month.	75	Relative order for month	I1
	" " " " " " " " " day.	76	" " " day	"
	" " " " " " " " " year.	77	" " " year	"
	" " " " " " " " " max temp.	78	" " " max temp	"
	" " " " " " " " " min temp.	79	" " " min temp	"
	" " " " " " " " " precip.	80	" " " precip	"
	Example: If the items were ordered year, month, day, precip, temp max, and temp min, the relative order would be 231564.			
9	Identified by the words: SPECIFIED CONDITIONS. Include one card for each water year to be simulated.	1-20	"SPECIFIED CONDITIONS"	2A10
	Specify the observed peak water equivalent.	21-25	Observed peak water equivalent	F5.2
	Specify the date of the observed peak W.E.	32-37	Date of peak W.E. (MMDDYY)	3I2
	Specify the date by which the pack must be isothermal.	39-44	Isothermal date (MMDDYY)	3I2
10	Identified by the words: END OF NATURAL COND.	1-20	"END OF NATURAL COND."	2A10

MANAGEMENT STRATEGY

Note: The results from simulating natural conditions prescribed by the above cards are used repeatedly in simulating each of the management plans which make up the management strategy. Thus, the above cards are included only once, and each step (management plan) in the management strategy is described on a card as explained below. The cards which comprise the strategy are collectively termed the management strategy deck.

Card		Columns	Contents	Format
11a	Timber harvesting, Identified by the words: MANAGEMENT PLAN	1-20	"MANAGEMENT PLAN"	2A10
	A 1-5 digit non-zero response unit (managed area) number must be supplied. If more than one area is to be managed, unique numbers (not necessarily sequential) must be assigned to each of them.	21-25	Response unit number	I5
	Specify the year of initial timber harvest	28-30	Year of cut	I3
	Specify the percent of the total planning unit area represented by this response unit. (.15 = 15%)	31-35	Area weight	F5.0
	Specify the percent of the area of the response unit which is subjected to timber harvesting. 1.00 implies a complete removal of forest cover and the canopy will be reestablished with time; .99-.51 implies a partial removal of forest cover with the canopy being reestablished with time; and .50-.01 implies a reduction in the forest cover which does not permit an increase in canopy density subsequent to the initial cut.	36-40	Percent cut	F5.0

Note: If all of the boundary conditions below are left blank, the assumed values for each of the hydrologic functions will be used. The boundaries are expressed in terms of the number of years since the initial cut. The lower boundary is the number of years that the cut area retains the characteristics of an opening if patch-cut, and the upper boundary is the required number of years before the cut area reacts as it did under natural conditions.

Card		Columns	Contents	Format
	Assumed Years: lodgepole / spruce-fir / aspen			
	Soil Water, Lower — 15 / 30 / 7	43-45	Lower boundary, soil water function	I3
	Upper — 80 / 100 / 60	48-50	Upper " , " " "	I3
	Cover Density, Lower — 0 / 0 / 0	53-55	Lower " , cover density function	I3
	Upper — 40 / 80 / 20	58-60	Upper " , " " "	I3
	Precip Redist, Lower — 40 / 80 / 20	63-65	Lower " , precip redist. "	I3
	Upper — 120 / 160 / 80	68-70	Upper " , " " "	I3
	Max increase due to precip redist. — 0.0 / 0.0 / 0.0 (An increase in precipitation of .30 would correspond to 5-8H patches which occupy 40% of the planning unit. In this situation, the snowpack is increased 30% in the openings and decreased 20% in the uncut forest. For other combinations of opening size and area, the redistribution factor should be adjusted accordingly.)	71-75	Max increase due to precip redist.	F5.0
	If a desired cover density is known, rather than a percent cut (col 36-40), specify the desired cover density and the model will calculate the percent cut.	76-80	Desired cover density (col 36-40 must be blank if this is included)	F5.0
11b	Weather modification, Identified by the words: MANAGEMENT PLAN	1-20	"MANAGEMENT PLAN"	2A10
	There is no response unit number since cloud seeding affects the entire planning unit.	21-25	Must be blank	
	Specify the year cloud seeding begins.	28-30	Year cloud seeding begins	I3
	Specify the year cloud seeding ends.	33-35	Year cloud seeding ends	I3
	Specify the month and day that cloud seeding starts in a given year.	37-40	Date seeding starts (MMDD)	2I2
	Specify the month and day that cloud seeding ends in a given year.	42-45	Date seeding ends (MMDD)	2I2
	Specify the percent increase in precip due to cloud seeding	46-47	Percent increase	F5.0

ROAD CONSTRUCTION

Card		Columns	Contents	Format
12	Identified by the words: ROAD CONSTRUCTION Note: The road construction card should contain the same year as a management plan.	1-20	"ROAD CONSTRUCTION"	2A10
	If a road construction card (or more than one) is included, the sediment yield model will execute. There are no options on its output, so if it is not wanted, exclude road construction cards.			
	Specify the year of construction.	28-30	Year of construction	I3
	Specify the 1) number of miles of road system	31-35	Miles of road	F5.0
	2) "effective" width of the road	36-40	Effective width of road	"
	3) index of the normal rate of erosion	41-45	Index, normal rate	"
	4) index of the soil available for erosion	46-50	Index, available soil	"
	5) index of the rate of decline of erosion	51-55	Index, rate of decline (positive number)	"
	6) average slope of the cut expressed as tan θ_C (.20 = 20%)	56-60	Slope of cut	"
	7) average slope of the fill expressed as tan θ_F (.20 = 20%)	61-65	Slope of fill	"
	8) average watershed sideslope on which the road is constructed	66-70	Slope of planning unit	"
13	Identified by the words: END OF STRATEGY	1-15	"END OF STRATEGY"	A210

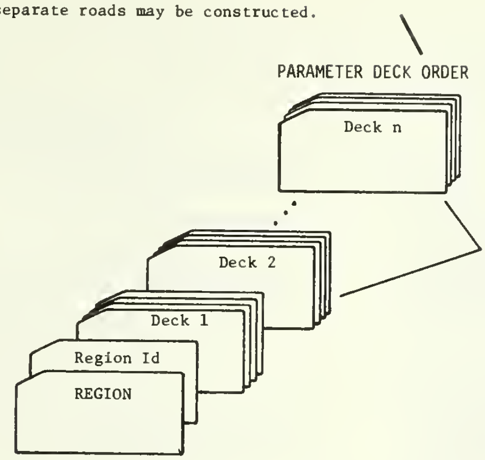
Note: The following are the limitations of the management strategy deck:

1. The cards must all be in order by the year specified in col 28-30. There may be more than one card for any given year, and within that year, no particular order is mandatory. For example, in year 75, the management strategy may require road construction (1 card) and two response units (2 cards). All 3 cards would have year 75.

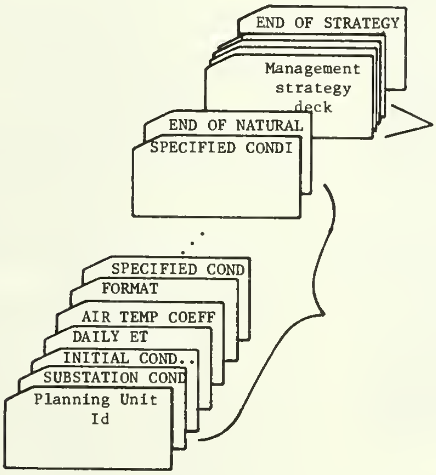
2. A maximum of 7 separate response units may be designated. However, an existing response unit may be reentered any number of times, within a limit of 11 individual managemental strategies.

3. A maximum of 11 separate roads may be constructed.

PARAMETER DECK ORDER



Decks 1,2,...n may be Planning Unit Decks, or Recovery Decks in any combination and in any order



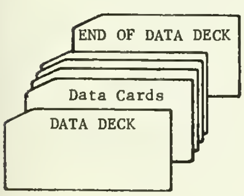
Management plans or road construction, in any order, but years must be in order

Omitted if input file is 14 (Extended Data Base saved on a previous run)

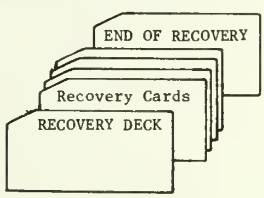
DATA DECK

The climatological data may be read from cards, if the card is preceded by a card containing the words: "DATA DECK" in columns 1-9, and terminated by a card containing the words: "END OF DATA DECK" in columns 1-16. This deck may appear anywhere in the parameter deck following the region cards (cards 1 & 2).

DATA DECK ORDER



RECOVERY DECK ORDER



RECOVERY DECK

In the event that a recovery deck is to be run, the recovery deck for any given planning unit may be identified from the punched output by one of the following methods:

1. Columns 5 and 6 contain the optional 2-digit ID discussed on the planning unit ID, or if not specified,

2. Column 37 will contain a 1, 2, 3, 4, or 5. There will be one card for each year in group 1, group 2, etc. Therefore, the end of the recovery deck in question will be the last card in the 5 group.

The deck must be preceded by a card containing the words: "RECOVERY DECK" in columns 1-13 and terminated by a card containing the words: "END OF RECOVERY DECK" in columns 1-20. (If the area weight is to be changed, punch the new weight in cols. 66-68 of the RECOVERY DECK card; otherwise, leave those columns blank.) The recovery deck replaces all cards pertaining to the planning unit in the parameter card deck (Planning unit deck.)

APPENDIX II: COMPLETE LISTING FOR SUBALPINE LAND USE MODEL

Program LUMOD

```
      OVERLAY (OLAYS,0,0)
      PROGRAM LUMOD (INPUT=512,OUTPUT=512,DATFIL=65,PLNFIL=65,
     1 PLNLST=512,PROOFO=65, PUNCH=512,SAVNEW=513,SAVOLO=513,SCRFIL=65,
     2 TIMFIL=512,UNEUIT=512,TAPE5=INPUT,TAPE6=OUTPUT,TAPE10=UNEOIT,
     3 TAPE11=OATFIL,TAPE12=PLNFIL,TAPE13= PUNCH,TAPE14=SAVOLO,
     4 TAPE15=SAVNEW,TAPE16=SCRFIL,TAPE17=TIMFIL,TAPE18=PLNLST,
     5 TAPE19=PROOFO)
C-----THIS IS THE CONTROLLING ROUTINE OF THE LAND USE PLANNING MODEL FOR
C----- THE SUBALPINE ZONE (WATER, TIMBER, SOIL)
C-----
C-----THE FILE BUFFER SIZES ARE LIMITED ABOVE TO SAVE MEMORY.  THOSE
C----- WHICH HANOLE FORMATTED READS AND WRITES ARE ALLOWED ABOUT HALF OF
C----- THEIR NORMAL BUFFER, BUT THOSE WHICH ARE ACCESSED ONLY BY BUFFER
C----- IN AND BUFFER OUT ARE LIMITED TO THE MINIMUM BUFFER SIZE
C-----
C-----THE REGION FILE (-RNGFIL-) WAS CHANGED TO THE PUNCH FILE (-PUNCH-)
C----- TO PROVIDE RECOVERY DECKS IN CASE OF ABNORMAL TERMINATION.  BY
C----- OPTION, THE USER MAY CAUSE THE DECK TO BE PUNCHED EVEN UNDER
C----- NORMAL TERMINATION, BUT IF THE OPTION IS NOT SPECIFIED, THE FILE
C----- IS REWOUND AND AN END OF FILE IS WRITTEN WHEN TERMINATING
C----- NORMALLY
C-----
C-----SEDIMENT YIELD, AN INDEPENDENT SIMULATION MODEL, HAS BEEN INCLUDED
C----- WITHIN THE GENERAL FLOW OF THE LAND USE MODEL.  HOWEVER, THE ONLY
C----- FUNCTION THAT IS PERFORMED BY THE LAND USE MODEL FOR SEDIMENT
C----- MODELING IS THAT OF PROOFREADING AND INPUT OF PARAMETERS.  ALL
C----- ROUTINES OF THE LAND USE MODEL WHICH WERE MODIFIED CONTAIN THE
C----- COMMON BLOCK /S/ (EXCEPT THIS MAIN PROGRAM WHICH CONTAINS THE
C----- DICTIONARY DEFINITIONS OF THE VARIABLES LISTED IN COMMON BLOCK
C----- /S/).  THE SEDIMENT MODEL ITSELF IS A SECONDARY OVERLAY WHICH IS
C----- LOADED AND EXECUTED BETWEEN THE EXECUTION OF THE MANAGEMENT
C----- SIMULATION AND THE PRINTING OF THE COMPOSITE PLANNING UNIT OUTPUT
C-----
C-----DICTIONARY
C       AIRTMC - THE MEAN AIRTEMPERATURE IN DEGREES CENTIGRADE
C       ALLOW = 0, DO NOT ALLOW ANY INTERCEPTION
C             = 1, INTERCEPTION ALLOWED
C       ALTYR - YEAR OF MANAGEMENT PLAN ON GIVEN RESPONSE UNIT
C       AVSOIL - SEDIMENT MODEL, AN INDEX OF THE AMOUNT OF SOIL AVAILABLE
C                 FOR EROSION
C       BIMNTH - ARRAY FOR ACCUMULATING BIMONTHLY TOTALS FOR GENERATED
C                 RUNOFF DURING THE SNOWMELT SEASON
C       BLOCK - DATA ARRAY FOR TRANSFER OF ONE ENTIRE YEAR TO AND/OR FROM
C                 TAPE FILES
C                 (1) - YEAR AND ID, YY.ID
C                 (2) - (373) - MAXIMUM TEMPERATURE
C                 (374) - (745) - MINIMUM TEMPERATURE
C                 (746) - (1117) - ACCUMULATED PRECIPITATION
C                 (1118) - (1489) - INCIDENT SHORTWAVE RADIATION
C                 (1490) - (1861) - ENERGY ADJUSTED EVAPOTRANSPIRATION
C                 (1862) - TRANSMISSIVITY COEFFICIENT
C                 (1863) - COVER DENSITY
C                 (1864) - MAXIMUM COVER DENSITY
C                 (1865) - VEGETATION TYPE
C                 (1866) - REFLECTIVITY THRESHOLD
C                 (1867) - MELT THRESHOLD
C                 (1868) - WILTING POINT
C                 (1869) - DECIDUOUS WINTER TRANSMISSIVITY COEFFICIENT
C                 (1870) - DECIDUOUS WINTER COVER DENSITY
C                 (1871) - DECIDUOUS WINTER MAXIMUM COVER DENSITY
C                 (1872) - SPECIFIED ISOTHERMAL DATE (PSEUDO-JULIAN)
C                 (1873) - SPECIFIED PEAK WATER EQUIVALENT DATE (PSEUDO
C                 JULIAN)
C                 (1874) - INITIAL WATER EQUIVALENT
C                 (1875) - INITIAL RECHARGE REQUIREMENT
C                 (1876) - YEARLY TOTAL GENERATED RUNOFF
C                 (1877) - YEARLY TOTAL EVAPOTRANSPIRATION
C                 (1878) - CHANGE IN RECHARGE REQUIREMENT OVER THE
C                 WATER YEAR
C                 (1879) - CHANGE IN THE SNOWPACK WATER EQUIVALENT OVER
C                 THE WATER YEAR
C                 (1880) - APRIL 16-30 GENERATED RUNOFF
C                 (1881) - MAY 1-15 GENERATED RUNOFF
C                 (1882) - MAY 16-31 GENERATED RUNOFF
C                 (1883) - JUNE 1-15 GENERATED RUNOFF
C                 (1884) - JUNE 16-30 GENERATED RUNOFF
C                 (1885) - JULY 1-15 GENERATED RUNOFF
C                 (1886) - ACTUAL PEAK WATER EQUIVALENT
C                 (1887) - ACTUAL PEAK WATER EQUIVALENT DATE (PSEUDO-
C                 JULIAN)
C                 (1888) - PEAK 7-DAY GENERATED RUNOFF
C                 (1889) - DATE OF FIRST DAY OF PEAK 7-DAY GENERATED
C                 RUNOFF
C       BOUND - THE BOUNDARIES ON THE TIME FUNCTIONS
C                 (1) - NUMBER OF YEARS BEFORE REGROWTH BEGINS TO
C                 INCREASE SOIL WATER USE
C                 I2) NUMBER OF YEARS WHEN REGROWTH IS COMPLETE AS FAR
C                 AS SOIL WATER USE IS CONCERNFD
C                 (3) - NUMBER OF YEARS BEFORE REGROWTH BEGINS TO ALTER
C                 THF COVER DENSITY AND CANOPY REFLECTIVITY
C                 (4) - NUMBER OF YEARS WHEN REGROWTH IS COMPLETE AS
C                 FAR AS CANOPY REFLFCTIVITY IS CONCERNED
C                 (4) - NUMBER OF YEARS BEFORE REGROWTH BEGINS TO ALTER
C                 THE PRECIP REDISTRIBUTION FACTORS
C                 (6) - NUMBER OF YEARS WHEN REGROWTH IS COMPLETE AS
C                 FAR AS PRECIP REDISTRIBUTION IS CONCERNED
C       CALDEF - THE CALORIE DEFICIT IS THE NUMBER OF CALORIES NEEDED
C                 TO BRING THE SNOWPACK TEMPERATURE TO ZERO DEGREES
C                 CENTIGRADE (NOTE SHOULD BE MADE THAT IS IS A POSITIVE
C                 QUANTITY)
C       CANREF - THE FACTOR FOR ADJUSTING THE EVAPOTRANSPIRATION FOR
C                 CANOPY DENSITY (RECOMPUTED EACH YEAR UNDER THE
C                 MANAGEMENT STRATEGY TO INCORPORATE THE EFFECTS OF
C                 REGROWTH)
C       COMAX - MAXIMUM COVER DENSITY ON THE PLANNING UNIT
C       COMAX2 - HALF OF -COMAX-.  USED AS THE CRITICAL POINT IN SFLECTION
C                 CUTTING TO DETERMINE WHETHER OR NOT THE WATFR BALANCE
C                 ROUTINES ARF TO BE ALTERED BY THF TIME TRFNDS
C       CHANGR - CHANGE IN THE RECHARGE REQUIREMENT OVER THF WATER YEAR
C       CHANGW - CHANGE IN THE SNOWPACK WATER EQUIVALENT OVER THF WATER
C                 YEAR
C       CONAV - THE TIME DEPENDENT CONSTANT FOR ADJUSTING EVAPOTRANSPIRA-
C                 TION FOR AVAILABLE SOIL WATER (RECOMPUTED EACH YEAR
C                 UNDER THE MANAGEMENT SIMULATION TO INCORPORATE THE
C                 EFFECTS OF REGROWTH)
C       COVDEN - THE COVER DENSITY IS THE FRACTION OF THE GROUND OR SNOW
C                 SURFACE SHADED FROM DIRECT SUNLIGHT OR RADIATION
C       CUT - THE PERCENT OF THE COVER DENSITY REMOVED (0.0 THROUGH 1.0).
C                 SEE -SPECCO-
C       DATE - MONTH, DAY
C       DATES - SAME AS -DATE- BUT FOR TWO DATES
C       DATIME - DATE AND TIME OF RUN IN ALPHANUMERIC FORMAT AS FOLLOWS
C                 MM.DD.YY  HH.MM.SS.
C       DCDMAX - THE WINTER VALUE FOR -COMAX- ON DECIDUOUS FORESTS
C       DECIDS - AN ARRAY USED IN WORKING WTIH DECIDUOUS FORESTS FOR
C                 RETAINING THE COVER DENSITY, MAXIMUM COVER DENSITY
C                 AND TRANSMISSIVITY COEFFICIENT FOR ONF SEASON WHILE
C                 THE OTHER IS BEING PROCESSFD.  (IN OTHER WORDS, WHILE
C                 OPERATING DURING THE SUMMER, THE WINTER VALUES ARE
C                 STORED.  LIKEWISE, IN THE WINTER, THE SUMMER VALUES
C                 ARE STORED.  LOCATION 1 IS FOR THE TRANSMISSIVITY
C                 COEFFICIENT, 2 IS FOR THE COVER DENSITY AND 3 IS FOR
C                 THE MAXIMUM COVER DENSITY)
C       DECLIN - SEDIMENT MODEL, AN INDEX OF DECLINE OF EROSION FOLLOWING
C                 DISTURBANCE
C       DECMAL - OPTIONAL TWO DIGIT INTEGER WHICH IDENTIFIES THE FILES ON
C                 -SAVNEW-.  EACH PLANNING UNIT MAY BE GIVEN AN ID
C                 WHICH IS THEN APPENDED AS A DECIMAL TO THF YEAR IN
C                 EACH BLOCK OF THE FILE.  THE NUMBERIC VALUE THUS
C                 BECOME YY.ID
C       DREADY = 0, DIFFUSION MODEL (SUBROUTINE DIFMOD) NOT INITIALIZED
C              = 1, DIFFUSION MODEL INITIALIZED AND READY FOR SNOWPACK
C                 TEMPERATURE SIMULATION
C              = -1, DIFFUSION MODEL MAY NOT BE USED
C       ETDALY - ARRAY OF DAILY AVERAGE EVAPOTRANSPIRATION FOR EACH MONTH
C       ETFROM = 1, EVAPORATION IS FROM THE CANOPY
C              = 2, EVAPORATION IS FROM THF SURFACE OF THE SNOWPACK
C              = 3, BOTH 1 AND 2
C              = 4, EVAPOTRANSPIRATION IS FROM SNOWMELT, RAIN OR THE
C                 SOIL MANTLE STORAGE
C       ETO - ARRAY OF POTENTIAL EVAPOTRANSPIRATION VALUES (ALREADY
C                 ADJUSTED FOR SLOPE, ASPECT, ETC) FOR AN ENTIRE YEAR
C       EVAPTR - WHEN FIRST RECEIVED, THIS VARIABLE IS THE POTENTIAL
C                 FVAPOTRANSPIRATION AS COMPUTED BY THE HAMON METHOD
C                 AND ADJUSTED FOR AVAILABLE RADIATION.  AFTER ACTION
C                 IS TAKEN BY THE WATER BALANCE ROUTINES, THE ORIGINAL
C                 VALUE HAS BEEN ADJUSTED FURTHER BY THE METHODS
C                 DISCUSSED IN SUBROUTINES CANVAP, EVTRAN, AND SNOWVAP.
C                 IT THEN REPRESENTS THE EVAPOTRANSPIRATION DURING THIS
C                 INTERVAL
C       EXPK - THE -K- FROM THE TIME FUNCTION FOR COMPUTING THE AVAILABLE
C                 SOIL WATER ADJUSTMENT FACTOR
C       EXPK1 - THE -K1- FROM THE TIME FUNCTION FOR COMPUTING THE PRECIP
C                 REDISTRIBUTION FACTOR
C       FORNXT - A UTILITY ARRAY WHOSE ONLY PURPOSE IS FOR READING AND
C                 WRITING CURRENT MODEL CONDITIONS ON THE SCRATCH
C                 FILE.  IT IS EQUIVALENCED WITH THE ENTIRF COMMON
C                 BLOCK /M/.  SEE -L4NXT-
C       FRACTN -THE FRACTIONAL PART NEEDED IN THE INTERPOLATION BETWEEN
C                 TABLE VALUES IN THE COMPUTATION DF THE RADIATION
C       GENRO - DAILY GENERATED RUNOFF
C       INFILE = 10, DATA IS ON FILE -UNEDIT-.  SEE -NFILE-
C              = 14, DATA IS ON FILE -SAVOLO- IN STANDARD MODEL FORMAT
C       ISOTRM - THE MANDATORY ISOTHERMAL DATE (NOTE, MUST BE IN THF
C                 CALENDAR YEAR WICH CORRESPONDS TO THE WATER YEAR.
C                 THAT IS, IT MUST BE BETWEEN JAN 1 AND SEP 30)
C       LAST1 - RETAINS THE OLD VALUE OF -NEXTYR- WHEN A NEW ONE IS READ
C       LCOPY - ARRAY FOR COPYING LINES FROM ONE FILE TO ANOTHER
C       LINES - LINE COUNTER
C       NAME - AN ALPHANUMERIC IDENTIFIER USED PRIMARILY TO VERIFY THE
C                 PARAMETER CARD ORDER.  ALSO USED IN ARRAY FORM AS
C                 IDENTIFIERS FOR THE PRINTOUTS DURING THE PLANNING
C                 UNIT AND REGION PHASES
C       NDAY - THE PSEUDO JULIAN WATER YEAR DATE (1 = OCT 1)
C       NEXTYR - THE YEAR ON THE NEXT MANAGEMENT PLAN
C       NFILE - THE NUMBER OF THE FILE ON -UNEDIT- WHICH CONTAINS THE DATA
C                 FOR THIS PLANNING UNIT
C       NPLAN - THE NUMBER OF THIS PLAN IN THE SEQUENCE MAKING UP THE
C                 MANAGEMENT STRATEGY
C       NRMANG - A SWITCH INDICATING THE MODE OF OPFRATION (0 OR 1 IS FOR
C                 THE NORMAL SIMULATION, 2 FOR MANAGFMENT)
C       NROADS - SEDIMENT MODEL, THE NUMBER OF TIMES ROADS WERE
C                 CONSTRUCTED DURING A MANAGEMFNT STRATEGY PERIOD
C       NSAVED - NUMBER OF FILES WRITTEN ON -SAVNEW- DURING THE RUN
C       NUM - THE RFSPONSE UNIT CODE ON THE NFXT MANAGEMENT PLAN
C       NUNIT - THE NUMBER OF RFSPONSE UNITS AT ANY GIVEN POINT IN TIME
C       NYEARS - NUMBER OF YEARS FOR MANAGEMENT STRATEGY (IF THE ORIGINAL
C                 DATA BASE DOES NOT HAVE THIS NUMBER OF YFARS, IT WILL
C                 BE EXPANDED OR CONTRACTED AS NEEDED)
C       PARAM - AN ARRAY OF PARAMETERS READ FROM THE MANAGEMENT PLAN CARD
C                 (1) - RESPONSE UNIT WEIGHT
C                 (2) - PERCFNT CUT
C                 (3) - (8) - CORRESPONDS TO -BOUND(1) - (6)-
C                 (9) - MAXIMUM INCREASE IN PPT DUE TO REDISTRIBUTION
C       PEAKED = 0, THE PEAK WATER EQUIVALENT HAS NOT BEEN REACHED
C              = 1, THE PEAK WATFR EQUIVALENT HAS BEEN REACHED
C       PEAKRO - THE YEARLY 7 DAY PEAK RUNOFF
C       PEAKWE - THE YEARLY PEAK WATER EQUIVALENT
C       PEKDAT - THE SPECIFIED PEAK WATER EQUIVALENT DATE
C       PEKPPT - THE OBSERVED ACCUMULATED PRECIPITATION ON THE SPECIFIED
C                 PEAK WATER EQUIVALENT DATE
C       PHISQ - PHI SQUARED, USED IN THE TIME FUNCTIONS FOR COVER DENSITY
```

```
            AND CANOPY REFLECTIVITY
PLNOPT - ARRAY OF OUTPUT OPTIONS FOR PLANNING UNIT PHASE (0 = NO
            OUTPUT, 1 = PRINT OUTPUT)
            (1) - DETAILED YEARLY OUTPUT FOR NORMAL SIMULATION
            (2) - LIST OF YEARS IN ORIGINAL DATA BASE AND THOSE
                  GENERATED DURING EXTENSION OF THAT DATA BASE
            (3) - DETAILED YEARLY OUTPUT FOR MANAGEMENT
                  SIMULATION
            (4) - LIST OF CHANGES MADE BY THE TIME TRENDS
                  FUNCTIONS
           SUMMARIES FOR PLANNING UNIT (0=NO OUTPUT, 1=ACTUAL
            TOTALS, 2=DIFFERENCES AND PLOT OF DIFFERENCES,
            3=BOTH 1 AND 2)
            (5) - GENERATED RUNOFF
            (6) - PRECIPITATION
            (7) - EVAPOTRANSPIRATION
            (8) - CHANGE IN RECHARGE REQUIREMENT
            (9) - CHANGE IN SNOWPACK WATER EQUIVALENT
            (10)-(15) - BIMONTHLY GENERATED RUNOFF DIFFERENCES
            AND PLOTS (0=NONE WANTED, 2 IN (10) IMPLIES ALL)
            (16)-(17) - SNOWPACK PEAK WATER EQUIVALENT AND DATE,
            DIFFERENCES AND PLOTS (0=NEITHER WANTED, 2 IN (16)
            IMPLIES BOTH)
            (18)-(19) - PEAK 7-DAY GENERATED RUNOFF AND STARTING
            DATE, DIFFERENCES AND PLOTS (0=NEITHER WANTED, 2
            IN (18) IMPLIES BOTH)
PLUNIT - 60 CHARACTER NAME AND/OR DESCRIPTION OF THE PLANNING UNIT
POTENT - ARRAY OF POTENTIAL INCIDENT SHORTWAVE RADIATION VALUES AT
            APPROXIMATELY TWO WEEK INTERVALS THROUGH THE YEAR
POTRAD - THE INTERPOLATED VALUE SELECTED FROM -POTENT-
PPT - ARRAY OF ACCUMULATED PRECIPITATION FOR THE ENTIRE YEAR
PPTNOW - THE OBSERVED ACCUMULATED PRECIP UP TO THE DAY BEING
            PROCESSED
PRECIP - DAILY PRECIPITATION AMOUNT
PREWEQ - PREDICTED SNOWPACK WATER EQUIVALENT
RAD - ARRAY OF THE RADIATION (ALREADY ADJUSTED FOR SLOPE, ASPECT,
            ETC.) FOR THE ENTIRE YEAR
RADIN - RADIATION IN IS THE TOTAL INCIDENT SHORT WAVE RADIATION
RADLWN - NET LONG WAVE RADIATION IS THE ALGEBRAIC SUM OF THE LONG
            WAVE RADIATION FROM THE FOREST AND THE LONG WAVE
            RADIATION LOST BY THE SNOWPACK TO THE CANOPY
RADSUB - SUBSCRIPT USED IN THE CALCULATION OF -POTRAD-
RADSWN - THE CALORIC INPUT TO THE PACK BY THE NET SHORT WAVE
            RAUIATION
RATNRM - SEDIMENT MODEL, AN ESTIMATE OF THE LONG-TERM NORMAL
            EROSION RATE
RCHRGO - THE RECHARGE REQUIREMENT AT THE BEGINNING OF THE WATER
            YEAR
RDIST - THE FACTOR FOR REDISTRIBUTING THE PRECIP
RDMAX - THE MAXIMUM INCREASE IN PRECIP DUE TO REDISTRIBUTION
RECHRG - RECHARGE REQUIREMENT OR SOIL MANTLE STORAGE DEFICIT
RECOVR = 0, DO NOT PUNCH RECOVERY DECKS UNDER NORMAL TERMINATION
         1, PUNCH RECOVERY DECKS EVEN UNDER NORMAL TERMINATION
REGION - 80 CHARACTER NAME AND/OR DESCRIPTION OF REGION
REGOPT - ARRAY OF OUTPUT OPTIONS FOR REGIONAL PHASE (0 = NO
            OUTPUT, 1 = PRINT OUTPUT)
           SUMMARIES FOR REGIONAL PHASE
            (1) - GENERATED RUNOFF
            (2) - PRECIPITATION
            (3) - EVAPOTRANSPIRATION
            (4) - CHANGE IN RECHARGE REQUIREMENT
            (5) - CHANGE IN SNOWPACK WATER EQUIVALENT
REGROW(1,-) - SEE -CONAV-
      (2,-) - SEE -CANREF-
RO - ARRAY OF DAILY GENERATED RUNOFF FOR AN ENTIRE YEAR
ROADMI - SEDIMENT MODEL, THE NUMBER OF MILES OF ROAD CONSTRUCTED
ROADW - SEDIMENT MODEL, THE EFFECTIVE WIDTH OF THE ROAD
RUNUM - THE RESPONSE UNIT CODES
RUWT - THE PERCENT OF THE PLANNING UNIT REPRESENTED BY EACH
            RESPONSE UNIT
SAVE = 0, DO NOT SAVE THE EXTENDED DATA BASE
     = 1, SAVE THE EXTENDED DATA BASE ON -SAVNEW-.  (NOTE,
            -SAVNEW- IS NOT POSITIONED FOR THE SAVING OF THE FILE
            WITHIN THE RUN - THE USER MUST REWIND OR POSITION IT
            BEFORE EXECUTION.  THE LIST AT THE END OF THE RUN
            WILL INCLUDED ALL FILFS CURRENTLY ON -SAVNEW-)
     = 2, SAME AS 1 EXCEPT ALL OF THE FILES FROM -SAVOLD- ARE
            COPIED TO -SAVNEW- AFTER THE PROOFREADING PHASE AND
            BEFORE THE EXECUTION PHASE
SEDINC -THE PERCENT INCREASE IN PRECIP DUE TO CLOUD SEEDING
SEDRN2 - SEED FOR RANDOM NUMBER GENERATOR, USED IN EXTENDING THE
            ORIGINAL DATA BASE TO A SPECIFIED NUMBER OF YEARS
SEEDAT - THE DATES OF CLOUD SEEDING (MMDD THROUGH MMDD)
SEEDYR - THE YEARS OF CLOUD SEED
SEEDYR - THE YEARS OF CLOUD SEEDING (Y1 THROUGH Y2)
SIMTM1 - AN ARRAY USED PRIMARILY IN SUBROUTINE DIFMOD IN THE
            SIMULATION OF THE AVERAGE SNOWPACK TEMPERATURE
SLPASP - THE SLOPE/ASPECT ADJUSTMENT FACTORS FOR TRANSLATING THE
            VALUES IN -POTENT- TO THE INDIVIDUAL STATION
SPECCO - IF THE MANAGEMENT PLAN SPECIFIES A COVER DENSITY RATHER
            THAN A PERCENT CUT (SEE -CUT-), THE MODEL WILL
            CALCULATE THE PERCENT OF THE COVER DENSITY THAT MUST
            BE REMOVED TO ACHIEVE THE SPECIFIED COVER DENSITY
SUMMER - THE POST-PEAK PRECIPITATION ADJUSTMENT FACTOR (EXPRESSED
            AS A DECIMAL PERCENT OF THE SUMMER BASE STATION
            PRECIP.  EXAMPLE 1.05)
TANCUT - SEDIMENT MODEL, THE SLOPE OF THE CUT IN ROAD CONSTRUCTION
            AS A PERCENT
TANFIL - SEDIMENT MODEL, THE SLOPE OF THE FILL IN ROAD
            CONSTRUCTION AS A PERCENT
TANRHO - SEDIMENT MODEL, THE AVERAGE SLOPE AS A PERCENT ON WHICH A
            ROAD IS CONSTRUCTED
TCOEFF - THE TRANSMISSIVITY COEFFICIENT USED TO ESTIMATE THE NET
            SHORT WAVE RADIATION REACHING THE SNOWPACK
TMAX - ARRAY OF DAILY MAXIMUM TEMPERATURES FOR AN ENTIRE YEAR
TMIN - ARRAY OF DAILY MINIMUM TEMPERATURES FOR AN ENTIRE YEAR
TMPMAX - THE MAXIMUM TEMPERATURE DURING THE INTERVAL IN DEGREES
            FARENHEIT
TMPMIN - THE MINIMUM TEMPERATURE DURING THE INTERVAL IN DEGREES
            FARENHEIT
TMPMLT - THE TEMPERATURE BELOW WHICH THE FALL RADIATION ROUTINE
            MAY NOT CREATE MELT OR FREE WATER
TYPCUT = 0, THIS TYPE OF CUT DOES NOT HAVE REDISTRIBUTION
            ASSOCIATED WITH IT
       = 1, THIS TYPE OF CUT HAS REDISTRIBUTION ASSOCIATED WITH IT
VARFMT - VARIABLE FORMAT FOR READING FROM FILE -UNEDIT-
C      VARIN - INPUT ARRAY TO BE READ BY -VARFMT- (ALLOWS THE VARIABLES
C                  TO BE IN ANY ORDER AT INPUT TIME)
C      VEGTYP = 1, FOREST COVER PREDOMINATELY LODGEPOLE PINE
C             = 2, FOREST COVER PREDOMINATELY SPRUCE-FIR
C             = 3, FOREST COVER PREDOMINATELY ASPEN (DECIDUOUS)
C             = 4, INTERNAL USE ONLY TO SPECIFY DEFOLIATED DECIDUOUS
C                  FORESTS (DURING THE WINTER)
C      WATRIN - THE SUM OF ANY SNOWMELT AND ANY RAIN WHICH PROVIDES
C                  DIRECT INPUT TO THE WATER BALANCE
C      WE - ARRAY OF DAILY PACK WATER EQUIVALENTS FOR AN ENTIRE YEAR
C      WEIGHT - THE PERCENT OF THE REGION AREA REPRESENTED BY THIS
C                  PLANNING UNIT (A DECIMAL PERCENT BETWEEN 0.0 AND 1.0)
C      WEO - THE SNOWPACK WATER EQUIVALENT AT THE BEGINNING OF A WATER
C                  YEAR
C      WILTPT - THE WILTING POINT
C      YEAR - CURRENT YEAR BEING PROCESSED
C      YRCNST - SEDIMENT MODEL, YEAR OF ROAD CONSTRUCTION
C      YRTOT - ARRAY OF THE YEARLY ACCUMULATED VALUES OF THE CONTINUITY
C                  EQUATION
C-----
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,PLNOPT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
      INTEGER DATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
C-----PROOFREAD THE CARD DECK
      CALL OVERLAY (5HOLAYS,7,0)
C-----IF SPECIFIED, COPY -SAVOLD- TO -SAVNEW-
      IF(SAVE.EQ.2) CALL OVERLAY (5HOLAYS,3,0)
C-----READ A PLANNING UNIT CARD
   20 READ (19) PLUNIT,DECMAL,INFILE,WEIGHT,PLNOPT
C-----AT THE END OF FILE, PROCESS THE REGIONAL FILE
      IF(EOF(19)) 80,30
C-----IF -INFILE- IS 14, THE NORMAL SIMULATION AND EXPANDED DATA FILE
C----- WERE SAVED FROM A PREVIOUS RUN.  FIND THE FILE ON -SAVOLD- AND
C----- IF IT HAS THE SPECIFIED NUMBER OF YEARS, COPY IT TO -DATFIL- AND
C----- JUMP DIRECTLY TO THE MANAGEMENT PLANS SIMULATION.  OTHERWISE,
C----- COPY IT TO -SCRFIL- AND JUMP TO CREATE THE SPECIFIED NUMBER OF
C----- YEARS
   30 IF(INFILE - 14) 50,40
   40 CALL OVERLAY (5HOLAYS,1,0)
      IF(NRMANG) 70,60
C-----PROCESS THE NORMAL SIMULATION AND GENERATE THE ORIGINAL DATA FILE
   50 NRMANG = 1
   60 CALL OVERLAY (5HOLAYS,2,0)
C-----PERFORM THE MANAGEMENT PLANS SIMULATION
   70 NRMANG = 2
      CALL OVERLAY (5HOLAYS,2,0)
C-----SUMMARIZE THE RESULTS FOR THIS PLANNING UNIT AND GO ON TO THE NEXT
      CALL OVERLAY (5HOLAYS,4,0)
      GO TO 20
C-----REGIONAL SUMMARY
   80 CALL OVERLAY (5HOLAYS,5,0)
      IF(RECOVR) 100,90
   90 REWIND 13
      END FILE 13
C-----IF ANY FILES WERE SAVED, LIST THEM
  100 IF(SAVE.NE.0) CALL OVERLAY (5HOLAYS,6,0)
C-----TERMINATE THE RUN
      END
```

Subroutine GDATE

```
      SUBROUTINE GDATE (NDAY,DATE)
C-----CONVERT THE PSEUDO-JULIAN DATE TO MONTH AND DAY
      INTEGER DATE(2),MONTHS(12)
      DATA MONTHS/10,11,12,1,2,3,4,5,6,7,8,9/
      DATE(2) = MOD(NDAY,31)
      IF(DATE(2)) 10,20
   10 DATE(1) = MONTHS((NDAY/31)+1)
      RETURN
   20 DATE(2) = 31
      DATE(1) = MONTHS(NDAY/31)
      RETURN
      END
```

Subroutine GETREC

```
      SUBROUTINE GETREC (IFILE,ARRAY,N,IEND)
C-----READ A RECORD
      DIMENSION ARRAY(1)
      BUFFER IN (IFILE,1) (ARRAY(1),ARRAY(N))
      IF(UNIT(IFILE)) 10,20,30
C-----OK TO PROCEED
   10 IEND = 0
      RETURN
C-----END OF FILE
   20 IEND = 1
      RETURN
C-----PARITY ERROR
   30 WRITE (6,910) IFILE
  910 FORMAT(*0PARITY ERROR ON FILE*I3,* WHILE READING - JOB ABORTED*)
      CALL ABORT
      END
```

Subroutine PUTREC

```
      SUBROUTINE PUTREC (IFILE,ARRAY,N)
C-----WRITE A RECORD
      DIMENSION ARRAY(1)
      BUFFER OUT (IFILE,1) (ARRAY(1),ARRAY(N))
      IF(UNIT(IFILE)) 10,10,20
   10 RETURN
   20 WRITE (6,910) IFILE
  910 FORMAT(*0PARITY ERROR ON FILE*I3,* WHILE WRITING - JOB ABORTED*)
      CALL ABORT
      END
```

Program GETOLD

```
      OVERLAY (OLAYS,1, )
      PROGRAM GETOLD
C-----GET THE DATA FILE FROM -SAVOLD-
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,PLNOPT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
      INTEGER DATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
      DIMENSION BLOCK(1889),ID(9)
      CALL CORE (-1)
      JEND =
C-----PREPARE THE DATA FILE AND GET AN ID RECORD
   10 CALL GETREC (14,ID,9,IEND)
C-----IF THE END OF FILE WAS READ, CHECK TO SEE IF A COMPLETE PASS HAS
C----- BEEN MADE OR IF THE FILE SHOULD BE REWOUND AND SEARCHED AGAIN
      IF(IEND) 20,90
   20 REWIND 14
      IF(JEND) 30,80
   30 WRITE (6,910) PLUNIT
  910 FORMAT(*CTHE PLANNING UNIT CARD ENTITLED *6A10/*  INDICATES THE EX
     1PANDED DATA FILE WAS CREATED AND SAVED ON AN OLD RUN.  HOWEVER, AS
     2 THE LIST BELOW INDICATES,*/*  NO SUCH FILE EXITS ON -SAVOLD-*/)
      IFILE = 0
   40 CALL GETREC (14,ID,9,IEND)
      IF(IEND) 70,50
   50 IFILE = IFILE + 1
      WRITE (6,920) IFILE,(ID(I),I=1,6)
  920 FORMAT(* SAVOLD FILE*I3,5X6A10)
C---BYPASS THE DATA
   60 CALL GETREC (14,BLOCK,1889,IEND)
      IF(IEND) 40,60
   70 WRITE (6,930)
  930 FORMAT(*0JOB ABORTED*)
      CALL ABORT
   80 JEND = 1
      GO TO 10
C-----IF THIS IS NOT THE DESIRED FILE, BYPASS THE DATA
   90 DO 100 I = 1,6
      IF(PLUNIT(I).NE.ID(I)) GO TO 110
  100 CONTINUE
      GO TO 120
  110 CALL GETREC (14,BLOCK,1889,IEND)
      IF(IEND) 10,110
C-----THIS IS THE FILE.  IF IT HAS THE SAME NUMBER OF YEARS AS IS
C----- CURRENTLY BEING PROCESSED, JUST COPY IT TO THE EXPANDED DATA FILE
C----- AND RETURN.  BUT IF IT HAS A DIFFERENT NUMBER OF YEARS, COPY IT
C----- TO THE SCRATCH FILE FOR EXPANSION OR CONTRACTION
  120 IF(NYEARS - ID(7)) 130,140
  130 NRMANG = 0
      IFILE = 16
      GO TO 150
  140 NRMANG = 2
      IFILE = 11
  150 REWIND IFILE
      GO TO 170
  160 CALL PUTREC (IFILE,BLOCK,1889)
  170 CALL GETREC (14,BLOCK,1889,IEND)
      IF(IEND) 180,160
  180 END FILE IFILE
      CALL CORE (0)
C-----RETURN TO THE PRIMARY OVERLAY
      END
```

Program LOADS

```
      OVERLAY (OLAYS,2,0)
      PROGRAM LOADS
C-----THIS OVERLAY CONTAINS THE WATER BALANCE AND UTILITY ROUTINES SO
C----- THEY ARE AVAILABLE FOR EITHER THE NORMAL OR THE MANAGEMENT
C----- SIMULATION AND IT CALLS FOR THE LOADING OF THE APPROPRIATE
C----- PERIPHERAL ROUTINES
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,PLNOPT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
      INTEGER DATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRO,PEAKED,PRECIP,RADIN,
     1 RADLWN,RADSWN,TMPMAX,TMPMIN,WATRIN
      COMMON/S/AVSOIL(11),DECLIN(11),NROADS,RATNRM(11),ROADM1(11),
     1 ROADW(11),TANCUT(11),TANFIL(11),TANRHO(11),YRCNST(11)
      INTEGER YRCNST
      COMMON/TIME/CANPEF,COMAX2,CONAV
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRGO,RO(372),WE(372),WED,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETC(372),PPT(372),RAD(372),TMAX(372),TMIN(372)
      EQUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(1490),ETD(1)),(BLOCK(1864),
     2 COMAX),(BLOCK(1865),VEGTYP),(BLOCK(1866),TRSHLD),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1869),WILTPT),(BLOCK(1871),DCOMAX),(BLOCK(1872),
     4 ISTRM),(BLOCK(1873),PEKDAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
      INTEGER PEKDAT,VEGTYP
      NROADS =
      N = NRMANG
      IF(N.EQ.0) N = 1
      CALL OVERLAY (5HOLAYS,2,N)
      IF(NROADS.NE.0) CALL OVERLAY (5HOLAYS,2,3)
C-----RETURN TO THE MAIN OVERLAY
      END
```

Subroutine WATBAL

```
      SUBROUTINE WATBAL (F1,F2,F3,I1,F4,F5,I2,I3,F6,I4,F7,F8,F9,F10,F11,
     1 F12,F1 ,F14,I5,F15)
C-----THIS SUBROUTINE IS THE MAIN ROUTINE OF THE WATER BALANCE MODEL. IT
C----- RECEIVES THE DRIVING, STATIC AND CONTINUOUS VARIABLES FROM THE
C----- OPERATING ROUTINES, CONTROLS THE COMPUTATIONS ON THEM, AND
C----- RETURNS THE NEW VALUES FOR THE CONTINUOUS VARIABLES AND THE
C----- RESULTS OF THIS INTERVAL.  SEE THE REPLACEMENT STATEMENTS BELOW
C----- FOR THE VARIABLE DEFINITIONS OF THE PARAMETERS
      COMMON/ONLYCR/ AVETMC,BASTMF,CALOF,COMAX,COVDN,DREDY,ENGBL,
     1 ENGBLO,FIELDC,FREWT,LSUSD,NOSNO,ONTRE,PHASE,PREWE,
     2 RCHRG,SMTM1(3),SMTM3,TCOEF,TMPMLT,TRSHLD,VEGTYP
      INTEGER DREDY,PHASE,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRO,PEAKED,PRECIP,RADIN,
     1 RADLWN,RADSWN,TMPMAX,TMPMIN,WATRIN
      DATA AVETMC,BASTMF,ENGBL,SMTM3/0.0,35.0,-1.0,0.0/
C-----OBTAIN THE STATION DESCRIPTORS
      COVDN = F3
      COMAX = F2
      FIELDC = -F15
      TCOEF = F12
      TMPMLT = F13
      TRSHLD = F14
      VEGTYP = I5
C-----RECALL THE CONTINUOUS VARIABLES NECESSARY FOR THE OPERATION OF THE
C----- MODEL DURING THIS INTERVAL
      CALOF = F1
      DREDY = I1
      ENGBLO = F4
      FREWT = F5
      LSUSD = I2
      NOSNO = I3 + 1
      ONTRE = F6
      PHASE = I4
      PREWE = F7
      RCHRG = F8
      IF(DREDY) 20,20,10
   10 SMTM1(1) = F9
      SMTM1(2) = F10
      SMTM1(3) = F11
C-----AVETMC = (((TMPMAX-32)+(TMPMIN-32))/2)*5/9)
   20 AVETMC = (TMPMAX + TMPMIN - 64.0) * 0.2777777778
C-----START THE ENERGY BALANCE AND THE INPUT AT ZERO FOR THIS INTERVAL
      ENGBL = 0.0
      WATRIN = 0.0
C-----IF THERE IS NO PRECIP, THERE IS NO NEED TO PASS THROUGH THE
C----- CLASSIFICATION STATEMENTS
      IF(PRECIP) 90,90,30
C-----SEE IF THE PRECIP IS ALL SNOW
   30 IF(TMPMIN.LE.32.0.OR.TMPMAX.LT.BASTMF) GO TO 80
C-----SEE IF ANY OF IT IS SNOW
      IF(TMPMIN - BASTMF) 40,50,50
   40 CALL MIXTUR
      GO TO 90
C-----THIS IS A RAIN EVENT.  IF THERE IS NO PACK, THE RAIN IS DIRECT
C----- INPUT TO THE WATER BALANCE.  BUT IF THERE IS A PACK, DETERMINE
C----- THE EFFECTS OF THE RAIN
   50 IF(PREWE) 60,60,70
   60 WATRIN = PRECIP
      GO TO 130
   70 CALL RAINED (AVETMC,PRECIP)
      GO TO 90
C-----THIS IS A SNOW EVENT
   80 CALL SNOWED (AMIN1 (AVETMC,0.0),PRECIP)
C-----IF THERE IS SNOW ON THE TREES, EVAPORATE ONLY FROM THE CANOPY
   90 IF(ONTRE) 130,130,100
  100 CALL CANVAP
C-----ON THE FIRST DAY AFTER FRESH SNOW, ASSUME TURBULENCE HAS REMOVED
C----- ANY REMAINING INTERCEPTED SNOW AND ADDED IT TO THE PACK
      IF(NOSNO - 1) 120,110,110
  110 PREWE = PREWE + ONTRE
      ONTRE = 0.0
C-----IF THERE IS NO SNOWPACK, BYPASS THE RADIATION ROUTINES
  120 IF(PREWE) 190,190,180
C-----DETERMINE THE FOREST TYPE - CONIFEROUS OR DECIDUOUS
  130 IF(VEGTYP.NE.3.AND.VEGTYP.NE.4) GO TO 135
C-----DECIDUOUS
      CALL DECID
      GO TO 200
C-----CONIFEROUS - DETERMINE WHETHER TO SATISFY THE EVAPOTRANSPIRATION
C----- REQUIREMENTS UNDER GROWING SEASON OR WINTER CONDITIONS
  135 IF(PREWE) 160,160,140
  140 IF(PREWE - 5.0) 150,150,170
C-----USE THE GROWING SEASON ROUTINES TO INCLUDE TRANSPIRATION
  150 CALL RADBAL
C-----ADD -WATRIN- TO THE RECHARGE REQUIREMENTS SO THE ET ROUTINE CAN
C----- OPERATE ON THE INPUT AS WELL AS THE STORAGE
  160 RCHRG = RCHRG + WATRIN
C-----0.22388 = 0.15/0.67 (SEE THE COMMENT IN SUBROUTINE EVTRAN FOR THE
C----- USE OF THE CONSTANT)
      CALL EVTRAN (0.22388)
      GO TO 200
C-----USE THE WINTER ROUTINES TO EVAPORATE FROM THE SNOWPACK SURFACE
  170 CALL SNOVAP
  180 CALL RADBAL
C-----ADD -WATRIN- TO THE RECHARGE REQUIREMENTS
  190 RCHRG = RCHRG + WATRIN
C-----IF THE RECHARGE REQUIREMENTS WERE SATISFIED, THE EXCESS IS
C----- CONSIDERED TO BE GENERATED RUNOFF
  200 IF(RCHRG) 220,220,210
  210 GENRO = RCHRG
      F8 = 0.0
      GO TO 230
  220 GENRO = 0.0
      F8 = RCHRG
  230 I1 = DREDY
      F1 = CALOF
      F4 = ENGBL
      F5 = FREWT
      I2 = LSUSD
      I3 = NOSNO
      F6 = ONTRE
      F7 = PREWE
C-----WHEN THE PACK IS GONE, RESET THE PHASE INDICATOR
      IF(PREWE) 240,240,250
  240 I4 = 0
      RETURN
  250 I4 = PHASE
      IF(DREDY) 270,270,260
  260 F9 = SMTM1(1)
      F10 = SMTM1(2)
      F11 = SMTM1(3)
  270 RETURN
      END
```

Subroutine CALIN

```
      SUBROUTINE CALIN (CALRIN)
C-----THIS SUBROUTINE COMPUTES THE EFFECTS OF THE CALORIC INPUT ON THE
C----- SNOWPACK
      COMMON/ONLYCR/ AVETMC,BASTMF,CALDF,COMAX,COVDN,OREDY,ENGBL,
     1 ENGBLO,FIELDC,FREWT,LSUSO,NOSNO,ONTRE,PHASE,PREWE,
     2 RCHRG,SMTMI(3),SMTM3,TCOEF,TMPMLT,TRSHLD,VEGTYP
      INTEGER DREDY,PHASE,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRO,PEAKED,PRECIP,RADIN,
     1 RADLWN,RADSWN,TMPMAX,TMPMIN,WATRIN
C-----ADD THESE CALORIES INTO THE ENERGY BALANCE
      ENGBL = ENGBL + CALRIN
C-----SEE IF A CALORIE DEFICIT EXISTS IN THE PACK
      COMPAR = CALRIN - CALDF
      IF(COMPAR) 10,20,30
C-----THERE IS A CALORIE DEFICIT, BUT THE INPUT DID NOT COMPLETELY
C----- WIPE IT OUT.  ALL OTHER CONDITIONS ARE UNCHANGED
   10 CALDF = - COMPAR
      RETURN
C-----THE CALORIE DEFICIT WAS WIPED OUT, BUT ALL OTHER CONDITIONS ARE
C----- UNCHANGED
   20 CALDF = 0.0
      RETURN
C-----ANY DEFICIT WHICH DID EXIST WAS WIPED OUT.  COMPUTE THE POTENTIAL
C----- MELT FROM THE REMAINING CALORIES (CALORIES/(80.D * 2.54))
   30 POTMLT = COMPAR/203.2
      CALDF = D.0
C-----IF THE INPUT WAS ENOUGH TO MELT THE WHOLE PACK, CONTRIBUTE THE
C----- WATER EDUIVALENT TO THE SNOWMELT ANO ZERO ALL CONDITIONS
      IF(POTMLT.LT.PREWE-FREWT) GO TO 4D
      WATRIN = WATRIN + PREWE
      PREWE = C.D
      FREWT = 0.0
      RETURN
C-----OEPLETE THE ICE PACK BY THE AMOUNT MELTED AND CONTRIBUTE THAT
C----- AMOUNT TO THE FREE WATER
   4D FREWT = FREWT + POTMLT
C-----COMPUTE THE NEW HOLDING CAPACITY OF THE PACK AND COMPARE IT WITH
C----- THE FREE WATER TO SEE IF SNOWMELT IS PROOUCED
      HOLDCP = D.04 * (PREWE - FREWT)
      COMPAR = FREWT - HOLDCP
      IF(COMPAR.LE.D.0) RETURN
C-----THE SNOWMELT CONTRIBUTED IS IN -COMPAR-.  REDUCE THE FREE WATER
C----- TO LEAVE A PRIMED PACK AND REDUCE THE PREOICTED WATER EDUIVALENT
      PREWE = PREWE - COMPAR
      WATRIN = WATRIN + COMPAR
      FREWT = HOLDCP
      RETURN
      END
```

Subroutine CALOSS

```
      SUBROUTINE CALOSS (CALOUT)
C-----THIS SUBROUTINE COMPUTES THE EFFECTS OF THE CALORIC LOSS ON THE
C----- SNOWPACK
      COMMON/ONLYCR/ AVETMC,BASTMF,CALDF,COMAX,COVDN,DREDY,ENGBL,
     1 ENGBLO,FIELDC,FREWT,LSUSD,NDSNO,ONTRE,PHASE,PREWE,
     2 RCHRG,SMTMI(3),SMTM3,TCOEF,TMPMLT,TRSHLO,VEGTYP
      INTEGER DREDY,PHASE,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRO,PEAKED,PRECIP,RADIN,
     1 RADLWN,RADSWN,TMPMAX,TMPMIN,WATRIN
C-----AOD ALGEBRAICALLY THESE CALORIES INTO THE ENERGY BALANCE
      ENGBL = ENGBL + CALOUT
C-----SEE IF THERE IS ANY FREE WATER IN THE PACK.  IF NOT, THE LOSS IS
C----- JUST CONTRIBUTED TO THE CALORIC DEFICIT OF THE SNOWPACK.
C----- REMEMBER THAT -CALOUT- IS NEGATIVE
      IF(FREWT.GT.0.D) GO TO 1D
      CALDF = CALDF - CALOUT
      RETURN
C-----COMPUTE THE CALORIC LOSS NECESSARY TO FREEZE ALL OF THE FREE WATER
C----- (FREE WATER * 80.0 * 2.54)
   10 CALNED = FREWT * 203.2
C-----NOW COMPARE THAT NECESSARY LOSS WITH THE ACTUAL LOSS.  IF THEY ARE
C----- THE SAME, THE FREE WATER IS WIPED OUT BUT NO OTHER CONDITIONS ARE
C----- ALTERED
      COMPAR = CALOUT + CALNEO
      IF(COMPAR) 20,30,40
C-----THE LOSS WAS MORE THAN ENOUGH TO FREEZE IT.  THE BALANCE CREATES
C----- AN ENERGY OEFICIT IN THE PACK AND THE FREE WATER IS WIPED OUT
   2D CALDF = - COMPAR
   30 FREWT = D.D
      RETURN
C-----ONLY PART OF THE FREE WATER FROZE.  COMPUTE THE BALANCE REMAINING
C----- BALANCE = EXISTING FREE WATER - AMOUNT FROZEN, WHERE
C----- AMOUNT FROZEN = CALORIES/(8D.0 * 2.54)
   4D FREWT = FREWT + (CALOUT/203.2)
      RETURN
      END
```

Subroutine CANVAP

```
      SUBROUTINE CANVAP
C-----COMPUTE THE EVAPORATION FROM THE INTERCEPTED SNOW AS A FUNCTION OF
C----- THE CANOPY COVER DENSITY.  NOTE - THIS VERSION REPLACED THE
C----- ORIGINAL SUBROUTINE CANVAP IN OECEMBER, 1973, TO INCORPORATE THE
C----- TIME TRENDS OF REGROWTH
      COMMON/ONLYCR/ AVETMC,BASTMF,CALDF,COMAX,COVON,DREOY,ENGBL,
     1 ENGBLO,FIELDC,FREWT,LSUSD,NOSNO,ONTRF,PHASE,PREWF,
     2 RCHRG,SMTMI(3),SMTM3,TCOEF,TMPMLT,TRSHLD,VEGTYP
      INTEGER DREDY,PHASE,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRO,PEAKED,PRECIP,RADIN,
     I RADLWN,RAOSWN,TMPMAX,TMPMIN,WATRIN
      COMMON/TIME/CANREF,COMAX2,CONAV
C-----IF THE COVER DENSITY IS GREATER THAN OR EDUAL TO HALF OF THE
C----- MAXIMUM COVER DENSITY (ASSUMES COMPLETE OR NEARLY COMPLETE
C----- CROWN COVER AT COMAX/2), EVAPORATE ONLY FROM THE CANOPY
      IF(COMAX2 - COVDN) 10,10,40
   10 ETFROM = 1.0
      EVAPTR = EVAPTR/COVDN
      ONTRE = ONTRE - EVAPTR
      IF(ONTRE) 20,3D,30
   20 EVAPTR = ONTRE + EVAPTR
      ONTRE = 0.0
   3D RETURN
C-----EVAPORATE FROM THE SNOWPACK SURFACE (USING THE PROCEOURES OF
C----- SUBROUTINE SNOVAP) AND FROM THE CANOPY, COMBINING THE RESULTS AS
C----- A FUNCTION OF THE PRESENT PERCENTAGE OF CROWN COVER
   40 ETFROM = 3.0
      PRCNTC = COVDN/CDMAX2
      ETS = ((1.0 - CDVDN) * EVAPTR) * (1.D - PRCNTC)
      IF(PREWE - ETS) 50,50,6D
   50 FTS = PREWE
      PREWE = 0.0
      GD TO 70
   6D PREWE = PREWE - ETS
   7D ETC = (EVAPTR/COVDN) * PRCNTC
      DNTRE = ONTRE - ETC
      IF(ONTRE) 80,90,90
   80 FTC = ONTRE + ETC
      ONTRE = 0.C
   90 EVAPTR = ETC + FTS
      RETURN
      END
```

Subroutine DECID

```
      SUBROUTINE DECID
C-----DECIDUOUS FOREST - DETERMINE THE SOURCE OF THE EVAPOTRANSPIRATION
      COMMON/ONLYCR/ AVETMC,BASTMF,CALOF,COMAX,COVDN,DREOY,ENGBL,
     I ENGBLO,FIELOC,FREWT,LSUSD,NDSNO,ONTRF,PHASE,PREWE,
     2 RCHRG,SMTMI(3),SMTM3,TCOEF,TMPMLT,TRSHLD,VEGTYP
      INTEGER DREDY,PHASE,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRD,PEAKED,PRECIP,RADIN,
     1 RADLWN,RADSWN,TMPMAX,TMPMIN,WATRIN
C-----IF FOLIAGE IS PRESENT, USE EVAPOTRANSPIRATION
      IF(VEGTYP - 3) 4D,10
C-----IF THERE IS NO PACK, BYPASS THE RADIATION ROUTINES
   10 IF(PREWE) 20,3D
   20 CALL RADBAL
C-----ADD -WATRIN- TO THE RECHARGE REDUIREMENTS SD THE ET ROUTINE CAN
C----- OPERATE ON THE INPUT AS WELL AS THE STORAGE
   30 RCHRG = RCHRG + WATRIN
C-----0.14925 = D.10/0.67 (SEE THE COMMENT IN SUBROUTINE EVTRAN FOR THE
C----- USE OF THE CONSTANT)
      CALL EVTRAN (0.14925)
      RETURN
C-----SINCE FOLIAGE IS NOT PRESENT, EVAPORATE FROM THE PACK SURFACE IF A
C----- PACK EXISTS
   4C IF(PREWE) 5D,6D
   50 CALL SNOVAP
      CALL RADBAL
C-----ADO -WATRIN- TO THE RECHARGE REQUIREMENTS
      RCHRG = RCHRG + WATRIN
      RETURN
C-----NEITHER FOLIAGE NOR PACK ARE PRESENT.  ADJUST THE EVAPORATION FOR
C----- AVAILABLE SOIL WATER BY THE SAME RELATIONSHIP USED IN EVTRAN FOR
C----- OPENINGS, THEN ADJUST FOR COVER DENSITY AS IN SNOWVAP (USE ANY
C----- INPUT TO HELP SATISFY THE REQUIREMENTS)
   60 ETFRUM = 4.0
      RCHRG = RCHRG + WATRIN
      IF(RCHRG + (FIELDC/4.D)) 70,7D,80
   7D EVAPTR = 0.C
      RETURN
   80 AVABLE = ((4.D/FIELDC) * (FIELDC + RCHRG)) - 3.D
      EVAPTR = EVAPTR * AVABLE * (1.0 - COVDN)
      IF(RCHRG - EVAPTR + FIELDC) 90,1DD,1DD
   90 EVAPTR = RCHRG + FIELDC
      RCHRG = - FIELDC
      RETURN
  1CD RCHRG = RCHRG - EVAPTR
      RETURN
      END
```

Subroutine DIFMOD

```
      SUBROUTINE DIFMOD
C-----THIS SUBROUTINE WAS DERIVED FROM PROGRAM SMTM, A SNOWPACK
C----- TEMPERATURE DIFFUSION MODEL OEVELOPED BY LEAF (1970 STUDY PLAN
C----- FS-RM-1602, NO. 224, RMF+RES).  USING THE AVERAGE SURFACE TEMP
C----- AND THE GROUND TEMP AS BOUNDARY CONDITIONS, THE NEW AVERAGE
C----- SNOWPACK TEMPERATURE IS CALCULATED
      COMMON/ONLYCR/ AVETMC,BASTMF,CALDF,COMAX,COVDN,OREDY,ENGBL,
     1 ENGBLO,FIELDC,FREWT,LSUSO,NDSNO,ONTRE,PHASE,PREWF,
     2 RCHRG,SMTMI(3),SMTM3,TCOEF,TMPMLT,TRSHLD,VEGTYP
      INTEGER DREDY,PHASE,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRD,PEAKED,PRECIP,RADIN,
     I RAGLWN,RADSWN,TMPMAX,TMPMIN,WATRIN
C-----COMPUTE THE DENSITY OF THE SNOWPACK (THE FUNCTION WAS DERIVED FROM
C----- OBSERVEO CONDITIONS ON THE FRASER EXPERIMENTAL FOREST)
      OFNSTY = (EXP(ID.0179 * PREWE) + 3.02))/100.D
C-----COMPUTE THE DISTANCE BETWEEN THE TWO NOOES IN CENTIMETERS
C-----DEPTH = PREWE/DENSTY
C-----H = (DEPTH/2)*2.54
      H = (PREWE/DENSTY) * 1.27
C-----THE THERMAL DIFFUSIVITY IS CALCULATED FROM THE FUNCTION
C----- KV = 0.01/((2.751 - DENSTY)* D.48).  MATHEMATICAL STABILITY
C----- REQUIRES THAT THE VALUE OF THE QUANTITY (INTERVAL IN SECONDS *
C----- KV/H**2) BE LESS THAN 0.5.  WHEN A 24 HOUR INTERVAL IS USED, THE
C----- SNOW DEPTH MUST EXCEED 30 INCHES (20 PERCENT DENSITY) TO ACHIEVE
C----- STABILITY.  IN ORDER TO INSURE STABILITY WITH SOMEWHAT SHALLOWER
C----- PACKS (ABOUT 18 INCHES), THE OAY IS OIVIDEO INTO 2 TIME INTERVALS
C----- OF 12 HOURS (43200 SECONDS)
C-----CONSTI = (43200 * D.01/((2.75I - OENSTY) * 0.48))/H**2
      CONSTI = 900.0/((2.75I - DENSTY)*H*H)
C-----THE MINIMUM WATER EQUIVALENT WHICH WILL ACHIEVE STABILITY USING
C----- THE ABOVE DENSITY FUNCTION IS 4.7 INCHES
      IF(CONSTI - 0.5) 20,10,10
```

```
C-----THE MODEL IS UNSTABLE - )NDICATE THAT IT IS NOT READY FOR USE NOW.
C----- (IT MAY BE INITIALIZED AGAIN BY AN OBSERVED PACK TEMPERATURE CARD
C----- AND STABIL)TY WILL BE ASCERTAINED FROM THE WATER EQUIVALENT AT
C----- THAT TIME)
   10 DREDY = 0
      RETURN
C-----GET THE SECOND CONSTANT
   20 CONST2 = 1.0 - CONST1 - CONSTI
C-----PERFORM THE SIMULATION )N TWO PARTS )ONE FOR EACH 12 HOUR PERIODI.
C----- -SMTMI- HOLDS THE THREE TEMPERATURES FROM THE PREVIOUS INTERVAL
C----- THAT ARE NEEDED TO SIMULATE SMTM2, THE NODE AT THE CENTER OF
C----- THE PACK.  SIMULATE THE FIRST 12 HOURS NOW
      SMTM2 = (CONSTI * (SMTMI(I) + SMTM1)3I)I + )CONST2 * SHTM1
     1(2I)
C-----THE AVERAGE SNOWPACK TEMPERATURE IS THE AVERAGE OF THE 2 NODES
C----- (MIDDLE AND GROUNDI IN BOTH INTERVALS.  GROUND TEMPERATURE IS
C----- CONSTANT, SO START THE AVERAGE NOW
      SMTM3 = SMTMI(3I + SMTM1)3) + SMTM2
C-----RESET -SMTMI- TU THE TEMPERATURES OF THE )NTERVAL JUST SIMULATED
C----- FOR USE IN THE SECOND 12 HOUR INTERVAL SIMULATION.  THE SURFACE
C----- AIR TEMPERATURE IS SPL)T INTO A LOW AVERAGE ( )MEAN+MIN)/2 I AND
C----- A HIGH AVERAGE ) (MEAN+MAXI/2 I FOR USE WITH THE TWELVE HOUR
C----- INTERVALS.  USE THE LOW AVERAGE NOW
      SMTM1)1) = AMINI )0.0,(((TMPMIN-32.0I*0.5555555556)+AVETMCI/
     1 2.0)
      SMTMI(2) = SHTM2
C-----SIMULATE THE SECOND 12 HOURS AND COMPUTE THE AVERAGE SNOWPACK
C----- TEMPERATURE
      SMTM2 = (CONST1 * (SMTM1(1I + SMTM1(3II) + (CONST2 * SHTH1
     1)2II
      SHTM3 = (SMTM3 + SHTM2I/4.D
C-----RESET -SMTM1- USING THE HIGH AVERAGE FOR USE ON THE FIRST
C----- INTERVAL OF THE NEXT DAY
      SMTMI(II = AMINI (0.0,(((TMPHAX-32.D)*0.5555555556I+AVETMCI/
     1 2.0I
      SMTM1(2) = SHTM2
C-----CHECK TO SEE IF THE GROUND TEMPERATURE SHOULD BE RAISED
      IF)SMTM3 + 1.5I 60,40,3D
   3D IF)SMTM3 + D.5I 40,50,50
   4D IF)SMTMI(3I.LT.-D.5I SMTM1)3I = -D.5
      RETURN
   50 SMTM1(3) = 0.0
   6D RETURN
      END
```

Subroutine EVTRAN

```
      SUBROUTINE EVTRAN
C-----COMPUTE THE EVAPORATION AND TRANSPIRATION DURING THE GROWING
C----- SEASON.  NOTE - THIS VERSION REPLACED THE ORIGINAL SUBROUTINE
C----- EVTRAN IN DECEMBER, 19T3, TO INCORPORATE THE TIME TRENDS OF
C----- REGROWTH
      COMMON/ONLYCR/ AVETMC,BASTMF,CALDF,CDMAX,COVDN,OREDY,ENGBL,
     1 ENGBLD,FIELDC,FREWT,LSUSD,NDSNO,ONTRE,PHASE,PREWE,
     2 RCHRG,SMTM1(3),SHTM3,TCOEF,THPMLT,TRSHLD,VEGTYP
      INTEGER OREDY,PHASE,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRO,PEAKED,PRECIP,RADIN,
     1 RADLWN,RADSWN,IMPHAX,THPHIN,WATRIN
      COMMON/TIME/CANREF,CDMAX2,CONAV
      ETFROM = 4.0
C-----GET THE ADJUSTMENT FACTOR FOR AVAILABLE SOIL WATER
C-----AVABLE = 4*EXP(-K*(T-TC))*(BETA/M - EXP(-K*(T-TCII + 1.0, WHEN
C----- T (YEARS SINCE TREATMENT) IS GREATER THAN OR EQUAL TO TC (BASE
C----- YEAR OF FUNCTIONI.  THE CONSTANT K IS CALCULATED WHEN THE
C----- MANAGEMENT PLAN CARD IS READ, AND THE CONSTANT -CONAV- IS
C----- COMPUTED AT THE BEGINNING OF EACH WATER YEAR BY THE TIME TRENDS
C----- ROUTINE.  BETA IS THE AVAILABLE WATER
      AVADLE = (4.0*CONAV*)((RCHRG+FIELDCI/FIELOCI-CONAV)) + 1.0
      IF(AVABLEI 1D,1D,2D
C-----THE WILTING POINT HAS BEEN REACHED
   1D EVAPTR = D.0
      RETURN
   2D IF(1.0 - AVABLEI 30,4D,40
C-----THE FACTOR IS MAXIMIZED
   30 AVABLE = 1.D
C-----THE ADJUSTMENT FOR CANOPY REFLECTIVITY IS RECOMPUTED EACH YEAR.
C----- PERFORM THE ADJUSTMENTS NOW
   4D EVAPTR = EVAPTR * AVABLE * CANREF
C-----IF THE EVAPOTRANSPIRATION WILL DEPLETE THE MANTLE STORAGE BELOW
C----- THE WILTING POINT, ALTER THE EVAPOTRANSPIRATION
      IF(RCHRG - EVAPTR + FIELDC) 5D,6D,6D
   50 EVAPTR = RCHRG + FIELDC
      RCHRG = - FIELDC
      RETURN
   60 RCHRG = RCHRG - EVAPTR
      RETURN
      END
```

Subroutine LINK

```
      SUDROUTINE LINK (CALAIR,CALRIE,IRETRN)
C-----THIS SUBROUTINE IS THE INTERFACE BETWEEN THE RADIATION BALANCE
C----- (SUBROUTINE RADBALI AND THE DIFFUSION MODEL (SUBROUTINE DIFMODI
      COMMON/ONLYCR/ AVETMC,BASTMF,CALDF,CDMAX,COVDN,DREDY,ENGBL,
     1 ENGBLC,FIELDC,FREWT,LSUSO,NDSNO,ONTRE,PHASE,PREWE,
     2 RCHRG,SMTM1)3I,SMTM3,TCOEF,THPMLT,TRSHLD,VEGTYR
      INTEGER DREDY,RHASE,VEGTYR
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRO,PEAKED,PRECIP,RADIN,
     1 RADLWN,RADSWN,TMPMAX,TMPMIN,WATRIN
C-----SEE IF THE RADIATION BALANCE IS AN ENERGY LOSS OR GAIN
      IF(CALRIE) 10,10,3D
C-----THERE WAS A LOSS.  IF THIS IS STILL WINTER (NO FREE WATERI, JUST
C----- GO AHEAD AND USE THE DIFFUSION MODEL
   10 IF(FREWT) 20,20,50
C-----USE THE DIFFUSION MODEL TO SIMULATE THE CURRENT AVERAGE SNOWPACK
C-----TEMPERATURE
   20 IF)DREDY.NE.1I GO TO 140
      CALL DIFMOD
      IF)DREDY) 40,4D,30
C-----NOW MAKE ANY NECESSARY ADJUSTMENTS IN THE RADIATION BALANCE TO
C----- CAUSE THE PACK TEMPERATURE TO BE THE SAME AS -SMTH3-. GET THE
C----- DIFFERENCE BETWEEN THE CALORIE DEFICITS AS COMRUTED BY THE
C----- OIFFERENT METHUOS
   30 CALOM = CALDF + (SMTM3 * PREWE * 1.27I
C-----ADJUST THE LONG WAVE PORTION OF THE RAOIATION BALANCE BY THE
C----- OIFFERENCE BETWEEN THE CALORIES DERIVED FROM THE OIFFUSION MODE
C----- AND THE ENERGY BALANCE
      CALRIE = CALOM
      RADLWN = CALRIE - RADSWN
   40 IRETRN = 0
      RETURN
C-----THE LOSS IS USED TO FREEZE PART OR ALL OF THE FREE WATER, BUT IT
C----- MAY NOT CREATE COLD CONTENT.  IF IT WOULO CREATE CULD CONTENT,
C----- RE-INITIALIZE THE DIFFUSION MODEL TO 0 AND AOJUST THE ENERGY
C----- BALANCE ACCORDINGLY
   50 CALL CALOSS )CALRIEI
      IF)FREWT - 0.05I 60,60,7D
   60 SMTM1(1) = AMIN1 )AVETHC.0.0I
      SMTM1(2) = 0.D
      SMTMI(3I = 0.0
      DREDY = I
C-----MAKE ANY NECESSARY ADJUSTMENTS TO THE ENERGY BALANCE TO COMPENSATE
C----- FOR THE COLD CONTENT THAT WOULD HAVE BEEN GENERATED BY THIS LOSS
C----- AND ZERO THE COLD CONTENT
      ENGBL = ENGBL + CALDF
      RAOLWN = RADLWN + CALDF
      FREWT = 0.0
      CALDF = 0.0
   TO IRETRN = 1
      RETURN
C-----THERE IS CALORIC INPUT TO THE PACK.  CHECK TO SEE IF CONOITIONS
C----- INDICATE THAT THE OIFFUSION MOOEL SHOULD BE TURNED OFF AND THE
C----- ENERGY BALANCE USEO FOR SPRINGTIME SIMULATION.  CONSIDER FIRST
C----- ANY COLD CONTENT )INCLUDING THAT OF THE PREVIOUS DAY AND ANY
C----- CREATED BY A SNOW EVENT ON THIS OAYI.  IF THERE IS COLD CONTENT,
C----- CHECK THE AVERAGE AIR TEMPERATURE AND THE SNOWPACK TEMPERATURE
C----- FROM THE PREVIOUS DAY FOR ARBITRARILY CHOSEN SPRINGTIME
C----- CONDITIONS AND IF ALL ARE NOT SATISFIEO, GO AHEAD AND USE THE
C----- DIFFUSION MODEL
   80 IF(CALOFI 1T0,1TD,9D
C-----0.889 = 1.27 * 0.7 OEGREES C (ARBITRARY TEMP)
   90 IF(AVETMC.LE.0.0.OR.CALOF.GT.PREWE*D.889I GO TO 2D
C-----SINCE SPRINGTIME CONDITIONS PREVAIL, RECOMPUTE THE BACK RADIATION
C----- AND THE NET RADIATION BALANCE (REMEMBER, IF THERE IS SNOW, THE
C----- LONGWAVE IS ASSUMED TO BE ZERO, SO THERE WOULD BE NO NEED TO MAKE
C----- ANY AOJUSTMENTSI
      IF(NOSNO) 140,140,10D
  10D USE = (THPMIN - 32.0) * D.5555555556
      IF(USE.GT.0.0) USE = D.0
      CALSNO = 1.1TE-T * ((USE + 2T3.16) ** 4)
      IF(PRECIPI 110,11D,12D
  11D RADLWN = ((1.0 - COVONI * ((D.757 * CALAIR) - CALSNO)I + (COVDN
     1 * (CALAIR - CALSNOII
      GO TO 130
  120 RADLWN = CALAIR - CALSNO
  130 CALRIE = RADSWN + RADLWN
C-----RE-INITIALIZE THE DIFFUSION MODEL TO THESE CONDITIONS IBUT IF THE
C----- INPUT IS MORE THAN ENOUGH TO WIPE OUT THE CALORIE DEFICIT, JUST
C----- LET IT BRING THE PACK TO ISOTHERMAL.  IN THIS WAY, TWO CONSECU-
C----- TIVE DAYS OF INPUT ARE REQUIRED TO GENERATE FREE WATER)
  140 COMPAR = CALRIE - CALDF
      IF(COMPARI 160,15D,15D
C-----INITIALIZE THE DIFFUSION MOOEL TO ISOTHERMAL CONDITIONS
  150 SMTM1(1I = 0.0
      SMTM1(2I = D.0
      SHTMI)3) = D.0
      SMTM3 = 0.0
      OREDY = 1
      GO TO 30
C-----REOEFINE THE SURFACE TEMPERATURE AND COMPUTE THE NEW AVERAGE PACK
C----- TEMPERATURE.  THEN COMPUTE THE MIDDLE NODE AS A FUNCTION OF THAT
C----- AVERAGE, THE SURFACE TEMPERATURE ANO THE GROUND TEMPERATURE
C----- (WHICH REMAINED UNCHANGED)
  160 SHTH1)1I = AMIN1 (D.D,AVETHCI
      SMTM3 = COMPAR/(PREWE * 1.27)
      SHTMI)2) = )3.D * SMTM3) - SHTM1(1I - SHTH1(3)
      SMTMI(3) = D.0
      DREDY = 1
      GO TO 30
C-----THERE )S INPUT TD THE PACK AND THE PACK IS ALREAOY ISOTHERMAL.  IF
C----- THIS ENERGY WILL CREATE AT LEAST 0.05 INCH (ARBITRARY AMOUNTI OF
C----- FREE WATER, SET THE DIFFUSION MODEL TO STANDBY STATUS AND LET THE
C----- ENERGY BALANCE TAKE ITS COURSE
  1TD IF)FREWT + (CALRIE/203.2) - 0.05) 150,180,180
  180 DREDY = D
      IRETRN = 0
      RETURN
      END
```

Subroutine MIXTUR

```
      SUBROUTINE MIXTUR
C----THIS SUBROUTINE CONTROLS THE COMPUTATIONS FOR A PRECIPITATION
C----- EVENT THAT IS A MIXTURE OF SNOW AND RAIN
      COMMON/ONLYCR/ AVETMC,BASTMF,CALOF,CDMAX,COVDN,DREDY,ENGBL,
     1 ENGBLO,FIELDC,FREWT,LSUSD,NDSNO,ONTRE,PHASE,PREWE,
     2 RCHRG,SMTMI(3I,SMTM3,TCOEF,TMPMLT,TRSHLD,VEGTYP
      INTEGER DREDY,RHASE,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRO,PEAKED,PRECIP,RADIN,
     1 RADLWN,RADSWN,TMPMAX,TMRMIN,WATRIN
C-----COMPUTE THE AMOUNT OF PRECIPITATION OCCURRING AS RAIN
C----- AMOUNT RAIN = P * (B/A), WHERE
C----- P = PRECIPITATION IN INCHES
C----- B = DAILY MAXIMUM TEMPERATURE - BASE TEMPERATURE (DEGREES F)
C----- A = DAILY MAXIMUM TEMRERATURE - MINIMUM TEMRERATURE (DEGREES F)
      B = TMPMAX - BASTMF
      A = TMPMAX - TMRMIN
      AMTRAN = PRECIP * (B/A)
C-----NOW COMPUTE THE AVERAGE TEMPERATURES (DEGREES C) WHICH PRODUCE
C----- SNOW AND RAIN
      TMSNO = (TMRMIN + BASTMF - 64.0I * D.277777777B
      TMAIN = (TMPMAX + BASTMF - 64.0) * D.2777777778
C-----COMPUTE THE EFFECT OF THE SNOW ON THE SNOWPACK
```

```
      CALL SNOWED (TMSNO,PRECIP-AMTRAN)
C-----COMPUTE THE EFFECT OF THAT PORTION OF THE PRECIPITATION OCCURRING
C----- AS RAIN ON THE SNOWPACK
      CALL RAINED (TMAIN,AMTRAN)
      RETURN
      END
```

Function PACKRF

```
      FUNCTION PACKRF (DUMMY)
C-----GET THE REFLECTIVITY OF THE SNOWPACK
      COMMON/ONLYCR/ AVETMC,BASTMF,CALDF,CDMAX,COVON,DREDY,ENGBL,
     1 ENGBLO,FIELOC,FREWT,LSUSD,NDSNO,ONTRE,PHASE,PREWE,
     2 RCHRG,SMTM1(3),SMTM3,TCDEF,TMPMLT,TRSHLD,VEGTYP
      INTEGER DREDY,PHASE,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRD,PEAKED,PRECIP,RADIN,
     1 RADLWN,RADSWN,TMPMAX,TMPMIN,WATRIN
      DIMENSION REFACM(15),REFMLT(15)
      INTEGER PASINT
      DATA REFACM/.80, .77, .75, .72, .70, .69, .68, .67, .66, .65,
     1 .64, .63, .62, .61, .60/
      DATA REFMLT/.72, .65, .60, .58, .56, .54, .52, .50, .48, .46,
     1 .44, .43, .42, .41, .40/
      PASINT = NDSNO
      IF(NDSNO) 80,80,10
C-----USE THE SAME FUNCTION AS LAST TIME
   10 IF(LSUSD) 20,20,50
C-----ACCUMULATION PHASE - AFTER 15 DAYS, USE THE MELT FUNCTION
C----- STARTING AT THE FOURTH DAY
   20 IF(PASINT - 15) 30,30,40
   30 PACKRF = REFACM(PASINT)
      RETURN
   40 PASINT = PASINT - 11
C-----MELT FUNCTION - AFTER 15 DAYS, USE A CONSTANT 40 PERCENT
   50 IF(PASINT - 15) 70,70,60
   60 PASINT = 15
   70 PACKRF = REFMLT(PASINT)
      RETURN
C-----THERE IS NEW SNOW - DETERMINE IF THE FUNCTION IS TO BE RE-
C----- INITIALIZED
   80 IF(TMPMAX - TRSHLD) 90,90,10
C-----IT IS, SO SEE WHICH FUNCTION IS TO BE USED
   90 IF(CALDF) 110,110,100
  100 PACKRF = 0.91
      LSUSD = 0
      RETURN
C-----THE PACK IS ISOTHERMAL, BUT IF THE ENERGY BALANCE FROM THE
C----- PREVIOUS INTERVAL WAS NEGATIVE, USE THE ACCUMULATION PHASE
C----- FUNCTION ANYWAY
  110 IF(ENGBLO) 100,120,120
  120 PACKRF = 0.81
      LSUSD = 1
      RETURN
      END
```

Subroutine RADBAL

```
      SUBROUTINE RADBAL
C-----THIS SUBROUTINE COMPUTES THE RADIATION BALANCE AND TRANSFERS
C----- CONTROL TO THE DIFFUSION MODEL THROUGH SUBROUTINE LINK IF IT IS
C----- NEEDED
      COMMON/ONLYCR/ AVETMC,BASTMF,CALDF,CDMAX,COVON,DREOY,ENGBL,
     1 ENGBLO,FIELOC,FREWT,LSUSD,NDSND,DNTRE,PHASE,PREWE,
     2 RCHRG,SMTM1(3),SMTM3,TCDEF,TMPMLT,TRSHLO,VEGTYP
      INTEGER OREDY,PHASE,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRD,PEAKED,PRECIP,RADIN,
     1 RAOLWN,RADSWN,TMPMAX,TMPMIN,WATRIN
C-----COMPUTE THE CALORIC INPUT FROM NET SHORT WAVE RAOIATION AS A
C----- FUNCTION OF THE SNOWPACK REFLECTIVITY
      RADSWN = RADIN * (1.0 - PACKRF (0.0)) * TCDEF
C-----IF THE PACK IS ACCUMULATING, BUT IS NOT DEEP ENOUGH FOR STABILITY
C----- IN THE DIFFUSION MOOEL, USE THE FOLLOWING SIMPLIFIED METHOO FOR
C----- DERIVING THE RAOIATION BALANCE
      IF(PHASE) 70,10,110
   10 IF(PREWE - 4.7) 20,50,50
C-----USE ONLY THE SHORTWAVE INPUT (THIS IMPLIES THAT THE ONLY COLD
C----- CONTENT GENERATED IN THE ACCUMULATING PACK IS THAT OF NEW SNOW)
   20 CALRIE = RADSWN
      RADLWN = 0.0
      CALL CALIN (CALRIE)
C-----MELT CAN OCCUR ONLY WHEN THE MEAN TEMPERATURE IS GREATER THAN THE
C----- SPECIFIED MINIMUM
      IF(AVETMC - TMPMLT) 30,30,40
   30 PREWE = PREWE + WATRIN
      RADLWN = -ENGBL
      ENGBL = 0.0
      WATRIN = 0.0
      FREWT = 0.0
      CALOF = 0.0
   40 RETURN
C-----THE PACK HAS JUST REACHED A SUFFICIENT DEPTH.  INITIALIZE THE
C----- DIFFUSION MOOEL, BUT RETAIN PSEUOO-CONTROL UNTIL THE DIFFUSION
C----- MODEL IS WELL ALONG INTO STABLE CONTROL
   50 PHASE = -1
   60 DREDY = 1
      PREWE = PREWE + WATRIN
      WATRIN = 0.0
      RAOLWN = - RAOSWN
      CALDF = 0.0
      ENGBL = 0.0
      SMTM1(1) = AMIN1 (AVETMC,0.0)
      SMTM1(2) = 0.0
      SMTM1(3) = 0.0
      FREWT = 0.0
      RETURN
C-----THE DIFFUSION MODEL HAS BEEN INITIALIZED PREVIOUSLY.  IF IT IS
C----- STILL STABLE AND IF THE PACK IS DEEP ENOUGH TO INSURE CONTINUEO
C----- STABILITY UNTIL MELT, RELINQUISH CONTROL COMPLETELY TO THE
C----- NORMAL METHOO OF COMPUTING THE RAOIATION BALANCE, INTERFACED WITH
C----- THE DIFFUSION MODEL
   70 IF(DREDY) 170,80,90
   80 PHASE = 0
      GO TO 10
   90 CALRIE = RADSWN
      CALAIR = 0.0
      RADLWN = 0.0
      IF(PREWE - 5.0) 230,230,100
  100 PHASE = 1
C-----USE THE NORMAL METHOD OF COMPUTING THE RADIATION BALANCE.  IF ANY
C----- OF THE PRECIP WAS SNOW, THE NET LONG WAVE RADIATION BALANCE IS
C----- ASSUMED TO BE ZERO
      GO TO 170
C-----SEE IF THIS IS THE ACCUMULATION PHASE OR MELT PHASE
  110 IF(PHASE - 2) 120,170
C-----ACCUMULATING - IF THE DIFFUSION MODEL IS STILL READY, GO ON TO THE
C----- NORMAL ROUTINE.  BUT IF NOT, JUST USE THE SIMPLE ONE
  120 IF(DREDY) 170,130,150
  130 CALRIE = RADSWN
      RADLWN = 0.0
      CALL CALIN (CALRIE)
      IF(AVETMC - TMPMLT) 140,40,40
  140 IF(PREWE - 4.7) 30,60,60
C-----SEE IF THE PEAK WATER EQUIVALENT DATE HAS BEEN REACHED
  150 IF(PEAKED) 160,170
  160 PHASE = 2
  170 IF(NDSND) 180,180,190
  180 RADLWN = 0.0
      CALAIR = 0.0
      GO TO 220
C-----TO COMPUTE THE LONG WAVE RADIATION COMPONENTS, CONVERT THE AIR
C----- AND SNOW TEMPERATURES TO POTENTIAL CALORIES BY THE STEFAN -
C----- BOLTZMANN FUNCTION, CALORIES = S * (T ** 4), WHERE
C----- S = 1.17E-7 CAL/((CM**2)(DEGREES KELVIN)**4), AND
C----- T = ABSOLUTE TEMPERATURE (DEGREES KELVIN)
  190 CALAIR = 1.17E-7 * ((AVETMC + 273.16) ** 4)
      USE = AVETMC
C-----IF THE SNOWPACK IS ISOTHERMAL, USE THE MINIMUM TEMPERATURE FOR
C----- COMPUTING THE BACK RADIATION
      IF(CALOF.EQ.0.0) USE = (TMPMIN - 32.0) * 0.555555556
C-----UNDER NO CIRCUMSTANCES MAY THE TEMPERATURE FOR COMPUTING THE BACK
C----- RADIATION BE GREATER THAN ZERO
      IF(USE.GT.0.0) USE = 0.0
      CALSND = 1.17E-7 * ((USE + 273.16) ** 4)
C-----COMPUTE THE LONG WAVE RADIATION COMPONENTS AS A FUNCTION OF THE
C----- FIRST, DETERMINE WHETHER THE SKIES ARE CLEAR OR CLOUDY
      IF(PRECIP) 200,200,210
C-----WITH CLEAR SKIES, THE DOWNWARD LONGWAVE RADIATION COEFFICIENT IS
C----- .757 (RUNOFF FROM SNOWMELT, EM1110-2-1406, US ARMY CORPS OF
C----- ENGINEERS, 1960, PAGE 7)
  200 SNOSKY = (1.0 - COVON) * ((0.757 * CALAIR) - CALSND)
C-----THE DOWNWARD LONGWAVE RADIATION COEFFICIENT IS 1.0 BENEATH THE
C----- FOREST CANOPY (OR BENEATH CLOUDY SKIES)
      SNDCAN = COVDN * (CALAIR - CALSND)
      RADLWN = SNDCAN + SNOSKY
      GO TO 220
C-----WITH CLOUDY SKIES, WHEN THE DOWNWARD LONGWAVE RADIATION COEFFI-
C----- CIENT IS 1.0 INSTEAD OF .757, THE ABOVE THREE EQUATIONS MAY BE
C----- REDUCED ALGEBRAICALLY TO THE FOLLOWING SINGLE EQUATION
  210 RADLWN = CALAIR - CALSND
C-----COMPUTE THE CALORIC INPUT OR LOSS FROM THE NET EFFECT OF SHORT
C----- WAVE AND LONG WAVE RADIATION
  220 CALRIE = RADSWN + RADLWN
C-----THE SNOWPACK TEMPERATURE DIFFUSION MODEL (LEAF, 1970, STUOY PLAN
C----- FS-RM-1602, NO. 224.  ROCKY MOUNTAIN FOREST AND RANGE EXP STA) IS
C----- INCORPORATEO TO CONTROL THE SNOWPACK TEMPERATURE AND COLD CONTENT
C----- DURING NON-ISOTHERMAL CONDITIONS.  SEE NOW IF THE DIFFUSION MODEL
C----- MAY BE USEO (DREDY MAY NOT BE -1 AND PASS THROUGH LINK SINCE IT
C----- IS NOT DESIGNED TO WORK WITH IT.  THE -1 IS USED TO INOICATE THAT
C----- THE RADIATION ROUTINES ARE TO BE USED EXCLUSIVELY).  IF IT MAY BE
C----- USED, PASS THROUGH THE LINKING ROUTINE WHICH INTERFACES THE
C----- DIFFUSION MODEL AND THE RADIATION ROUTINES
      IF(DREDY) 240,230,230
  230 CALL LINK (CALAIR,CALRIE,IRETRN)
      IF(IRETRN) 240,240,260
  240 IF(CALRIE) 250,260,270
  250 CALL CALOSS (CALRIE)
  260 RETURN
  270 CALL CALIN (CALRIE)
      RETURN
      END
```

Subroutine RAINED

```
      SUBROUTINE RAINED (TRAIN,AMTRAN)
C-----THIS SUBROUTINE COMPUTES THE EFFECT OF RAIN ON SNOW
      COMMON/ONLYCR/ AVETMC,BASTMF,CALOF,CDMAX,COVON,DREDY,ENGBL,
     1 ENGBLO,FIELDC,FREWT,LSUSD,NDSND,DNTRE,PHASE,PREWE,
     2 RCHRG,SMTM1(3),SMTM3,TCDEF,TMPMLT,TRSHLD,VEGTYP
      INTEGER DREDY,PHASE,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFRDM,EVAPTR,GENRD,PEAKED,PRECIP,RAOIN,
     1 RADLWN,RADSWN,TMPMAX,TMPMIN,WATRIN
C-----ADD THIS AMOUNT OF PRECIPITATION TO THE PREDICTED WATER EQUIVALENT
      PREWE = PREWE + AMTRAN
C-----SEE IF THERE IS A CALORIE DEFICIT IN THE PACK
      IF(CALDF) 50,50,10
C-----COMPUTE THE AMOUNT OF RAIN AT THIS TEMPERATURE THAT IS NEEDED TO
C----- WIPE OUT THE DEFICIT AND COMPARE IT WITH THE ACTUAL AMOUNT
   10 CALRAN = (80.0 + TRAIN) * 2.54
      AMTNED = CALDF/CALRAN
      COMPAR = AMTRAN - AMTNED
      IF(COMPAR) 30,20,40
C-----THERE WAS JUST ENOUGH TO WIPE OUT THE DEFICIT
   20 CALDF = 0.0
      ENGBL = ENGBL + CALRAN
      RETURN
C-----THERE WAS NOT ENOUGH TO WIPE IT OUT COMPLETELY.  JUST DEPLETE
C----- THE DEFICIT
   30 CALDF = CALDF - (CALRAN * AMTRAN)
      ENGBL = ENGBL + (CALRAN * AMTRAN)
      RETURN
C-----THERE WAS MORE THAN ENOUGH TO WIPE OUT THE DEFICIT.  THE AMOUNT
C----- OF RAIN NOT FROZEN IS FREE WATER
   40 FREWT = COMPAR
```

```
      CALL CALIN (TRAIN * COMPAR * 2.54)
      RETURN
C-----ALL OF THE RAIN IS ADDED TO THE FREE WATER AND CONTRIBUTES CALORIC
C----- INPUT TO THE PACK
   50 FREWAT = FREWT + AMTRAN
      CALL CALIN (TRAIN * AMTRAN * 2.54)
      RETURN
      END
```

Subroutine SNOWED

```
      SUBROUTINE SNOWED (TSNOW,AMTSNO)
C-----THIS SUBROUTINE COMPUTES THE EFFECTS OF A SNOW EVENT ON THE
C----- SNOWPACK
      COMMON/ONLYCR/ AVETMC,BASTMF,CALOF,COMAX,COVDN,DREDY,ENGBL,
     1 ENGBLC,FIELOC,FREWT,LSUSD,NOSNO,ONTRE,PHASE,PREWE,
     2 RCHRG,SMTM1(3),SMTM3,TCOEF,TMPMLT,TRSHLD,VEGTYP
      INTEGER DREDY,PHASE,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRO,PEAKED,PRECIP,RADIN,
     1 RADLWN,RADSWN,TMPMAX,TMPMIN,WATRIN
      REAL INTCPT
C-----SEE IF INTERCEPTION IS ALLOWED NOW
      IF(ALLOW) 10,30
C-----DETERMINE THE AMOUNT OF INTERCEPTED SNOW AS A FUNCTION OF COVER
C----- COMPOSITION AND COVER DENSITY (WATCH FOR OPENINGS AND DECIDUOUS
C----- FORESTS WITHOUT FOLIAGE)
   10 IF(COMAX) 20,30
   20 GO TO (40,50,40,30),VEGTYP
C-----NO INTERCEPTION
   30 INTCPT = 0.0
      GO TO 90
C-----LODGEPOLE PINE AND FOLIATED DECIDUOUS FORESTS
   40 PERCNT = 0.10
      GREAT = 0.20
      GO TO 60
C-----SPRUCE FIR
   50 PERCNT = 0.15
      GREAT = 0.30
   60 INTCPT = AMTSNO * PERCNT * (COVDN/COMAX)
      IF(ONTRE + INTCPT - GREAT) 80,80,70
   70 INTCPT = GREAT - ONTRE
   80 ONTRE = ONTRE + INTCPT
   90 NOSNO = 0
C-----ADD THIS AMOUNT OF PRECIPITATION TO THE PREDICTED WATER EQUIVALENT
      PREWE = PREWE + AMTSNO - INTCPT
C-----THE SNOW FALLING WHEN THE TEMPERATURE IS BETWEEN 35 AND 32 DEGREES
C----- DOES NOT ALTER THE CALORIC DEFICIT
      IF(TSNOW.GE.0.0) RETURN
C-----COMPUTE THE CALORIE DEFICIT FOR THIS SNOW BY THE EQUATION
C----- CALORIE DEFICIT = S(I)*DELTA T*P, WHERE
C----- S(I) = SPECIFIC HEAT OF ICE (.5 CAL/CM/DEGREES C),
C----- DELTA T = CHANGE IN TEMPERATURE WITH RESPECT TO FREEZING (0.0
C-----  DEGREES CENTIGRADE), AND
C----- P = PRECIPITATION IN CM (CONVERSION FACTOR = 2.54 CM/IN).
C----- THEREFORE, CALORIE DEFICIT = 0.5 * (TFORSNO) * (AMTSNO * 2.54)
      CALL CALOSS (TSNOW * (AMTSNO - INTCPT) * 1.27)
      RETURN
      END
```

Subroutine SNOVAP

```
      SUBROUTINE SNOVAP
C-----COMPUTE THE EVAPORATION FROM THE SURFACE OF THE SNOWPACK AS A
C----- FUNCTION OF THE COVER DENSITY AND REDUCE THE PACK ACCORDINGLY
      COMMON/ONLYCR/ AVETMC,BASTMF,CALDF,COMAX,COVDN,DREDY,ENGBL,
     1 ENGBLO,FIELDC,FREWT,LSUSD,NOSNO,ONTRE,PHASE,PREWE,
     2 RCHRG,SMTM1(3),SMTM3,TCOEF,TMPMLT,TRSHLD,VEGTYP
      INTEGER DREDY,PHASE,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRO,PEAKED,PRECIP,RADIN,
     1 RADLWN,RADSWN,TMPMAX,TMPMIN,WATRIN
      ETFROM = 2.0
      EVAPTR = (1.0 - COVDN) * EVAPTR
C-----SINCE DECIDUOUS FOREST AREAS MAY EVAPORATE FROM THE SNOWPACK WITH
C----- NO REGARD FOR PACK DEPTH, DO NOT ALLOW EVAPOTRANSPIRATION TO TAKE
C----- MORE THAN IS IN THE PACK
      IF(PREWE - EVAPTR) 10,10,20
   10 EVAPTR = PREWE
      PREWE = 0.0
      RETURN
   20 PREWE = PREWE - EVAPTR
      RETURN
      END
```

Subroutine DECDUS

```
      SUBROUTINE DECDUS
C-----CHECK FOR A CHANGE OF SEASON IN DECIDUOUS FORESTS
      COMMON/M/ALTYR(8),BOUND(6,8),CALDEF(8),COVDEN(8),CUT(8),
     1 DECIDS(2,8),DREADY(8),ENGBAL(8),EXPK(8),EXPK1(8),FREWAT(8),LAST1,
     2 LASUSD(8),LCOPY(14),NDYSNO(8),NEXTYR,NPLAN,NUM,NUNIT,ONTRES(8),
     3 PARAM(9),PHASE(8),PHISQ(8),PREWEO(8),RDIST(8),ROMAX(8),RECHRG(8),
     4 REGROW(2,8),RUNUM(8),RUWT(8),SEDINC,SEEDAT(2),SEEDYR(2),
     5 SIMTM1(3,8),TCOEFF(8),TYPCUT(8)
      INTEGER ALTYP,BOUND,DREADY,PHASE,RUNUM,SEEDAT,SEEDYR,TYPCUT
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRGD,RO(372),WE(372),WEO,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETO(372),PPT(372),RAD(372),TMAX(372),TMIN(372)
      EQUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(1490),ETO(1)),(BLOCK(1864),
     2 COMAX),(BLOCK(1865),VEGTYP),(BLOCK(1866),TRSHLD),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),DCOMAX),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEKDAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
      INTEGER PEKDAT,VEGTYP
C-----CHECK THE DATE (BETWEEN APRIL 1 AND OCTOBER 15, IT IS POSSIBLE TO
C----- HAVE FOLIAGE.  BUT DURING THE REMAINDER OF THE YEAR, IT IS
C----- ASSUMED THAT THE TREES ARE LEAFLESS)
      IF(NDAY.GE.187.OR.NDAY.LE.15) GO TO 30
C-----THE TREES SHOULD BE LEAFLESS.  IF THEY ARE NOT, SWITCH TO THE
C----- LOWER COVER DENSITY
   10 IF(VEGTYP - 4) 20,80
   20 VEGTYP = 4
      GO TO 60
C-----THE FOLIAGE MAY BE PRESENT, BUT IF THE PACK WATER EQUIVALENT IS
C----- MORE THAN 5 INCHES, THE TREES ARE STILL ASSUMED TO BE LEAFLESS
   30 DO 40 I = 1,NUNIT
      IF(PREWEO(I) - 5.0) 40,40,10
   40 CONTINUE
C-----THE FOLIAGE SHOULD BE PRESENT.  IF NOT, SWITCH TO THE HIGHER COVE
C----- DENSITY
      IF(VEGTYP - 3) 50,80
   50 VEGTYP = 3
   60 DO 70 I = 1,NUNIT
      TCOEFF(I) = SWITCH (TCOEFF(I),DECIDS(1,I))
      COVDEN(I) = SWITCH (COVDEN(I),DECIDS(2,I))
      COMAX = SWITCH (COMAX,DCOMAX)
   70 CONTINUE
   80 RETURN
      END
```

Subroutine GBIMON

```
      SUBROUTINE GBIMON
C-----GET THE BIMONTHLY RUNOFF
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRGD,RO(372),WE(372),WEO,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETO(372),PPT(372),RAD(372),TMAX(372),TMIN(372
      EQUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(1490),ETO(1)),(BLOCK(1864),
     2 COMAX),(BLOCK(1865),VEGTYP),(BLOCK(1866),TRSHLD),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),DCOMAX),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEKDAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
      INTEGER PEKDAT,VEGTYP
C-----APRIL 16 - APRIL 30
      BIMNTH(1) = 0.0
      DO 10 I = 202,216
   10 BIMNTH(1) = BIMNTH(1) + RO(I)
C-----MAY 1 - MAY 15
      BIMNTH(2) = 0.0
      DO 20 I = 218,232
   20 BIMNTH(2) = BIMNTH(2) + RO(I)
C-----MAY 16 - MAY 31
      BIMNTH(3) = 0.0
      DO 30 I = 233,248
   30 BIMNTH(3) = BIMNTH(3) + RO(I)
C-----JUNE 1 - JUNE 15
      BIMNTH(4) = 0.0
      DO 40 I = 249,263
   40 BIMNTH(4) = BIMNTH(4) + RO(I)
C-----JUNE 16 - JUNE 30
      BIMNTH(5) = 0.0
      DO 50 I = 264,278
   50 BIMNTH(5) = BIMNTH(5) + RO(I)
C-----JULY 1 - JULY 15
      BIMNTH(6) = 0.0
      DO 60 I = 280,294
   60 BIMNTH(6) = BIMNTH(6) + RO(I)
      RETURN
      END
```

Subroutine GPEAK

```
      SUBROUTINE GPEAK (IDATE1)
C-----GET THE PEAK 7-DAY FLOW AND PEAK WATER EQUIVALENT
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRGD,RO(372),WE(372),WEO,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETO(372),PPT(372),RAD(372),TMAX(372),TMIN(37
      EQUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(1490),ETO(1)),(BLOCK(1864),
     2 COMAX),(BLOCK(1865),VEGTYP),(BLOCK(1866),TRSHLD),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),DCOMAX),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEKDAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
      INTEGER PEKDAT,VEGTYP
C-----PEAK WATER EQUIVALENT
      PEAKWE = 0.0
      PEKDAT = 1
      DO 40 I = 1,372
      IF(TMAX(I) + 1.E50) 10,40
   10 IF(PEAKWE - WE(I)) 20,30,40
   20 PEAKWE = WE(I)
   30 PEKDAT = I
   40 CONTINUE
      CALL GDATE (PEKDAT,DATE)
C-----7-DAY PEAK FLOW
      IDATE1 = 1
      IDATE2 = 7
      PEAKRO = 0.0
      DO 110 I = 187,272
      IF(TMAX(I) + 1.E50) 50,110
   50 ACCUM = RO(I)
      J = 6
      K = I + 1
   60 IF(TMAX(K) + 1.E50) 70,80
   70 ACCUM = ACCUM + RO(K)
      J = J - 1
      IF(J) 80,90
   80 K = K + 1
      GO TO 60
   90 IF(PEAKRO - ACCUM) 100,110,110
  100 PEAKRO = ACCUM
      IDATE1 = I
      IDATE2 = K
```

```
.10 CONTINUE
----CONVERT THE DATES
    CALL GDATE (IDATE1,DATES(1))
    CALL GDATE (IDATE2,DATES(3))
    RETURN
    END
```

nction JWYDAT

```
   FUNCTION JWYDAT (MONTH,IDAY)
---CONVERT THE DATE TO A PSEUDO-JULIAN DATE SYSTEM, WHERE OCT 1 IS
--- DAY 1.  CONSIDER ALL MONTHS AS HAVING 31 DAYS
---PSEUDO-JULIAN WATER YEAR DATE CONVERSION TABLE
--- DAY  OCT  NOV  DEC  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP
---   1    1   32   63   94  125  156  187  218  249  280  311  342
---   2    2   33   64   95  126  157  188  219  250  281  312  343
---   3    3   34   65   96  127  158  189  220  251  282  313  344
---   4    4   35   66   97  128  159  19D  221  252  283  314  345
---   5    5   36   67   98  129  160  191  222  253  284  315  346
---   6    6   37   68   99  130  161  192  223  254  285  316  347
---   7    7   38   69  100  131  162  193  224  255  286  317  348
---   8    8   39   7D  101  132  163  194  225  256  287  318  349
---   9    9   40   71  102  133  164  195  226  257  288  319  35G
---  10   10   41   72  103  134  165  196  227  258  289  320  351
---  11   11   42   73  104  135  166  197  228  259  29D  321  352
---  12   12   43   74  1D5  136  167  198  229  26D  291  322  353
---  13   13   44   75  106  137  168  199  230  261  292  323  354
---  13   13   44   75  1D6  137  168  199  23D  261  292  323  354
---  14   14   45   76  1D7  138  169  20D  231  262  293  324  355
---  15   15   46   77  1D8  139  17D  2D1  232  263  294  325  356
---  16   16   47   78  1D9  14D  171  202  233  264  295  326  357
---  17   17   48   79  110  141  172  203  234  265  296  327  358
---  18   18   49   80  111  142  173  204  235  266  297  328  359
---  19   19   5D   81  112  143  174  2D5  236  267  298  329  360
---  20   20   51   82  113  144  175  2D6  237  268  299  33D  361
---  21   21   52   83  114  145  176  207  238  269  30G  331  362
---  22   22   53   84  115  146  177  2D8  239  27D  3D1  332  363
---  23   23   54   85  116  147  178  2D9  240  271  3D2  333  364
---  24   24   55   86  117  148  179  210  241  272  3D3  334  365
---  25   25   56   87  118  149  180  211  242  273  304  335  366
---  26   26   57   88  119  150  181  212  243  274  305  336  367
---  27   27   58   89  12D  151  182  213  244  275  306  337  368
---  28   28   59   9D  121  152  183  214  245  276  307  338  369
---  29   29   6D   91  122  153  184  215  246  277  308  339  370
---  3D   30   61   92  123       185  216  247  278  3D9  34D  371
---  31   31        93  124       186       248       310  341
   1F(MONTH - 10) 3D,2D,10
---NOVEMBER - DECEMBER
1D JWYDAT = ((MONTH-1D)*31) + 1DAY
   GO TO 40
---OCTOBER
20 JWYDAT = 1DAY
   GO TO 40
---JANUARY - SEPTEMBER
3D JWYDAT = ((MONTH+2)*31) + 1DAY
40 1F(JWYDAT.GT.0.AND.JWYDAT.LT.373) RETURN
   WRITE (6,910) MONTH,1DAY
10 FORMAT(*01NVALID MONTH/DAY*15,*/*12,* - JOB ABORTED*)
   CALL ABORT
   END
```

broutine OUTPT

```
   SUBROUTINE OUTPT
---OUTPUT THE COMPILED RESULTS AND WRITE THE BASIC DATA ON THE FILE
   COMMON DATIME(2),DECMAL,NRMANG,NSAVEO,NYEARS,PLNOPT(19),PLUNIT(6),
  1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
   INTEGER DATIME,PLNDPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
   COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
  1 NAME,NDAY,RCHRGO,RD(372),WE(372),WEO,YEAR,YRTOT(3)
   INTEGER DATE,DATES,YEAR
   DIMENSION BIMNTH(6),ETD(372),PPT(372),RAD(372),TMAX(372),TMIN(372)
   EDUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
  1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(1490),ETD(1)),(BLOCK(1864),
  2 CDMAX),(BLDCK(1865),VEGTYP),(BLOCK(1866),TRSHLD),(BLOCK(1867),
  3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),DCDMAX),(BLOCK(1872),
  4 ISOTRM),(BLOCK(1873),PEKDAT),(BLOCK(188D),BIMNTH(1)),
  5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRG)
   INTEGER PEKDAT,VEGTYP
   INTEGER HEADER(2)
   DATA HEADER/8HNATURAL ,8HALTERED /
---CHECK THE LINE COUNTER
   IF(LINES) 10,1D,2G
10 WRITE (6,910) REGION,DATIME,PLUNIT,HEADER(NRMANG)
1D FORMAT(*1*8A10,32X2A10/1X6A1D,54XA8,*CONDITIONS*/
  1 *GYEAR    - - - -BIMONTHLY GENERATED RUNOFF- - - -     - - - - - - -
  2YEARLY - - - - - - -     9/3G    - - - - - - - - PEAK - - - - - - - -*/
  3 *          APRIL    MAY     MAY     JUNE    JUNE    JULY     GEN
  4       CHANGE CHANGE    RECH                          7-DAY*/
  5 *          16-30   1-15  16-31   1-15  16-30   1-15       RO     PPT
  6    ET    RECH    W.E.     REQ    W.E.    DATE  GENRO       DATES*/)
   LINES = 50
---PRINT THE LINE
20 WRITE (6,920) YEAR,BIMNTH,YRTDT,CHANGR,CHANGW,RCHRGO,PEAKWE,DATE,
  1 PEAKRO,DATES
2D FORMAT(2XI3,1X13F7.2,2XI2,*/*12,F7.2,2(2XI2,*/*12))
   LINES = LINES - 1
   RETURN
   END
```

nction SWITCH

```
    FUNCTION SWITCH (VALNOW.STORED)
---SWITCH THE PRESENT VALUE AND ITS STORED COUNTERPART
    SWITCH = STORED
    STORED = VALNOW
    RETURN
    END
```

Function TC

```
      FUNCTION TC (CD)
C-----GENERATE THE TRANSMISSIVITY COEFFICIENT WHICH CORRESPONDS TO THE
C----- SPECIFIED COVER DENSITY
C-----THE .06 BELOW IS DEPENDENT ON THE FUNCTION VALUES AT STATEMENT 40
      IF(CD - .06) 10,10,20
   10 TC = 1.0
      RETURN
   20 IF(CD - 1.0) 40,30,30
   30 TC = 0.0
      RETURN
C-----THE FOLLOWING RELATIONSHIP REPRESENTS THE RESULTS OBTAINED DURING
C----- THE CALIBRATION OF THE WATER BALANCE MODEL WHEN THE COVER DENSITY
C----- AND TRANSMISSIVITY COEFFICIENT WERE ALLOWED TO VARY TO ESTABLISH
C----- REASONABLE MELT RATES ON EACH OF THE FRASER EXPERIMENTAL FOREST
C----- SUBSTATIONS IN 1969.  ONCE A COMBINATION HAD BEEN ESTABLISHED,
C----- IT WAS TESTED FOR 29 OTHER YEARS AND WAS FOUND TO BE SATISFACTORY
   40 TC = 0.18995/ICD ** 0.5786)
      RETURN
      END
```

Program NORMAL

```
      OVERLAY (OLAYS,2,1)
      PROGRAM NORMAL
C-----PERFORM THE NORMAL SIMULATION AND CREATE THE BASIC DATA FILE
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,PLNOPT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
      INTEGER DATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
      COMMON/N/ACCUM,AIRTMC(4),ASPECT,CALDEF,COVDEN,DECIDS(3),DREADY,
     1 ENGBAL,ETDALY(12),FRACTN,FREWAT,ID,IM,IMN,IMX,IP,IY,LASUSD,LAT,
     2 NDYSND,ONTRES,PEKPPT,PHASE,POTENT(24),POTRAD,PPTNOW,PREWED,
     3 RADSUB,RECHPG,SIMTM1(3),SLOPE,SLPASPI24),SUMMER,TCOEFF,
     4 VARFMT(7),VARIN(6)
      INTEGER ASPECT,DREADY,PHASE,RADSUB,SLOPE,VARFMT
      COMMON/TIME/CANREF,CDMAX2,CONAV
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,DATE(2),OATES(4),LINES,
     1 NAME,NDAY,RCHRGO,RO(372),WE(372),WED,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETD(372),PPT(372),RAD(372),TMAX(372),TMIN(372)
      EOUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(149D),ETD(1)),(BLOCK(1864),
     2 CDMAX),(BLOCK(1865),VEGTYP),(BLOCK(1866),TRSHLD),(BLDCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),DCDMAX),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEKDAT),(BLOCK(188D),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRD)
      INTEGER PEKDAT,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRO,PEAKED,PRECIP,RADIN,
     1 RADLWN,RADSWN,TMPMAX,TMPMIN,WATRIN
      CALL CORE (-1)
      REWIND 16
C-----IF THIS IS FOR DATA BASE EXTENSION ONLY, BYPASS THE NORMAL PARTS
      IF(NRMANG.ED.0) GO TO 100
C-----READ THE STATION PARAMETERS
      CALL GPARAM
      ENGBAL = 0.0
      FREWAT = 0.0
      LASUSD = 0
      NDYSNO = 0
      ONTRES = 0.0
      PHASE = 0
      RCHRGO = RECHRG
      WEO = PREWED
      BLOCK(1862) = TCOEFF
      BLOCK(1863) = COVDEN
      BLOCK(1869) = DECIDS(1)
      BLOCK(187D) = DECIDS(2)
      BLOCK(1871) = DECIDS(3)
C-----THE TIME RELATED PARAMETERS MUST BE DEFINED FOR USE IN SUBROUTINES
C----- CANVAP AND EVTRAN, EVEN THOUGH THEY REMAIN CONSTANT
      CDMAX2 = CDMAX/2.0
      IF(COVDEN) 10,20
   1D CONAV = 0.5
      CANREF = 0.9
      GO TO 30
   20 CONAV = 1.0
      CANREF = 0.5
C-----PRINT THE TITLE SHEET IF THE OUTPUT IS TO BE PRINTED
   30 IF(PLNOPT(1).NE.0) CALL TITLEN
      LINES = 0
C-----PERFORM THE SIMULATION ON EACH YEAR AS A UNIT.  READ THE SPECIFIED
C----- CONDITIONS CARD AND THE DATA FOR THE NEXT YEAR
   4D CALL GET1YR (IEND)
      IF(IEND.NE.0) GU TO 90
      BLOCK(1874) = PREWED
      BLOCK(1875) = RECHRG
C-----PERFORM THE SIMULATION ON EACH DAY
      PPTNOW = 0.0
      ALLOW = 1.0
      DO 50 I = 1,3
   50 YRTOT(I) = 0.0
      DREADY = 0
      DO 80 NDAY = 1,372
      IF(TMAX(NDAY) + 1.E50) 60,80
C-----GENERATE THE DATA FOR THIS DAY
   60 CALL GENDAT
C-----MAKE THE PASS THROUGH THE WATER BALANCE ROUTINES
      CALL WATBAL ICALDEF,CDMAX,COVDEN,DREADY,ENGBAL,FREWAT,LASUSD,
     1 NDYSNO,ONTRES,PHASE,PREWED,RECHRG,SIMTM1(1),SIMTM1(2),SIMTM1(3),
     2 TCOEFF,TMPMLT,TRSHLD,VEGTYP,WILTPT)
C-----STORE THESE RESULTS
      WE(NDAY) = PREWEQ
      RO(NDAY) = GENRO
      YRTOT(I) = YRTOT(I) + GENRO
      YRTOT(3) = YRTOT(3) + EVAPTR
C-----WATCH FOR THE MANDATORY ISOTHERMAL DATE
      IF(ISOTRM - NDAY) 8G,70
   70 DREADY = -1
      CALDEF = 0.0
   80 CONTINUE
C-----GET THE BIMONTHLY FLOWS AND THE PEAK INFORMATION
```

```
      CALL GRIMON
      ITEMP = PEKDAT
      CALL GPEAK (IDATE1)
C-----STORE THE FINAL INFORMATION AND WRITE THE RECORO
      BLOCK(1876) = YRTOT(1)
      BLOCK(1877) = YPTOT(3)
      BLOCK(1878) = RECHRG - RCHRGD
      RCHRGO = PECHRG
      BLOCK(1879) = PREWED - WEO
      WED = PREWEQ
C-----NOTE THAT -PEKDAT- WAS REOEFINED BY SUBPOUTINE GPEAK, SO
C----- -BLOCK(1887)- MAY OR MAY NOT BE THE SAME AS -BLOCK(1873)-
      BLOCK(1897) = PEKDAT
      PEKOAT = ITEMP
      BLOCK(1889) = IOATE1
      CALL PUTREC (16,BLOCK,1889)
C-----IF THE OUTPUT IS NOT TO BE PRINTED, GO ON TO THE NEXT YEAR. IF IT
C----- IS, OUTPUT THE COMPILEO RESULTS
      IF(PLNOPT(1).EQ.0) GO TO 4D
      YRTOT(2) = PPT(371)
      CHANGR = BLOCK(1878)
      CHANGW = BLOCK((879)
      CALL OUTPT
      GD TO 40
C-----THE NORMAL SIMULATION IS COMPLETE, SD ENO -SCRFIL-
   9D END FILE 16
  10D CALL EXTEND
      CALL CORE (0)
C-----RETURN TO THE PRIMARY OVERLAY
      END
```

Subroutine EXTEND

```
      SUBROUTINE EXTENO
C-----EXTEND (OP CONTRACT) THE OATA BASE ANO, IF SPECIFIEO, SAVE IT
      COMMON OATIME(2),OECMAL,NRMANG,NSAVEO,NYEARS,PLNOPT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEORN2,WEIGHT
      INTEGER OATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEORN2
      COMMON/E/CON,(OI9),NBLOCK,ORIGYR
      INTEGER ORIGYR
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,OATE(2I,OATES(4),LINES,
     I NAME,NDAY,RCHRGC,RO(372),WE(3T2),WEO,YEAR,YRTDT(3)
      INTEGER DATE,OATES,YEAR
      OIMENSION BIMNTH(6),ETO(372),PPT(3T2),RAO(372),TMAX(372),TMIN(3T2)
      EOUIVALENCE (BLOCK(2),TMAX[1)),(BLOCK(3T4),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK[1118),RAO(1)),(BLOCK(1490),ETO(1)),(BLOCK[1864),
     2 COMAX),(BLOCK(1865),VEGTYP),(BLOCK(1866),TRSHLO),IBLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK[18T1),OCOMAX),(BLOCK(18T2),
     4 ISOTRM),(BLOCK(1873),PEKOAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
      INTEGER PEKOAT,VEGTYP
      CALL CORE (-1I
      MYEARS = NYEARS
      LINES = 0
C-----IF THE FILE IS TO BE SAVEO, WRITE THE IO RECORD
      IF(SAVE) 10,30
   10 NSAVEO = NSAVEO + 1
      OO 20 I = 1,6
   20 ID(I) = PLUNIT(I)
      ID(T) = NYEARS
      ID(8) = OATIME(1)
      IO(9) = OATIME(2)
      CALL PUTREC (15,ID,9)
C-----PREPARE THE FILES.  IF OUTPUT IS WANTEO, PRINT THE HEAOING
   30 REWINO 16
      PEWINO 11
      GD TO 60
C-----COPY THE DRIGINAL OATA
   50 CALL PUTREC (11,BLOCK,1889)
      IF(SAVE.NE.D) CALL PUTREC (15,BLOCK,1889)
      YRNEXT = BLOCK(1)
      MYEARS = MYEARS - 1
      IF(MYEARS) 110,110,60
   60 CALL GETPEC (16,BLOCK,1889,IENO)
      IF(IEND) 70,50
C-----EXTEND THE OATA BASE.  START BY COMPUTING THE NUMBER OF YEARS IN
C----- THE ORIGINAL OATA BASE ANO THE PRESENT POSITION OF THE SCRATCH
C----- FILE
   TO DRIGYR = NYEARS - MYEARS
      NBLDCK = ORIGYR + 1
C-----OEFINE THE OEGREE OF THE CONSTANT TO BE USEO IN THE SELECTION
C----- PROCESS
      CON = 10.
      IF(ORIGYR.GE.10) CON = CON * 10.
      IF(ORIGYR.GE.100) CON = CON * 10.
   90 CALL RANSEL
      YRNEXT = YRNEXT + 1.0
C-----SIMULATE THE NORMAL CONDITIONS
      CALL SIMNRM
      IF(PLNOPT(2).EO.0) GO TO 100
      YRTOT(2) = PPT(371)
      CHANGR = BLOCK(1878)
      CHANGW = BLOCK(1879)
      YEAP = YRNEXT
      CALL OUTPT( (INT(BLOCK(1)))
  100 TEMP = BLGCK(1)
      TEMP = BLOCK(1)
      BLOCK(1) = YRNEXT
      CALL PUTREC (11,BLOCK,1889)
      IF(SAVE.NE.0) CALL PUTREC (15,BLOCK,1889)
      BLOCK(1) = TEMP
      MYEARS = MYEARS - 1
      IF(MYEARS) 110,110,90
  110 IF(SAVE.NE.0) END FILE 15
      CALL CORE (0)
C-----RETURN TO THE MAIN OVERLAY
      END
```

Subroutine GENDAT

```
      SUBROUTINE GENDAT
C-----GENERATE THE DATA FOR THIS SUBSTATION
      COMMON/N/ACCUM,AIRTMC(4),ASPECT,CALDEF,CDVDEN,DECIDS(3),OREADY,
     1 ENGBAL,ETDALY(12),FRACTN,FREWAT,IO,IM,IMN,IMX,IP,IY,LASUSO,LAT,
     2 NDYSNO,ONTRES,PEKPPT,PHASE,POTENT(24),POTRAD,PPTNOW,PREWED,
     3 RADSUB,RECHRG,SIMTM1(3),SLOPE,SLPASP(24),SUMMER,TCOEFF,
     4 VARFMT(7),VARIN(6)
      INTEGER ASPECT,DREADY,PHASE,RADSUB,SLOPE,VARFMT
      COMMON/UTILTY/BLDCK(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRGD,RO(372),WE(372),WED,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETD(372),PPT(372),RAD(3T2),TMAX(372),TMIN(372)
      EOUIVALENCE (DLOCK(2),TMAX(1)),(BLOCK(3T4),TMIN(1)),(BLDCK(746),
     1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(149D),ETD(1)),(BLOCK(1864),
     2 CDMAX),(BLOCK((B65),VEGTYP),(BLDCK(1866),TRSHLD),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(I871),DCOMAX),(BLDCK(18T2),
     4 ISDTRM),(BLOCK(18T3),PEKDAT),(BLDCK(1880),BIMNTM(1)),
     5 (BLOCK(1886),PEAKWE),IBLOCK(1888),PEAKRO)
      INTEGER PEKDAT,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFRDM,EVAPTR,GENRD,PEAKED,PRECIP,RADIN,
     1 RADLWN,RAOSWN,TMPMAX,TMPMIN,WATRIN
      EOUIVALENCE (DATE(1),MONTH)
      DIMENSION ODFACT(26)
      DATA ODFACT/ .20, .35, .45, .51, .56, .59, .62, .64, .655, .6T,
     1 .682, .69, .7D, .71, .T15, .72, .722, .T24, .726, .728, .T3,
     2 .T34, .T38, .742, .746, .75/
C-----DEFINE THE UNADJUSTED PRECIP
      PPMSTR = PPT(NDAY) - PPTNOW
C-----AOJUST THE TEMPERATURES
      TMPMAX = AIRTMC(1) + (TMAX(NDAY) * AIRTMC(2)I
      TMPMIN = AIRTMC(3) + (TMIN(NDAY) * AIRTMC(4))
      IF(TMPMAX - TMPMIN) 1D,2D,20
   1D TEMP = TMPMAX
      TMPMAX = TMPMIN
      TMPMIN = TEMP
C-----GET THE DATE ANO POTENTIAL RADIATION
   2D CALL GDATF (NOAY,OATEI
      CALL RAOCMP I(OATE(1)*100)+OATE(2)I
C-----COMPUTE THE INCOMING RADIATION AT THE BASE STATION FROM THE
C----- POTENTIAL BY THE OEGREE-OAY METHOO
      GO TO (5D,5D,50,50,6D,70,TO,70,60,50,50,50),MDNTH
C-----OCTOBER - APRIL, OEGREE DAYS = .44 * TEMPMAX - 15.9 (+1.0 FOR
C----- SUBSCRIPTING)
   50 OO = (0.44 * TMPMAX) - 14.9
      GO TO 100
C-----MAY ANO SEPTEMBER, OEGREE OAYS = .53 * TEMPMAX - 19.5 (+1.D FOR
C----- SUBSCRIPTING)
   60 OO = (0.53 * TMPMAX) - 18.5
      GO TO 100
C-----JUNE, JULY AND AUGUST, OEGREE OAYS = .63 * TEMPMAX - 24.1 (+1.0
C----- FOR SUBSCRIPTING), EXCEPT ON OAYS WITH PRECIP.  DURING THESE
C----- MONTHS, USE A CONSTANT 44 PERCENT ON PRECIP OAYS
   70 IF(PPMSTR) 90,90,80
   80 RAOHRZ = POTRAO * 0.44
      GO TO 150
   90 OO = (0.63 * TMPMAX) - 23.1
C-----WATCH FOR THE BOUNOARY VALUES, 0. ANO 25.  (WITH THE 1.0 AOOEO
C----- ABOVE, THE SUBSCRIPTS FOR THE TABULAR VALUES VARY FROM 1 TO 26)
  100 IF(OD - 1.0) 110,110,12D
C-----USE THE FIRST TABLE VALUE (NO INTERPOLATION IS NECESSARY)
  110 RADHRZ = POTRAO * OOFACT(1)
      GO TO 150
  12D IF(OO - 26.0) 140,130,130
C-----USE THE LAST TABLE VALUE (NO INTERPOLATION IS NECESSARY)
  130 RAOHRZ = POTRAO * OOFACT(26)
      GO TO 150
C-----THE SUBSCRIPT IS IN THE PROPER RANGE.  OBTAIN THE INTERPOLATION
C----- FRACTION ANO SUBSCRIPTS THROUGH TRUNCATION OF -OD-
  140 J1 = OO
      OO1 = J1
      J = J1 + 1
C-----THE TERM (OO-OO1)/1.0 IS THE INTERPOLATION FRACTION
      RADHRZ = PDTRAO * (OOFACT(J1) + I(OOFACT(J) - OOFACT(J1)) * (DO -
     1 OO1)))
C-----AOJUST THE POTENTIAL EVAPOTRANSPIRATION AS COMPUTEO BY THE HAMON
C----- METHOO FOR AVAILABLE RAOIATION AS A PERCENT OF POTENTIAL
  150 EVAPTR = ETOALY(MONTH) * (RAOHRZ/POTRAO)
C-----AOJUST THE RADIATION AT THE BASE STATION FOR SLOPE ANO ASPECT
      I = RAOSUB + 1
      IF(I.GT.24) I = 1
      RAOIN = RAOHRZ * (SLPASP(RAOSUB) + ((SLPASP(I) - SLPASP(RADSUB))
     1 * FRACTN))
C-----ADJUST THE PRECIP TO ENSURE REACHING THE PEAK WATER EOUIVALENT
      IF(PPMSTR) 160,160,170
  160 PRECIP = 0.D
      GD TO 200
  1TO IF(PEKPPT - PPTNOW) 19D,190,180
  180 PRECIP = PPMSTR * ((PEAKWE - PREWEO)/(PEKPPT - PPTNOW))
      PEAKEO = 0.0
      GO TO 200
C-----AFTEP THE PEAK, AOJUST THE BASE STATION PRECIP BY THE CONSTANT
C----- SUMMER FACTOR
  190 PRECIP = PPMSTR * SUMMER
      PEAKEO = 1.0
C-----OO NOT ALLOW INTERCEPTION IN JULY ANO AUGUST
      ALLOW = 1.D
      IF(NDAY.GE.280.AND.NOAY.LE.341) ALLOW = 0.0
  200 IF(VEGTYP.NE.3.AND.VEGTYP.NE.4) GO TO 270
C-----CHECK THE OATE (BETWEEN APRIL 1 ANO OCTOBER 15, IT IS POSSIBLE TO
C----- HAVE FOLIAGE.  BUT DURING THE REMAINOER OF THE YEAR, IT IS
C----- ASSUMED THAT THE TREES ARE LEAFLESS)
      IF(NDAY.GE.187.OR.NDAY.LE.15) GO TO 230
C-----THE TPEES SHOULD BE LEAFLESS.  IF THEY ARE NOT, SWITCH TO THE
C----- LOWER COVER OENSITY
  21D IF(VEGTYP - 4) 220,270
  220 VEGTYP = 4
      GO TU 260
C-----THE FOLIAGE MAY BE PRESENT, BUT IF THE PACK WATER EOUIVALENT IS
C----- MORE THAN 5 INCHES, THE TREES ARE STILL ASSUMED TO BE LEAFLESS
  230 IF(PREWEO - 5.0) 240,240,210
C-----THE FOLIAGE SHOULD BE PRESENT.  IF NOT, SWITCH TO THE HIGHEP COVER
C----- DENSITY
  240 IF(VEGTYP - 3) 250,2TD
  250 VEGTYP = 3
  260 TCDEFF = SWITCH (TCDEFF,OECIDS(1))
      COVOEN = SWITCH (COVOEN,OECIOS(2))
      COMAX = SWITCH (COMAX,OECIOS(3))
```

```
----STORE THESE VALUES FOR OUTPUT TO THE BASIC FILE
 270 TMAX(NOAY) = TMPMAX
     TMIN(NOAY) = TMPMIN
     YRTOT(2) = YRTOT(2) + PRECIP
     PPTNOW = PPT(NOAY)
     PPT(NOAY) = YRTOT(2)
     RAO(NDAY) = RADIN
     ETC(NDAY) = EVAPTR
     RETURN
     END
```

ubroutine GET1YR

```
     SUBROUTINE GET1YR (IEND)
----READ THE SPECIFIED CONOITIONS CARO AND THE OATA
     COMMON OATIME(2),OECMAL,NRMANG,NSAVEO,NYEARS,PLNOPT(19),PLUNIT(6),
    1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
     INTEGER OATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEORN2
     COMMON/N/ACCUM,AIRTMC(4),ASPECT,CALOEF,COVOEN,OECIOS(3),OREADY,
    I ENGBAL,ETOALY(I2),FRACTN,FREWAT,IO,IM,(MN,IMX,IP,(Y,LASUSO,LAT,
    2 NOYSNO,ONTRES,PEKPPT,PHASE,POTENT(24),PCTRAO,PPTNOW,PREWEO,
    3 RAOSUB,RECHRG,SIMTM1(3),SLOPE,SLPASP(24),SUMMER,TCOEFF,
    4 VARFMT(7),VARIN(6)
     (INTEGER ASPECT,OREAOY,PHASE,RADSUB,SLOPE,VARFMT
     COMMON/UTILTY/BLOCK(1BB9),CHANGR,CHANGW,DATE(2),OATES(4),LINES,
    1 NAME,NOAY,RCHRGO,RO(372),WE(372),WEO,YEAR,YRTOT(3)
     (INTEGER OATE,OATES,YEAR
     OIMENSION BIMNTH(6),ETO(372),PPT(372),RAO(372),TMAX(372),TMIN[372)
     EOU(VALENCE (BLOCK(2),TMAX(I)),(BLOCK(374),TMIN(1)),(BLOCK(746),
    I PPT(1)),(BLOCK(111B),RAO(1)),(BLOCK(I490),ETO(1)),(BLOCK(1B64),
    2 COMAX),IBLOCK(1865),VEGTYP),IBLOCKI1866),TRSHLO),(BLOCK(1B67),
    3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1B71),OCOMAX),(BLOCK(1B72),
    4 ISOTRM),(BLOCK(1873),PEKOAT),(BLOCK(1880),BIMNTH(1)),
    5 (BLOCKI1BB6),PEAKWE),(BLOCK(1BBBI,PEAKRO)
     (INTEGER PEKOAT,VEGTYP
     DIMENSION IDATES(6)
     READ (19) NAME,PEAKWE,IOATES
     IF(NAME.NE.IOHENO OF NAT) GO TO 10
     IENO = 1
     RETURN
  10 IENO = 0
----CONVERT THE OATES TO THE PSEUDO-JULIAN FORM  AND STORE THE YEAR
---- ALONG WITH THE OECIMAL ID
     PEKOAT = JWYDAT (1OATES(1),IDATES(2))
     ISOTRM = JWYOAT (1DATESI4),1OATESI5))
     YEAR = 1OATES(6)
     BLOCKI1) = FLOAT(YEAR) + OECMAL
----REAO THE OATA ANO COMPARE THE YEARS
     CALL REAOAT
----OEFINE THE ACCUMULATED PRECIP UP TO THE DAY OF THE PEAK
  20 IFITMAX(PEKOAT-1I + 1.E50) 40,30
  30 PEKOAT = PEKOAT - 1
     GO TO 20
  40 PEKPPT = PPT(PEKOAT-1)
     RETURN
     END
```

ubroutine GPARAM

```
     SUBROUTINE GPARAM
----REAO THE STATION PARAMETERS FROM THE PROOFREAO FILE
     COMMON DATIME(2),OECMAL,NRMANG,NSAVED,NYEARS,PLNDPT(19),PLUNITI6),
    1 RECOVR,REGION(8I,REGOPT(5),SAVE,SEDRN2,WEIGHT
     INTEGER DATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
     COMMON/N/ACCUM,A1RTMC(4),ASPECT,CALOEF,COVOEN,OECIOS(3),DREAOY,
    1 ENGBAL,ETOALY(12I,FRACTN,FREWAT,1D,IM,IMN,IMX,1P,IY,LASUSD,LAT,
    2 NDYSNO,ONTRES,PEKPPT,PHASE,POTENT(24),POTRAD,PPTNOW,PREWEO,
    3 RAOSUB,RECHRG,SIMTM1(3),SLOPE,SLPASP(24),SUMMER,TCOEFF,
    4 VARFMT(7),VAR1N(6)
     INTEGER ASPECT,DREADY,PHASE,RAOSUB,SLOPE,VARFMT
     COMMON/UT(LTY/BLOCK(1BB9),CHANGR,CHANGW,DATE(2),DATES(4),L1NES,
    1 NAME,NDAY,RCHRGO,RO(372),WE(372),WEO,YEAR,YRTDT[3)
     INTEGER OATE,DATES,YEAR
     OIMENSION BIMNTH(6),ETO(372),PPT(372),RAO(372I,TMAX(372),TMINI372)
     EOUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
    I PPTI1)),(BLOCK(111B),RAD(1)),(BLOCK(1490),ETO(1)),(BLOCK(1864),
    2 COMAX),(BLOCK(IB65),VEGTYP),(BLOCK(1866),TRSHLO),IBLOCK(1867),
    3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),DCOMAX),(BLOCK(1872),
    4 1SOTRM),(BLOCK(1873),PEKOAT),(BLOCK(1880),B1MNTH(1)),
    5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
     INTEGER PEKOAT,VEGTYP
     READ (19) TCOEFF,COVOEN,CDMAX,VEGTYP,TRSHLD,TMPMLT,WILTPT,OEC1DS,
    1 LAT,ASPECT,SLOPE,SIMTM1(2),PREWEO,RECHRG,ETOALY,AIRTMC,SUMMER
----IF THE TRANSM(SSIVITY COEFFICIENTS ARE NOT SPECIFIEO, COMPUTE THEM
     IF(TCOEFF.LE.C.O) TCOEFF = TC (COVOEN)
     IF(DECIDS(I).LE.O.O) OECIOS(1I = TC (DECIOS(2))
----CONVERT THE PACK TEMPERATURE TO CALORIE OEFICIT (AS A POSITIVE
---- OUANTITY), AND OEFINE THE GROUND TEMPERATURE FOR THE SIMULATION
     CALOEF = -SIMTMI(2) * PREWEO * 1.27
     SIMTM1(I) = SIMTM1(2)
     S(MTMI(3) = -I.5
----READ THE RAD(ATION, THEN THE VARIABLE FORMAT
     READ (I9) POTENT,SLPASP
     READ (I9) VARFMT,NFILE,(M,1O,IY,IMX,IMN,IP
----POSITION THE UNEDITEO FILE ANO READ THE F1RST CARO
     CALL SKPFIL (NFILE)
     READ (IO,VARFMT) VAR(N
     RETURN
     END
```

ibroutine OUTPT1

```
     SUBROUT(NE OUTPT1 (YRFROM)
(----OUTPUT THE COMPILED RESULTS ANO WRITE THE BASIC DATA ON THE FILE
     COMMON DAT(ME(2),OECMAL,NRMANG,NSAVED,NYEARS,PLNOPT(19),PLUNIT(6),
    1 RECOVR,REG(ON(B),REGOPT(5),SAVE,SEORN2,WEIGHT
     INTEGER DAT(ME,PLNOPT,PLUN(T,RECOVR,REGION,REGOPT,SAVE,SEORN2
     COMMON/UTILTY/BLOCK(IBB9),CHANGR,CHANGW,OATE(2),OATES(4),L(NES,
    1 NAME,NDAY,RCHRGO,RO(372),WE(372),WEO,YEAR,YRTOT(3)
     INTEGER OATE,OATES,YEAR
     OIMENS(ON BIMNTH(6),ETO(372),PPT(372),RAO(372),TMAX(372),TMIN(372)
     EOU(VALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TM(N(1)),(BLOCK(746),
    I PPT(1)),(BLOCK(III8),RAO(1)),(BLOCK(1490),ETO(1)),(BLOCK(I864),
    2 COMAX),(BLOCK(1B65),VEGTYP),(BLOCK(1B66),TRSHLD),(BLOCK(1B67),
    3 TMPMLT),(BLOCK(IB68),WILTPT),(BLOCK(IB71),OCOMAX),(BLOCK(IB72),
    4 ISOTRM),(BLOCK(IB73),PEKOAT),(BLOCK(1880),BIMNTH(1)),
    5 (BLOCK(IBB6),PEAKWE),(BLOCK(1BBB),PEAKRO)
     INTEGER PEKOAT,VEGTYP
     INTEGER YRFROM
C-----CHECK THE LINE COUNTER
     IF(L(NES) 10,10,20
  10 WRITE (6,9IO) REGION,OAT(ME,PLUNIT
 9IO FORMAT(*1*BA10,32X2A10/1X6AIO,45X*EXTENOEO NATURAL CONOITIONS*/
    1 *0        *
    1  *YEAR    - - - -B(MONTHLY GENERATEO RUNOFF- - - -    - - - - - - -
    2YEARLY - - - - - -     9/30    - - - - - - - - PEAK - - - - - - - -*/
    3 *         *
    3  *         APRIL    MAY     MAY     JUNE    JUNE    JULY     GEN
    4       CHANGE CHANGE   RECH                      7-OAY*/
    5 * (FROM)*
    5  *         16-30   1-I5  I6-3I    1-15  16-30    1-I5      RO     PPT
    6   ET    RECH    W.E.     REO    W.E.    DATE   GENRO      OATES*/)
     LINES = 50
C-----PRINT THE LINE
  20 WRITE (6,920) YRFROM,YEAR,BIMNTH,YRTOT,CHANGR,CHANGW,RCHRGO,
    1 PEAKWE,OATE,PEAKRO,OATES
 920 FORMAT(* (*I3,*)*2XI3,IXI3F7.2,2XI2,*/*12,F7.2,2(2X12,*/*I2))
     LINES = LINES - 1
     RETURN
     END
```

Subroutine RADCMP

```
      SUBROUT(NE RADCMP (MMOD)
C-----COMPUTE THE POTENTIAL RAOIATION AT THE BASE STATION
      COMMON/N/ACCUM,AIRTMC(4),ASPECT,CALOEF,COVOEN,OECIDS(3),DREADY,
     1 ENGBAL,ETOALY(12),FRACTN,FREWAT,IO,IM,IMN,IMX,1P,1Y,LASUSD,LAT,
     2 NOYSNO,ONTRES,PEKPPT,PHASE,POTENT[24),POTRAD,PPTNOW,PREWEO,
     3 RAOSUB,RECHRG,S1MTM1(3),SLOPE,SLPASP(24),SUMMER,TCOEFF,
     4 VARFMT(7),VARIN(6I
      (INTEGER ASPECT,DREADY,PHASE,RADSUB,SLOPE,VARFMT
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,OATE(2),DATES(4),LINES,
     1 NAMF,NOAY,RCHRGO,ROI372),WEI372),WEO,YEAR,YRTOT(3I
      INTEGER OATE,DATES,YEAR
      DIMENSION B(MNTH(6I,ETO(372),PPT(372),RAO(372),TMAX(372),TM1N(372I
      EOUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),IBLOCK(746),
     1 PPTI1)),(BLOCK(1118),RAD(1)),(BLOCK(1490),ETO(1)),IBLOCKI1864),
     2 CDMAX),(BLOCK(I865),VEGTYP),IBLOCK(1866),TRSHLO),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),OCDMAX),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEKOAT),(BLOCK(1880I,BIMNTH(1)I,
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
      INTEGER PEKDAT,VEGTYP
      DIMENSION BETWEN(24),NOATE(24)
      DATA BETWEN/13., 15., I3., 15., 14., 14., 15., 14., 15., 14.,
     1 21., 20., 15., 14., 15., 15., 14., 15., 14., 14., 14., 14., 19.,
     2 19./
      OATA NDATE/ 110,123,207,220,307,321,404,419,503,518,601,622,712,
     1 727,810,825,909,923,1008,1022,1105,1119,1203,1222/
C-----PLACE THIS OATE WITH RESPECT TO THE TABLES
      OO IO 1 = 1,24
      IF(NOATE(() - MMOO) 10,80,20
   IO CONTINUE
C-----A NORMAL TERMINATION OF THE DO LOOP MEANS THAT THIS DATE FALLS
C----- BETWEEN 12/23 ANO 12/31, INCLUSIVE.  USING THE ARRAY IN CIRCULAR
C----- FASHION, 1/10 (SUBSCRIPT 1) IS THE CONTROLLING OATE
      I = 1
      GO TO 30
C-----TH(S DATE FALLS BETWEEN THE ONES AT LOCATIONS I ANO 1-I.  IF I IS
C----- 1, USE 24 FOR (-I SINCE THE ARRAY IS CIRCULAR
   20 RADSUB = I - I
      IF(RADSUB) 30,30,40
   30 RADSUB = 24
C-----OBTAIN THE INTERPOLATION FRACTION.  START BY OETERMINING IF
C----- THIS OATE FALLS IN THE SAME MONTH AS THAT AT LOCATION I OR I-1
   40 IF(OATE(I) - (NDATE(RAOSUB)/100)) 60,50,60
C-----IT IS THE SAME AS I-I ANO IT (S LARGER, SO SUBTRACT THE I-I DATE
C----- TO OBTAIN THE NUMBER OF DAYS TO BE USED FOR (NTERPOLATING
   50 DAYS = MMDD - NOATE(RADSUB)
      GO TO 70
C-----IT IS THE SAME AS (, BUT IT IS SMALLER, SO SUBTRACT IT FROM THE I
C----- OATE.  THEN SUBTRACT THE RESULT FROM THE DAYS BETWEEN I AND 1-1
C----- TO OBTAIN THE NUMBER OF OAYS TO BE USED FOR INTERPOLATING
   60 DAYS = NDATE(() - MMDD
      OAYS = BETWEN(RADSUB) - DAYS
C-----COMPUTE THE INTERPOLATION FRACTION
   70 FRACTN = DAYS/BETWEN(RADSUB)
      POTRAO = POTENT(RADSUB) + (POTENT(I) - POTENTIRAOSUB)) * FRACTN
      RETURN
C-----THIS DATE IS IN THE TABLE - NO INTERPOLATION IS NECESSARY
   8D FRACTN = D.0
      RADSUB = I
      POTRAO = POTENT(I)
      RETURN
      END
```

Subroutine RANSEL

```
      SUBROUTINE RANSEL
C-----RANDOMLY SELECT THE NEXT YEAR FROM THE ORIG(NAL DATA BASE
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,PLNOPT(I9),PLUN(T(6),
     I RECOVR,REGION(8),REGOPT(5),SAVE,SEORN2,WEIGHT
      INTEGER OAT(ME,PLNOPT,PLUN(T,RECOVR,REG(ON,REGOPT,SAVE,SEDRN2
      COMMON/E/CON,IO(9),NBLOCK,ORIGYR
      INTEGER ORIGYR
      COMMON/UTILTY/BLOCK(I889),CHANGR,CHANGW,OATE(2),DATES(4),LINES,
     1 NAME,NOAY,RCHRGC,RO(372),WE(372),WEO,YEAR,YRTOT(3)
      INTEGER OATE,OATES,YEAR
```

```
      DIMENSION BIMNTH(6),ETO(372),PPT(372),RAD(372),TMAX(372),TMIN(372)
      EQUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(1490),ETO(1)),(BLOCK(1864),
     2 CGMAX),(BLOCK(1865),VEGTYR),(BLOCK(1866),TRSHLD),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),DCDMAX),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEKOAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),REAKRO)
      INTEGER PEKDAT,VEGTYP
C-----GET A RANDOM NUMBER BETWEEN I AND -ORIGYR- (SUBROUTINE RN2
C----- RETURNS A REAL VALUE BETWEEN 0 AND 1)
   10 CALL RN2 (SEDRN2,RANDOM)
      N = RANDOM * CDN
      IF(1.GT.N.DR.N.GT,DR(CYR) GD TD 10
C-----COMPARE THIS NUMBER WITH THE CURRENT BLOCK.  IF THEY ARE THE SAME,
C----- NO FURTHER READING IS NECESSARY.  IF THE CURRENT BLOCK NUMBER IS
C----- LARGER, THE FILE MUST BE REWOUND BEFORE THE SEARCH BECINS
      IF(N - NBLOCK) 20,40,30
   20 REWIND 16
      NBLDCK = 0
C-----RYPASS THE BLOCKS UNTIL THE SRECIFIED NUMRER IS FOUND
   30 CALL GETREC (16,BLOCK,1889,IEND)
      NBLDCK = NBLOCK + 1
      IF(N - NBLOCK) 30,40
   40 RETURN
      END
```

Subroutine READAT

```
      SUBROUTINE READAT
C-----READ THE YEAR OF OATA AND STORE IT
      COMMON/N/ACCUM,AIRTMC(4),ASPECT,CALDEF,COVDEN,OECIDS(3),OREADY,
     1 ENGBAL,ETOALY(12),FRACTN,FREWAT,ID,IM,IMN,IMX,IP,IY,LASUSD,LAT,
     2 NDYSND,DNTRES,PEKPPT,PHASE,RDTENT(24),PDTRAD,PRTNOW,RREWEO,
     3 RADSUB,RECHRG,SIMTMI(3),SLDPE,SLPASP(24),SUMMER,TCDEFF,
     4 VARFMT(7),VARIN(6)
      INTECER ASPECT,DREADY,PHASE,RAOSUB,SLDPE,VARFMT
      COMMON/UTILTY/BLDCK(1809),CHANGR,CHANCW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRCD,RD(372),WE(372),WED,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETO(372),PPT(372),RAD(372),TNAX(372),TNIN(372)
      EDUIVALENCE (BLDCK(2),TNAX(1)),(BLOCK(374),TNIN(1)),(BLDCK(746),
     1 PRT(1)),(BLDCK(1110),RAD(1)),(BLOCK(1490),ETD(1)),(BLDCK(1864),
     2 CDMAX),(BLDCK(1865),VECTYR),(BLOCK(1866),TRSHLO),(BLDCK(1867),
     3 TMPMLT),(BLDCK(1868),WILTPT),(BLOCK(1871),DCDMAX),(BLDCK(1872),
     4 ISDTRM),(BLOCK(1873),REKDAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLDCK(1886),REAKWE),(BLDCK(1888),PEAKRO)
      INTECER PEKDAT,VECTYR
      OATA MONTH/0/
      IF(MONTH.EO.-999999) GO TO 20
C-----FIND THE FIRST CARD FOR THIS YEAR
   10 MONTH = VARIN(IM)
      IYEAR = VARIN(IY)
      IF(((YEAR+1.EO.YEAR.AND.MONTH.GE,10).OR.(IYEAR.ED.YEAR.AND.NONTH.
     1 LE,9)) GO TD 30
      READ (10,VARFMT) VARIN
      IF(EOF(10)) 20,10
   20 WRITE (6,910) YEAR
  910 FORMAT(*OUNABLE TO FIND YEAR*I4,* ON -UNEOIT-.  JOB ABORTED*)
      CALL ABORT
C-----STORE THE LARGE VALUE IN THE MAXIMUN TEMRERATURE SO MISSINC OR
C----- NONEXISTENT DAYS (FEB 30) CAN BE DETECTED
   30 OD 40 I = 1,372
   40 TNAX(I) = -1.E50
C-----CONVERT THE DATE TO THE RSEUDO-JULIAN FORM AND STORE THE DRIVING
C----- VARIABLES
   50 IDAY = VARIN(ID)
      J = JWYDAT(MONTH,IDAY)
      TMAX(J) = VARIN(IMX)
      TMIN(J) = VARIN(IMN)
      RRT(J) = VARIN(IP)
C-----READ THE NEXT CARD AND IF THE WATER YEAR DOES NOT CHANGE, GO BACK
C----- TO STORE IT
      READ (10,VARFMT) VARIN
      IF(EOF(10)) 70,60
   60 MONTH = VARIN(IN)
      IYEAR = VARIN(IY)
      IF(((IYEAR+1.ED.YEAR.AND.NONTH.GE.10).DR.(IYEAR.EO.YEAR.AND.MONTH.
     1 LE.9)) GO TO 50
      GO TO 80
   70 MONTH = -999999
C-----THIS YEAR IS COMRLETE - ACCUMULATE THE PRECIP
   80 ACCUM = 0.0
      NDAY = 0
      DO 100 I = 1,372
      IF(TMAX(I) + 1.E50) 90,100
   90 ACCUM = ACCUM + PRT(I)
      RPT(I) = ACCUM
      NDAY = NDAY + 1
  100 CONTINUE
      IF(NDAY.GE.364.AND.NDAY.LE.367) RETURN
      WRITE (6,920) YEAR,NDAY
  920 FORMAT(*  NOTE - YEAR*I4,* HAS*I4,* DAYS*)
      RETURN
      END
```

Subroutine SIMNRM

```
      SUBROUTINE SIMNRM
C-----PERFORM THE NORMAL SINULATION FOR A YEAR CREATED DURING THE
C----- EXTENSION OF THE DATA BASE
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,PLNDPT(19),PLUNIT(6),
     1 REGDVR,REGION(8),REGDPT(5),SAVE,SEDRN2,WEIGNT
      INTEGER DATIME,PLNDRT,PLUNIT,RECDVR,REGION,REGDPT,SAVE,SEDRN2
      COMMON/N/ACCUM,AIRTMC(4),ASPECT,CALOEF,COVDEN,DECIDS(3),DREADY,
     1 ENGBAL,ETDALY(12),FRAGTN,FREWAT,ID,IM,IMN,IMX,IP,IY,LASUSD,LAT,
     2 NDYSND,DNTRES,PEKRPT,PHASE,RDTENT(24),POTRAD,PPTNDW,RREWED,
     3 RADSUB,REGHRG,SIMTM1(3),SLDRE,SLPASP(24),SUMMER,TCDEFF,
     4 VARFMT(7),VARIN(6)
      INTEGER ASPECT,DREADY,PHASE,RAOSUB,SLDPE,VARFMT
      COMMON/TIME/GANREF,CDMAX2,CONAV
      COMMON/UTILTY/BLOCK(1889),CHANGR,GNANGW,DATE(2),OATES(4),LINES,
     1 NAME,NOAY,RGHRG0,RD(372),WE(372),WE0,YEAR,YRTDT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETO(372),PRT(372),RAD(372),TMAX(372),TMIN(372)
      EDUIVALENGE (BLDCK(2),TMAX(1)),(BLDCK(374),THIN(1)),(BLOGK(746),
     1 PRT(1)),(BLDGK(1118),RAO(1)),(BLDGK(1490),ETO(1)),(BLDCK(1864),
     2 CDNAX),(BLOCK(1865),VEGTYR),(BLGGK(1866),TRSHLO),(BLDGK(1867),
     3 TMPMLT),(BLOGK(1868),WILTPT),(BLOGK(1871),DGDMAX),(BLDGK(1872),
     4 ISDTRN),(BLDCK(1873),PEKDAT),(BLOCK(1080),BINNTH(1)),
     5 (BLOGK(1886),PEAKWE),(BLOGK(1888),PEAKRO)
      INTEGER PEKDAT,VECTYR
      COMMON/WTRBAL/ALLDW,ETFROM,EVAPTR,GENRO,PEAKED,PRECIP,RADIN,
     1 RADLWN,RADSWN,TMRMAX,TMPMIN,WATRIN
C-----STORE TNE INITIAL GONDITIONS AND ZERO THE AGCUMULATORS
      BLOGK(1874) = PREWEO
      BLOCK(1875) = REGHRG
      YRTDT(1) = 0.0
      YRTDT(3) = 0.0
      DREADY = 0
      PPTNOW = 0.0
      PEAKED = 0.0
      DO 30 NDAY = 1,372
      IF(TMAX(NOAY) + 1.E50) 10,30
C-----DEFINE TNE DRIVING VARIABLES
   10 TMPMAX = THAX(NDAY)
      TMPMIN = TNIN(NDAY)
      PREGIP = PRT(NDAY) - PPTNDW
      PPTNDW = PPT(NDAY)
      EVAPTR = ETO(NOAY)
      RADIN = RAD(NDAY)
C-----DO NOT ALLOW INTERGEPTION IN JULY AND AUGUST
      ALLOW = 1.0
      IF(NDAY.GE.280.AND.NDAY.LE.341) ALLOW = 0.0
      IF(NDAY.EQ.PEKDAT) PEAKED = 1.0
G-----WATCN FOR DECIDUDUS FOREST AND THEIR CHANGE OF SEASONS
      IF(VEGTYP.EQ.3.DR.VEGTYP.ED.4) GD TD 40
   15 CONTIMUE
C-----MAKE TNE PASS THROUGN TNE WATER BALANCE ROUTINES
      CALL WATBAL (CALDEF,CDMAX,COVDEN,OREADY,ENGBAL,FREWAT,LASUSD,
     1 NDYSNO,ONTRES,PHASE,PREWEO,RECHRG,SIMTM1(1),SIMTM1(2),SIMTM1(3),
     2 TCOEFF,TMPMLT,TRSHLD,VEGTYP,WILTPT)
C-----STORE TNESE RESULTS
      WE(NDAY) = PREWED
      RD(NOAY) = GENRD
      YRTDT(1) = YRTDT(1) + GENRO
      YRTDT(3) = YRTDT(3) + EVAPTR
C-----WATCN FOR THE MANDATORY ISOTNERMAL DATE
      IF(ISDTRM - NDAY) 30,20
   20 DREADY = -1
      CALOEF = 0.0
   30 CONTINUE
C-----GET TNE BIMONTHLY FLOWS AND THE PEAK INFORMATION
      CALL GBIMDN
      ITEMP = PEKDAT
      CALL GPEAK(IOATE1)
C-----STORE TNE FINAL INFORMATION
      BLDCK(1076) = YRTDT(1)
      BLDCK(1877) = YRTDT(3)
      BLDCK(1878) = RECHRG - RCHRG0
      RCHRG0 = RECNRG
      BLOCK(1879) = PREWEQ - WE0
      WE0 = PREWEQ
C-----NOTE TNAT -PEKOAT- WAS REDEFINED BY SUBROUTINE GPEAK, SO
C----- -BLDCK(1887)- MAY OR NAY NOT BE TNE SANE AS -BLDCK(1873)-
      BLDCK(1887) = PEKDAT
      REKDAT = ITEMP
      BLDCK(1009) = IDATE1
      RETURN
C-----WATGN FOR TNE CHANGE OF SEASONS FOR DECIDUDUS FORESTS
   40 CONTINUE
C-----CNECK THE DATE (BETWEEN APRIL 1 AND OCTOBER 15, IT IS POSSIBLE TO
C----- NAVE FOLIAGE.  BUT OURING THE REMAINDER OF TNE YEAR, IT IS
C----- ASSUNEO TNAT TNE TREES ARE LEAFLESS)
      IF(NDAY.GE.187,OR.NDAY.LE.15) GD TD 230
C-----TNE TREES SNOULD BE LEAFLESS.  IF THEY ARE NOT, SWITCH TO THE
C----- LOWER COVER DEMSITY
  210 IF(VEGTYP - 4) 220,270
  220 VEGTYP = 4
      GD TD 260
C-----THE FOLIAGE MAY BE PRESENT, BUT IF THE PACK WATER EDUIVALENT IS
C----- MORE THAN 5 INGHES, THE TREES ARE STILL ASSUMED TO BE LEAFLESS
  230 IF(PREWED - 5.0) 240,240,210
C-----TNE FOLIAGE SNOULD BE PRESENT.  IF NOT, SWITCH TO THE HIGNER COVER
C----- DENSITY
  240 IF(VEGTYP - 3) 250,270
  250 VEGTYP = 3
  260 TCDEFF = SWITCH (TCDEFF,DECIDS(1))
      CDVDEM = SWITCN (CDVDEN,DECIOS(2))
      CDMAX = SWITCH (CDNAX,DEGIDS(3))
  270 GONTINUE
      GD TD 15
      END
```

Subroutine SKPFIL

```
      SUBROUTINE SKPFIL (NFILE)
C-----SKIR FILES ON THE UNEDITED DATA FILE
      REWIND 10
      MFILE = NFILE - 1
      IF(MFILE) 50,50,10
   10 DO 40 I = 1,MFILE
      READ (10,910)
  910 FORMAT(1X)
C-----AN END OF FILE ON THE FIRST READ INDICATES AN END OF INFORMATION
      IF(EOF(10)) 20,30
   20 J = I - 1
      WRITE (6,920) J,NFILE
  920 FORMAT(*OTHERE ARE ONLY*I3,* FILES ON -UNEDIT- BUT ACCORDING TO TH
     1E VARIABLE FORMAT CARD, THE DATA IS ON FILE*I3,* - JOB ABORTED*)
      CALL ABORT
C-----BYRASS THE REMAINDER OF THE FILE
   30 READ (10,910)
```

```
      IF(EOF(10)) 40,30
   40 CONTINUE
   5D RETURN
      END
```

Subroutine TITLEN

```
      SUBROUTINE TITLEN
C-----PRINT THE TITLE SHEET
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYFARS,PLNORT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
      INTEGER DATIME,PLNORT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
      COMMON/N/ACCUM,AIRTMC(4),ASPECT,CALDEF,COVDEN,DECIDS(3),DREADY,
     1 ENGBAL,ETDALY(12),FRACTN,FREWAT,ID,IM,IMN,IMX,IP,IY,LASUSD,LAT,
     2 NDYSNO,ONTRES,PEXPPT,PHASE,POTENT(24),POTRAD,PPTNOW,PREWEQ,
     3 RADSUR,RECHRG,SIMTM1(3),SLOPE,SLPASP(24),SUMMER,TCOEFF,
     4 VARFMT(7),VARIN(6)
      INTEGER ASPECT,DREADY,PHASE,RADSUB,SLOPE,VARFMT
      COMMON/UTILTY/BLOCX(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRGO,RO(372),WE(372),WEO,YEAR,YRTOT(3)
      INTEGFR DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETO(372),PPT(372),RAD(372),TMAX(372),TMIN(372)
      EQUIVALENCE (BLOCX(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCX(746),
     1 PPT(1)),(BLOCX(1118),RAD(1)),(BLOCX(1490),ETO(1)),(BLOCK(1864),
     2 CDMAX),(BLOCX(1865),VEGTYP),(BLOCX(1866),TRSHLD),(BLOCK(1867),
     3 TMPMLT),(BLOCX(1868),WILTPT),(BLOCX(1871),DCDMAX),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEXDAT),(BLOCX(188D),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCX(1888),PEAXRO)
      INTEGER PEXDAT,VEGTYR
      INTEGER TABLE1(13),TABLE2(13)
      DATA TABLE1/6HJUN 22,6HJUN 1 ,6HMAY 18,6HMAY 3 ,6HAPR 19,6HAPR 4 ,
     1 6HMAR 21,6HMAR 7 ,6HFEB 20,6HFEB 7 ,6HJAN 23,6HJAN 10,6H      /
      DATA TABLE2/6H      ,6HJUL 12,6HJUL 27,6HAUG 1D,6HAUG 25,6HSER 9 ,
     1 6HSEP 23,6HOCT 8 ,6HOCT 22,6HNOV 5 ,6HNDV 19,6HDEC 3 ,6HDEC 22/
      WRITE (6,910) PLUNIT,DATIME
  910 FORMAT(*1*6A10,52X2A10/115X*NATURAL CONDITIONS*)
      TMPMLF = (TMPMLT * 1.8) + 32.
      WRITE (6,920) TCOEFF,COVDEN,CDMAX,VEGTYP,TRSHLD,TMPMLF,WILTPT
  920 FORMAT(*DSUBSTATION CONSTANTS*/* TRANSMISSIVITY COEFF*10XF1D.2/
     1 * COVER DENSITY        *10XF1D.2/* MAXIMUM COVER DEN    *1DXF10.2/
     2 * VEGETATION TYPE      *10X11D  /* REFLECTIVITY THRSHLD*10XF10.2/
     3 * MELT THRESHOLD       *1DXF10.2/* WILTING POINT        *10XF10.2)
      IF(VEGTYP.ED.3) WRITE (6,930) DECIDS
  930 FORMAT(* DECIDUOUS WINTER TC *10XF10.2/
     1 * DECIDUOUS WINTER CD *10XF10.2/* DECIDUOUS WNTR CDMAX*10XF10.2)
      WRITE (6,940) SIMTM1(2),PREWED,RECHRG
  940 FORMAT(*OINITIAL CONDITIONS*/
     1 * AVERAGE PACX TEMP.  *10XF10.2/* PACX WATER EDUIV.    *10XF10.2/
     2 * RECHARGE REDUIREMENT*10XF10.2)
      WRITE (6,950) LAT,ASPECT,SLOPE,(TABLEI(I-11),TABLE2(I-11),
     1 POTENT(I),SLPASP(I),1=12,24)
  950 FORMAT(*OLATITUDE =*13,*, ASPECT = *A3,*, SLOPE =*13/
     1 *OROTENTIAL RADIATION INCIDENT TO HORIZONTAL SURFACE AND ADJUSTME
     INT FACTORS FOR ASPECT AND SLOPE*/22X*LY     ADJUST*,13(/1XA6,1XA6,
     3 2F10.2))
      RETURN
      END
```

Program MANAGE

```
      OVERLAY (OLAYS,2,2)
      PROGRAM MANAGE
C-----PERFORM THE MANAGEMENT STRATEGY SIMULATION AND CREATE THE PLANNING
C----- UNIT FILE
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,PLNOPT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
      INTEGER OATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
      COMMON/M/ALTYR(8),BOUND(6,R),CALDEF(8),COVDEN(R),CUT(8),
     1 DECIDS(2,8),DREADY(8),ENGBAL(8),EXPX(8),EXPX1(8),FREWAT(B),LAST1,
     2 LASUSD(B),LCOPY(14),NDYSNO(8),NEXTYR,NPLAN,NUM,NUNIT,ONTRES(B),
     3 PARAM(9),PHASE(8),PHISD(8),PREWED(8),RDIST(8),RDMAX(8),RECHRG(B),
     4 REGROW(2,8),RUNUM(8),RUWT(B),SEDINC,SEEDAT(2),SEEDYR(2),
     5 SIMTM1(3,8),TCOEFF(8),TYPCUT(8)
      INTEGER ALTYR,BOUND,DREADY,RHASE,RUNUM,SEEDAT,SEEDYR,TYPCUT
      COMMON/TIME/CANREF,CDMAX2,CONAV
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRGO,RO(372),WE(372),WEO,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETO(372),PPT(372),RAD(372),TMAX(372),TMIN(372)
      EDUIVALENCE (BLOCX(2),TMAX(1)),(BLOCX(374),TMIN(1)),(BLOCX(746),
     1 PPT(1)),(BLOCX(1118),RAD(1)),(BLOCK(1490),ET3(1)),(BLOCK(1864),
     2 CDMAX),(BLOCX(1865),VEGTYP),(BLOCX(1866),TRSHLD),(BLOCK(1867),
     3 TMPMLT),(BLOCX(1868),WILTPT),(BLOCK(1871),DCDMAX),(BLOCX(1872),
     4 (SOTRM),(BLOCK(1873),PEXDAT),(BLOCX(1880),BIMNTH(1)),
     5 (BLOCK(1886),REAKWE),(BLOCK(1888),PEAXRO)
      INTEGER PEKDAT,VEGTYP
C-----NOTE - THE DIMENSION OF -FORNXT- MUST BE EQUAL TO THE LENGTH OF
C----- COMMON BLOCK /M/ AND THAT LENGTH MUST BE STORED IN -L4NXT-
      DIMENSION FORNXT(313)
      EDUIVALENCE (ALTYR(1),FORNXT(1))
      CALL CORE (-1)
      L4NXT = 313
      REWIND 17
      REWIND 18
      WRITE (18,900) PLUNIT,DATIME
  9D0 FORMAT(*1*6A10,52X2A10/*OMANAGEMENT STRATEGY DESCRIPTION*)
      LAST1 = -1
      SEEDYR(1) = 9999
C-----MAKE A PASS THROUGH THE DATA TO TRANSFER THE YEARLY RESULTS OF THE
C----- NORMAL SIMULATION TO THE PLANNING UNIT FILE
      CALL NORM
C-----READ THE FIRST MANAGEMENT PLAN CARD - IF THERE IS NONE, THIS UNIT
C----- IS NOT MANAGFD, BUT WAS INCLUDED ONLY AS PART OF A REGION
      NRLAN = 0
      CALL ROPLAN
      IF(NEXTYR.EO.9999) GO TO 110
C-----BYPASS THE DATA ON THE BASIC FILE UNTIL THE FIRST YEAR OF THE
C----- MANAGEMENT PLAN IS FOUND
      CALL BYPASS
C-----DEFINE THE NATURAL RESRONSE UNIT
      CALL NATURL
C-----DEFINE AN ALTEREO RESPONSE UNIT
   10 CALL DEFRU
C-----PRINT THE TITLE PAGE IF THE OUTPUT IS TO BE PRINTED
      IF(PLNOPT(3).NE.0) CALL TITLEM
      LINES = 0
C-----SIMULATE ONE YEAR
   2D CALL SIM1YR
C-----GET THE CHANGE IN THE RECHARGE REQUIREMENT AND IN THE PACX WATER
C----- EQUIVALENT AND WRITE THE INFORMATION ON THE PLANNING UNIT FILE
      RCHRG = 0.0
      DO 30 I = 1,NUNIT
   30 RCHRG = RCHRG + (RECHRG(I) * RUWT(I))
      CHANGR = RCHRG - RCHRGO
      RCHRGO = RCHRG
      CHANGW = WE(371) - WEO
      WEO = WE(371)
C-----GET THE BIMONTHLY FLOWS AND THE PEAX INFORMATION
      CALL GBIMON
      CALL GPEAK (IDATE1)
      DATE1 = PEKDAT
      DATE2 = IDATE1
      WRITE (12,910) NPLAN,BLOCX(1),YRTOT,CHANGR,CHANGW,BIMNTH,PEAXWE,
     1 DATE1,PEAXRO,DATE2
  910 FORMAT(I2,16F6.2)
C-----IF SPECIFIED, OUTPUT THE COMPILED RESULTS
      IF(PLNOPT(3).EQ.0) GO TO 40
      CALL OUTPT
C-----DETERMINE THE EFFECTS OF THE TIME TRENDS
   40 CALL TRENDS
C-----IF THIS IS THE YEAR JUST BEFORE THE NEXT MANAGEMENT PLAN, STORE
C----- THE PRESENT MODEL CONDITIONS ON THE SCRATCH FILE TO PROVIDE THE
C----- STARTING POINT FOR THE NEXT PLAN
      IF(YEAR + 1 - NEXTYR) 60,50
   50 REWIND 16
      CALL PUTREC (16,FORNXT,L4NXT)
C-----READ THE NEXT YEAR
   60 CALL GETREC (11,BLOCX,1889,IEND)
      IF(IEND.EO.0) GO TO 20
C-----END OF FILE - IF THERE IS ANOTHER MANAGEMENT PLAN, READ THE
C----- INITIAL CONDITIONS BACK FROM THE SCRATCH FILE, BYPASS THE DATA
C----- TAPE UP TO THE FIRST YEAR, AND GO ON TO THE NEXT MANAGEMENT PLAN
      IF(NEXTYR - 9999) 70,80
   70 CALL BYPASS
      REWIND 16
      CALL GETREC (16,FORNXT,L4NXT,IEND)
      GO TO 10
C-----IF SPECIFIED, COPY THE TIME TRENDS FILE
   80 IF(PLNOPT(4).ED.0) GO TO 11D
      REWIND 17
      GO TO 100
   9D WRITE (6,990) LCOPY
  99D FORMAT(13A10,A6)
  1D0 READ (17,990) LCOPY
      IF(EOF(17)) 11D,90
C-----RETURN TO THE PRIMARY OVERLAY
  110 CONTINUE
      CALL CORE (0)
      END
```

Subroutine BYPASS

```
      SUBROUTINE BYPASS
C-----BYPASS THE DATA ON THE BASIC FILE UNTIL THE FIRST YEAR OF THE
C----- MANAGEMENT PLAN IS FOUND
      COMMON/M/ALTYR(8),BOUND(6,8),CALDEF(8),COVDEN(8),CUT(8),
     1 DECIOS(2,8),DREADY(8),ENGBAL(8),EXPX(8),EXPK1(B),FREWAT(8),LAST1,
     2 LASUSD(8),LCOPY(14),NDYSNO(B),NEXTYR,NPLAN,NUM,NUNIT,ONTRES(8),
     3 PARAM(9),PHASE(8),PHISQ(8),PREWED(8),RDIST(B),RDMAX(B),RECHRG(B),
     4 REGROW(2,B),RUNUM(8),RUWT(B),SEDINC,SEEDAT(2),SEEDYR(2),
     5 SIMTM1(3,B),TCOEFF(B),TYPCUT(8)
      INTEGER ALTYR,BOUND,DREADY,PHASE,RUNUM,SEFDAT,SEEDYR,TYPCUT
      COMMON/UTILTY/BLOCX(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRGO,RO(372),WE(372),WEO,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETO(372),PPT(372),RAD(372),TMAX(372),TMIN(372)
      EDUIVALENCE (BLOCX(2),TMAX(1)),(BLDCX(374),TMIN(1)),(BLOCX(746),
     1 PPT(1)),(BLOCX(1118),RAD(1)),(BLOCX(1490),ETO(1)),(BLDCX(1864),
     2 CDMAX),(BLOCK(1865),VEGTYP),(BLOCX(1866),TRSHLD),(BLOCX(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCX(1871),DCDMAX),(BLOCK(1872),
     4 ISOTPM),(BLOCK(1R73),PEXDAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLOCX(1886),PEAKWE),(BLOCX(1888),PEAXRO)
      INTEGFR PEXDAT,VEGTYP
      REWIND 11
C-----GET A YEAR
   1D CALL GETREC (11,BLOCK,1889,IEND)
      IF(IEND) 20,30
   2D WRITE (6,910) NEXTYR
  910 FORMAT(*CTHE EXTENDED DATA FILE ENDED BEFORE MANAGEMENT PLAN YEAR*
     1 I4,* WAS FOUND - JOB ABORTED*)
      CALL ABORT
   30 IF(NEXTYR - INT(BLOCK(1))) 40,50,10
   40 JYEAR = INT(BLOCX(1))
      WRITE (6,920) NEXTYR,JYEAR
  920 FORMAT(*OTHE EXTENDED DATA FILE DOES NOT CONTAIN MANAGEMENT PLAN Y
     1EAR*I4,*.  THE NEXT YEAR ON THE FILE IS*I4,* - JOB ABORTED*)
      CALL ABORT
   5G YEAR = BLOCK(1)
      RETURN
      END
```

Subroutine DEFRU

```
      SUBROUTINE DEFRU
C-----DEFINE A RESPONSE UNIT (OR REDEFINE ONE PREVIOUSLY DEFINED)
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,RLNORT(19),RLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
      INTEGER OATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
      COMMON/M/ALTYR(8),BOUND(6,8),CALDFF(8),COVDEN(8),CUT(8),
     1 DECIDS(2,8),DREADY(8),ENGBAL(8),EXRK(8),EXPX1(8),FREWAT(8),LAST1,
```

```
      2 LASUSO(8),LCOPY(14),NOYSNO(8),NEXTYR,NPLAN,NUM,NUNIT,ONTRES(8),
      3 PARAM(9),PHASE(8),PHISO(8),PREWEO(8),ROIST(8),ROMAX(8),RECHRG(8),
      4 REGROW(2,8),RUNUM(8),RUWT(8),SEOINC,SEEDAT(2),SEEOYR(2),
      5 SIMTM1(3,8),TCOEFF(8),TYPCUT(8)
       INTEGER ALTYR,BOUNO,OREADY,PHASE,RUNUM,SEEOAT,SEEOYR,TYPCUT
       COMMON/S/AVSOIL(11),OECLIN(11),NROAOS,RATNRM(11),ROAOMI(11),
      1 ROAOW(11),TANCUT(11),TANFIL(11),TANRHO(11),YRCNST(11)
       INTEGER YRCNST
       COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,OATE(2),OATES(4),LINES,
      1 NAME,NOAY,RCHRGO,RO(372),WE(372),WEO,YEAR,YRTOT(3)
       INTEGER DATE,OATES,YEAR
       OIMENSION BIMNTH(6),ETO(372),PPT(372),RAO(372),TMAX(372),TMIN(372)
       EOUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
      1 PPT(1)),(BLOCK(1118),RAO(1)),(BLOCK(1490),ETO(1)),(BLOCK(1864),
      2 COMAX),(BLOCK(1865),VEGTYP),(BLOCK(1866),TRSHLO),(BLOCK(1867),
      3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),OCOMAX),(BLOCK(1872),
      4 ISOTRM),(BLOCK(1873),PEKOAT),(BLOCK(1880),BIMNTH(1)),
      5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
       INTEGER PEKOAT,VEGTYP
       INTEGER YRALT
       YRALT = NEXTYR
C-----WATCH FOR ROAD CONSTRUCTION (SEOIMENT MODELING)
      IF(IROADS(N).EO.1) GO TO 140
      NPLAN = NPLAN + 1
C-----IF THE RESPONSE UNIT NUMBER IS ZERO, THIS IS WEATHER MODIFICATION
    1 IF(NUM) 20,10
   10 SEEOYR(1) = NEXTYR
      SEEOYR(2) = PARAM(1)
      SEEOAT(1) = JWYOAT (INT(PARAM(2)/100.),INT(AMOO(PARAM(2),100.)))
      SEEOAT(2) = JWYOAT (INT(PARAM(3)/100.),INT(AMOO(PARAM(3),100.)))
      SEDINC = 1.0 + PARAM(4)
      GO TO 140
C-----IF THIS RESPONSE UNIT NUMBER IS ALREADY IN THE TABLE, THIS CARO IS
C----- REDEFINING THE UNIT
   20 OO 30 I = 1,NUNIT
      N = I
      IF(RUNUM(N) - NUM) 30,80
   30 CONTINUE
      N = NUNIT + 1
      IF(8 - N) 40,50,50
   40 WRITE (6,910) NUM
  910 FORMAT(*0A MAXIMUM OF 7 ALTERED RESPONSE UNITS IS ALLOWEO OUE TO I
     1NTERNAL PROGRAMMING REQUIREMENTS AND *I6,* WILL BE NUMBER 8 - JOB
     2ABORTEO*)
      CALL ABORT
C-----START THIS RESPONSE UNIT OUT UNOER THE PRESENT CONOITIONS OF THE
C----- NATURAL RESPONSE UNIT
   50 NUNIT = N
      RUNUM(NUNIT) = NUM
      TCOEFF(NUNIT) = TCOEFF(1)
      COVOEN(NUNIT) = COVOEN(1)
      OECIOS(1,NUNIT) = OECIOS(1,1)
      OECIOS(2,NUNIT) = OECIOS(2,1)
      CALOEF(NUNIT) = CALOEF(1)
      OREAOY(NUNIT) = OREAOY(1)
      ENGBAL(NUNIT) = ENGBAL(1)
      FREWAT(NUNIT) = FREWAT(1)
      LASUSO(NUNIT) = LASUSO(1)
      NOYSNO(NUNIT) = NOYSNO(1)
      ONTRES(NUNIT) = ONTRES(1)
      PHASE(NUNIT) = PHASE(1)
      PREWEO(NUNIT) = PREWEO(1)
      RECHRG(NUNIT) = RECHRG(1)
      SIMTM1(1,NUNIT) = SIMTM1(1,1)
      SIMTM1(2,NUNIT) = SIMTM1(2,1)
      SIMTM1(3,NUNIT) = SIMTM1(3,1)
C-----OEFINE THE UNIT WEIGHT AND REOEFINE THE NATURAL RESPONSE UNIT
C----- WEIGHT
      RUWT(NUNIT) = PARAM(1)
      RUWT(1) = 1.0
      OO 60 I = 2,NUNIT
   60 RUWT(1) = RUWT(1) - RUWT(I)
      IF(RUWT(1)) 70,75,75
   70 WRITE (6,920)
  920 FORMAT(*0THE ALTEREO RESPONSE UNITS ACCOUNT FOR MORE THAN 100 PERC
     1ENT OF THE PLANNING UNIT - JOB ABORTEO*)
      CALL ABORT
C-----IF THE NATURAL RESPONSE UNIT IS LESS THAN 1/2 OF ONE PERCENT, SET
C----- IT TO ZERO
   75 IF(RUWT(1).LT.0.005) RUWT(1) = 0.0
C-----OEFINE (OR REOEFINE) THE PARAMETERS FOR THE RESPONSE UNIT
   80 ALTYR(N) = NEXTYR
C-----IF THE COVER DENSITY WAS SPECIFIEO (PARAM(2) WAS FLAGGED WITH A
C----- MINUS SIGN), GO OEFINE THE CORRESPONDING CUT
      IF(PARAM(2).LT.0.0) GO TO 160
      CUT(N) = PARAM(2)
C-----REOEFINE THE COVER OENSITY AND TRANSMISSIVITY COEFFICIENT
      COVOEN(N) = COVOEN(N) * (1.0 - CUT(N))
   90 TCOEFF(N) = TC (COVOEN(N))
      IF(COVDEN(N).EO.0.0) ONTRES(N) = 0.0
      IF(VEGTYP.NE.3.ANO.VEGTYP.NE.4) GO TO 100
      OECIOS(2,N) = OECIOS(2,N) * (1.0 - CUT(N))
      OECIOS(1,NI = TC (OECIOS(2,N))
C-----OEFINE THE BOUNDARIES FOR THE TIME TRENOS FUNCTIONS
  100 CALL G8OUNO (N)
C-----BALANCE THE REOISTRIBUTION FACTORS
      CALL BALANC
C-----REAO THE NEXT MANAGEMENT PLAN CARO AND IF IT IS FOR THE SAME YEAR,
C----- GO BACK TO OEFINE ANOTHER RESPONSE UNIT
  140 CALL ROPLAN
      IF(YRALT - NEXTYR) 150,145
  145 IF(IROAOS(N) - 1) 1,140
C-----OETERMINE THE INITIAL EFFECTS (IF ANY) OF THE TIME TRENOS
  150 WRITE (17,940) PLUNIT,OATIME
  940 FORMAT(*1*6A1C,52X2A10/115X*ALTERED CONOITIONS*/*OCHANGES IN PARAM
     1ETERS OUE TO THE EFFECTS OF THE TIME TRENOS*/)
      CALL TRENDS
C-----AOO THIS INFORMATION TO THE STRATEGY LIST
      CALL SLIST (YRALT)
      RETURN
C-----USE THE SPECIFIEO COVER OENSITY ANO OEFINE THE CUT (REMEMBER,
C----- PARAM(2) IS NEGATIVE)
  160 CUT(N) = 1.C + (PARAM(2)/COVOEN(N))
      IF(CUT(N)) 180,170,170
  170 COVOEN(N) = - PARAM(2)
      GO TO 90
  180 PARAM(2) = - PARAM(2)
      WRITE (6,950) COVOEN(N),PARAM(2)
  950 FORMAT(*0THE CURRENT COVER OENSITY IS ONLY*F5.2,*, BUT THE MANAGE
     1ENT PLAN IS REQUESTING A CUT*/*  WHICH WILL YIELO A SPECIFIEO COV
     2R OENSITY OF*F5.2,* - JOB ABORTEO*)
      CALL ABORT
      END
```

Function IROADS

```
      FUNCTION IROADS (OUMMY)
C-----CHECK FOR ROAD CONSTRUCTION (SEOIMENT MOOELING).  SINCE THE
C----- SEOIMENT MOOEL IS TOTALLY INOEPENOENT, MERELY STORE THE
C----- PARAMETERS NOW FOR MOOELING AFTER THE MANAGEMENT PHASE IS
C----- COMPLETE
      COMMON/M/ALTYR(8),BOUNO(6,8),CALOEF(8),COVOEN(8),CUT(8),
     1 OECIOS(2,8),OREAOY(8),ENGBAL(8),EKPK(8),EKPK1(8),FREWAT(8),LASTI
     2 LASUSO(8),LCOPY(14),NOYSNO(8),NEKTYR,NPLAN,NUM,NUNIT,ONTRES(8),
     3 PARAM(9),PHASE(8),PHISO(8),PREWEO(8),ROIST(8),ROMAK(8),RECHRG(8)
     4 REGROW(2,8),RUNUM(8),RUWT(8),SEOINC,SEEOAT(2),SEEOYR(2),
     5 SIMTM1(3,8),TCOEFF(8),TYPCUT(8)
      INTEGER ALTYR,BOUNO,OREAOY,PHASE,RUNUM,SEEOAT,SEEOYR,TYPCUT
      COMMON/S/AVSOIL(11),OECLIN(11),NROAOS,RATNRM(11),ROAOMI(11),
     1 ROAOW(11),TANCUT(11),TANFIL(11),TANRHO(11),YRCNST(11)
      INTEGER YRCNST
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,OATE(2),OATES(4),LINES,
     1 NAME,NOAY,RCHRGO,RO(372),WE(372),WEO,YEAR,YRTOT(3)
      INTEGER OATE,OATES,YEAR
      OIMENSION BIMNTH(6),ETO(372),PPT(372),RAO(372),TMAK(372),TMIN(372
      EOUIVALENCE (BLOCK(2),TMAK(1)),(BLOCK(3T4),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118),RAO(1)),(8LOCK(I490),ETO(1)),(BLOCK(1864),
     2 COMAX),(BLOCK(1865),VEGTYP),(8LOCK(1866),TRSHLO),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),OCOMAK),(BLOCK(1872),
     4 ISOTRM),(8LOCK(1873),PEKOAT),(8LOCK(1880),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
      INTEGER PEKOAT,VEGTYP
   10 IF(NAME.EO.10HROAD CONST) GO TO 20
      IROADS = 0
      RETURN
   20 IF(NROAOS - 11I 40,40,30
   30 WRITE (6,910I NEXTYR
  910 FORMAT(*0THERE ARE MORE THAN 11 ROAD CONSTRUCTION CAROS INCLUOEO,
     1SO YEAR*I4,* WAS IGNORED*)
      GO TO 50
C-----STORE THE PARAMETERS
   40 NROAOS = NROAOS + 1
      YPCNST(NROAOS) = NEXTYR
      ROAOMI(NROAOS) = PARAM(1)
      ROAOW(NROAOS) = PARAM(2I
      RATNRM(NROAOS) = PARAM(3I
      AVSOIL(NROAOS) = PARAM(4)
      OECLIN(NROAOS) = PARAM(5)
      TANCUT(NROAOS) = PARAM(6I
      TANFIL(NROAOS) = PARAM(7)
      TANRHO(NROAOS) = PARAM(8)
   50 IROADS = 1
      RETURN
      END
```

Subroutine NATURL

```
      SUBROUTINE NATURL
C-----OEFINE THE NATURAL RESPONSE UNIT
      COMMON/M/ALTYR(8),BOUNO(6,8),CALOEF(8),COVOEN(8),CUT(8),
     1 OECIOS(2,8),OREAOY(8),ENG8AL(8),EXPK(8),EXPK1(8),FREWAT(8),LASTI
     2 LASUSO(8),LCOPY(14),NOYSNO(8),NEKTYR,NPLAN,NUM,NUNIT,ONTRES(8),
     3 PARAM(9),PHASE(8),PHISO(8),PREWEO(8),ROIST(8),ROMAK(8),RECHRG(8)
     4 REGROW(2,8),RUNUM(8),RUWT(8),SEOINC,SEEOAT(2),SEEOYR(2),
     5 SIMTM1(3,8),TCOEFF(8),TYPCUT(8)
      INTEGER ALTYR,BOUNO,DREADY,PHASE,RUNUM,SEEOAT,SEEDYR,TYPCUT
      COMMON/UTILTY/8LOCK(1889),CHANGR,CHANGW,OATE(2),OATES(4),LINES,
     1 NAME,NDAY,RCHRGO,RO(372),WE(372),WEO,YEAR,YRTOT(3)
      INTEGER OATE,OATES,YEAR
      OIMENSION BIMNTH(6),ETO(372),PPT(372),RAO(372),TMAX(372),TMIN(372
      EOUIVALENCE (8LOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(8LOCK(746),
     1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(1490),ETO(1)),(BLOCK(1864),
     2 COMAX),(BLOCK(1865),VEGTYP),(8LOCK(1866),TRSHLO),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),OCOMAK),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEKOAT),(8LOCK(1880),8IMNTH(1)),
     5 (8LOCK(1886),PEAKWE),(8LOCK(1888),PEAKRO)
      INTEGER PEKOAT,VEGTYP
C-----THE NATURAL RESPONSE UNIT STARTS AS 100 PERCENT OF THE PLANNING
C----- UNIT ANO IS REOUCED AS MANAGEMENT PLANS ARE INTROOUCED
      RUWT(1) = 1.0
      ROIST(1) = 1.0
      RUNUM(1) = 0
C-----OEFINE THE COVER DENSITY, TRANSMISSIVITY COEFFICIENT, ETC., FROM
C----- THE BASIC FILE
      TCOEFF(1) = BLOCK(1862)
      COVOEN(1) = BLOCK(1863)
      DECIDS(1,1) = BLOCK(1869)
      OECIOS(2,1) = BLOCK(1870)
      PREWED(1) = 8LOCK(1874)
      RECHRG(1) = BLOCK(1875)
      RCHRGO = RECHRG(1)
      WEO = PREWEO(1)
C-----SEE SUBROUTINE TRENDS FOR DEVELOPMENT OF THE EOUATION BELOW
      REGROW (2,1) = 1.0 - (0.5 * EXP (-1.6094379(2 * COVOEN(1)/COMAX))
      REGROW (1,1) = 0.5
      CALOEF(1) = 0.0
      OREAOY(1) = 0
      ENGBAL(1) = 0.0
      FREWAT(1) = 0.0
      LASUSO(1) = 0
      NOYSNO(1) = 0
      ONTRES(1) = 0.0
      PHASE(1) = 0
      SIMTM1(1,1) = 0.0
      SIMTM1(2,1) = 0.0
```

```
      SIMTM1(3,1) = -1.5
      TYPCUT(1) = 0
      NUN(T = 1
      RETURN
      END
```

Subroutine NORM

```
      SUBROUTINE NORM
C-----TRANSFER THE YEARLY RESULTS OF THE NORMAL SIMULATION TO THE
C----- PLANNING UNIT FILE
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,PLNOPT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
      INTEGER DATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRGO,RO(372),WE(372),WEO,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION B(MNTH(6),ETO(372),PPT(372),RAD(372),TMAX(372),TMIN(372)
      EQUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(1490),ETO(1)),(BLOCK(1864),
     2 CDMAX),(BLOCK(1865),VEGTYP),(BLOCK(1866),TRSHLD),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),DCDMAX),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEKDAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
      INTEGER PEKDAT,VEGTYP
      REWIND 11
      REWIND 12
      DO 30 I = 1,NYEARS
      CALL GETREC (11,BLOCK,1889,IEND)
      IF(IEND) 10,20
   10 J = I - 1
      WRITE (6,910) NYEARS,J
  910 FORMAT(*OTHE REGION CARD SPECIFIES*I4,* YEARS, BUT THERE ARE ONLY*
     1 I4,* ON -DATFIL-.  JOB ABORTED*)
      CALL ABORT
C-----BLOCK(1116) = ACCUMULATED PRECIP ON 9/30
   20 WRITE (12,920) BLOCK(1),BLOCK(1876),BLOCK(1116),(BLOCK(K),K=1877,
     1 1889)
  920 FORMAT(* 0*16F6.2)
   30 CONTINUE
      RETURN
      END
```

Subroutine RDPLAN

```
      SUBROUTINE RDPLAN
C-----READ A MANAGEMENT PLAN CARD
      COMMON/M/ALTYR(8),BOUND(6,8),CALDEF(8),COVDEN(8),CUT(8),
     1 DECIDS(2,8),DREADY(8),ENGBAL(8),EXPK(8),EXPK1(8),FREWAT(8),LAST1,
     2 LASUSD(8),LCOPY(14),NDYSNO(8),NEXTYR,NPLAN,NUM,NUNIT,ONTRES(8),
     3 PARAM(9),PHASE(8),PHISO(8),PREWEQ(8),RDIST(8),ROMAX(8),RECHRG(8),
     4 REGROW(2,8),RUNUM(8),RUWT(8),SEDINC,SEEDAT(2),SEEDYR(2),
     5 SIMTM1(3,8),TCOEFF(8),TYPCUT(8)
      INTEGER ALTYR,BOUND,DREADY,PHASE,RUNUM,SEEDAT,SEEDYR,TYPCUT
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRGO,RO(372),WE(372),WEO,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETO(372),PPT(372),RAD(372),TMAX(372),TMIN(372)
      EQUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(1490),ETO(1)),(BLOCK(1864),
     2 CDMAX),(BLOCK(1865),VEGTYP),(BLOCK(1866),TRSHLD),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),DCDMAX),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEKDAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
      INTEGER PEKDAT,VEGTYP
C-----READ THE CARD
      READ (19) NAME,NUM,NEXTYR,PARAM,SPECCD
      IF(NAME.EQ.10HEND OF STR) 10,20
   10 NEXTYR = 9999
      RETURN
   20 LAST1 = NEXTYR
C-----IF A SPECIFIED COVER DENSITY IS INCLUDED, FLAG IT WITH A MINUS
      IF(SPECCD.NE.0.0) PARAM(2) = - SPECCD
      RETURN
      END
```

Subroutine SIM1YR

```
      SUBROUTINE SIM1YR
C-----SIMULATE ONE YEAR
      COMMON/M/ALTYR(8),BOUND(6,8),CALDEF(8),COVDEN(8),CUT(8),
     1 DECIDS(2,8),DREADY(8),ENGBAL(8),EXPK(8),EXPK1(8),FREWAT(8),LAST1,
     2 LASUSD(8),LCOPY(14),NDYSNO(8),NEXTYR,NPLAN,NUM,NUNIT,ONTRES(8),
     3 PARAM(9),PHASE(8),PHISO(8),PREWEQ(8),RDIST(8),ROMAX(8),RECHRG(8),
     4 REGROW(2,8),RUNUM(8),RUWT(8),SEDINC,SEEDAT(2),SEEDYR(2),
     5 SIMTM1(3,8),TCOEFF(8),TYPCUT(8)
      INTEGER ALTYR,BOUND,DREADY,PHASE,RUNUM,SEEDAT,SEEDYR,TYPCUT
      COMMON/TIME/CANREF,CDMAX2,CONAV
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRGO,RO(372),WE(372),WEO,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETO(372),PPT(372),RAD(372),TMAX(372),TMIN(372)
      EQUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(1490),ETO(1)),(BLOCK(1864),
     2 CDMAX),(BLOCK(1865),VEGTYP),(BLOCK(1866),TRSHLD),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),DCDMAX),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEKDAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
      INTEGER PEKDAT,VEGTYP
      COMMON/WTRBAL/ALLOW,ETFROM,EVAPTR,GENRO,PEAKED,PRECIP,RADIN,
     1 RADLWN,RADSWN,TMPMAX,TMPMIN,WATRIN
      YRTOT(1) = 0.0
      YRTOT(2) = 0.0
      YRTOT(3) = 0.0
      YEAR = BLOCK(1)
      DO 10 I = 1,NUNIT
   10 DREADY(I) = 0
C-----PERFORM THE SIMULATION
      PPTNOW = 0.0
      PEAKED = 0.0
      DO 90 NDAY = 1,372
      IF(TMAX(NDAY) + 1.E50) 30,90
C-----DEFINE THE DRIVING VARIABLES
   30 TMPMAX = TMAX(NDAY)
      TMPMIN = TMIN(NDAY)
      PPTNRM = PPT(NDAY) - PPTNOW
      PPTNOW = PPT(NDAY)
      RADIN = RAD(NDAY)
      WE(NDAY) = 0.0
      RO(NDAY) = 0.0
C-----DO NOT ALLOW INTERCEPTION IN JULY AND AUGUST
      ALLOW = 1.0
      IF(NDAY.GE.280.AND.NDAY.LE.341) ALLOW = 0.0
      IF(NDAY.EQ.PEKDAT) PEAKED = 1.0
C-----WATCH FOR DECIDUOUS FORESTS AND THEIR CHANGE OF SEASONS
      IF(VEGTYP.EQ.3.OR.VEGTYP.EQ.4) CALL DECDUS
C-----MAKE A PASS THROUGH THE WATER BALANCE ROUTINES FOR EACH RESPONSE
C----- UNIT
      DO 60 I = 1,NUNIT
      PRECIP = PPTNRM
      EVAPTR = ETO(NDAY)
C-----IF NECESSARY, ADJUST THE PRECIP
      IF(SEEDYR(1) - YEAR) 40,40,50
   40 IF(SEEDYR(2).LT.YEAR.OR.SEEDAT(1).GT.NDAY.OR.SEEDAT(2).LT.NDAY) GO
     1 TO 50
      PRECIP = PRECIP * SEDINC
   50 PRECIP = PRECIP * RDIST(I)
      CANREF = REGROW (2,I)
      CONAV = REGROW(1,I)
      CALL WATBAL (CALDEF(I),CDMAX,COVDEN(I),DREADY(I),ENGBAL(I),
     1 FREWAT(I),LASUSD(I),NDYSNO(I),ONTRES(I),PHASE(I),PREWEQ(I),
     2 RECHRG(I),SIMTM1(1,I),SIMTM1(2,I),SIMTM1(3,I),TCOEFF(I),
     3 TMPMLT,TRSHLD,VEGTYP,WILTPT)
C-----STORE THESE RESULTS
      WE(NDAY) = WE(NDAY) + (PREWEQ(I) * RUWT(I))
      RO(NDAY) = RO(NDAY) + (GENRO * RUWT(I))
      YRTOT(2) = YRTOT(2) + (PRECIP * RUWT(I))
      YRTOT(3) = YRTOT(3) + (EVAPTR * RUWT(I))
   60 CONTINUE
      YRTOT(1) = YRTOT(1) + RO(NDAY)
C-----WATCH FOR THE MANDATORY ISOTHERMAL DATE
      IF(ISOTRM - NDAY) 90,70
   70 DO 80 I = 1,NUNIT
      DREADY(I) = -1
   80 CALDEF(I) = 0.0
   90 CONTINUE
      RETURN
      END
```

Subroutine SLIST

```
      SUBROUTINE SLIST (YRALT)
C-----LIST THE MANAGEMENT STRATEGY
      COMMON/M/ALTYR(8),BOUND(6,8),CALDEF(8),COVDEN(8),CUT(8),
     1 DECIDS(2,8),DREADY(8),ENGBAL(8),EXPK(8),EXPK1(8),FREWAT(8),LAST1,
     2 LASUSD(8),LCOPY(14),NDYSNO(8),NEXTYR,NPLAN,NUM,NUNIT,ONTRES(8),
     3 PARAM(9),PHASE(8),PHISO(8),PREWEQ(8),RDIST(8),ROMAX(8),RECHRG(8),
     4 REGROW(2,8),RUNUM(8),RUWT(8),SEDINC,SEEDAT(2),SEEDYR(2),
     5 SIMTM1(3,8),TCOEFF(8),TYPCUT(8)
      INTEGER ALTYR,BOUND,DREADY,PHASE,RUNUM,SEEDAT,SEEDYR,TYPCUT
      COMMON/S/AVSOIL(11),DECLIN(11),NRDADS,RATNRM(11),RDADMI(11),
     1 ROADW(11),TANCUT(11),TANFIL(11),TANRHO(11),YRCNST(11)
      INTEGER YRCNST
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRGO,RO(372),WE(372),WEO,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETO(372),PPT(372),RAD(372),TMAX(372),TMIN(372)
      EQUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(1490),ETO(1)),(BLOCK(1864),
     2 CDMAX),(BLOCK(1865),VEGTYP),(BLOCK(1866),TRSHLD),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),DCDMAX),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEKDAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
      INTEGER PEKDAT,VEGTYP
      INTEGER YRALT
      IPRINT = 0
C-----CHECK FOR CLOUD SEEDING
      IF(YRALT - SEEDYR(1)) 20,10
   10 CALL GDATE (SEEDAT(1),DATES(1))
      CALL GDATE (SEEDAT(2),DATES(3))
      WRITE (18,910) SEEDYR,SEDINC,DATES
  910 FORMAT(*0(N YEAR*I4,* AND THROUGH YEAR*I4,*, CLOUD SEEDING MULTIPL
     1IES PPT BY*F5.2,* BETWEEN*(3,*/*I2,* AND*I3,*/*I2,*.*)
      IPRINT = 1
C-----CHECK THE YEAR OF THE MANAGED RESPONSE UNITS
   20 IF(NUNIT - 2) 80,30,30
   30 DO 70 I = 1,NUNIT
      IF(YRALT - ALTYR(I)) 70,40
   40 IPRCNT = (CUT(I) * 100.) + 0.5
      IF(IPRINT) 50,60
   50 WRITE (18,920) RUNUM(I),RUWT(I),IPRCNT
  920 FORMAT(13X*ON RESPONSE UNIT*I6,* (AREA WEIGHT =*F5.2,*),*I4,* PERC
     1ENT OF THE CURRENT COVER DENSITY WAS REMOVED.*)
      GO TO 70
   60 WRITE (18,930) YRALT,RUNUM(I),RUWT(I),IPRCNT
  930 FORMAT(*0IN YEAR*I4,* ON RESPONSE UNIT*I6,* (AREA WEIGHT =*F5.2,*)
     1,*I4,* PERCENT OF THE CURRENT COVER DENSITY WAS REMOVED.*)
      IPRINT = 1
   70 CONTINUE
C-----CHECK FOR ROAD CONSTRUCTION
   80 IF(NRDADS) 90,150
   90 DO 140 I = 1,NRDADS
      IF(YRALT - YRCNST(I)) 140,100
  100 IPRCNT = (TANRHO(I) * 100.) + 0.5
      IF(IPRINT) 120,110
  110 WRITE (18,940) YRALT,RDADMI(I),ROADW(I),IPRCNT
  940 FORMAT(*0IN YEAR*I4,* ROAD CONSTRUCTION CREATED*F6.1,* MILES OF RO
     1AD AVERAGING*F5.1,* FEET WIDE THROUGH AN AVERAGE SIDESLOPE OF*I3,
     2 * PERCENT.*)
      IPRINT = 1
```

```
      GO TO 130
  120 WRITE (18,950) ROADM)(I),ROADW()),IPRCNT
  950 FORMAT(13X*ROAO CONSTRUCTION CREATEO*F6.I,* MILES OF ROAD AVERAGIN
     1G*F5.I,* FEET WIDE THROUGH AN AVERAGE SLOPE OF*I3,* PERCENT.*)
  130 IPRCNT = (TANCUT()) * 100.) + D.5
      JPRCNT = (TANFIL()) * 1DO.) + 0.5
      WRITE (18,960) IPRCNT,JPRCNT,RATNRM(I),AVSOIL(I),DECLIN(I)
  960 FORMAT(14X*THE SLOPES OF CUT AND FILL AVERAGED*)3,* AND*I3,* PERCE
     1NT, RESPECTIVELY.  THE ESTIMATE OF THE LONG-TERM NORMAL*/14X*EROSI
     2ON RATE WAS*F7.2,*, THE INOEX OF THE AMOUNT OF SOIL AVAILABLE FOR
     3EROSION WAS*F7.2,*, ANO THE INDEX OF THE*/14X*RATE OF OECLINE OF E
     4ROSION FOLLOWING DISTURBANCE WAS*F7.2,*.*)
  140 CONTINUE
  150 RETURN
      ENO
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Subroutine TITLEM

```
      SUBROUTINE TITLEM
C-----PRINT THE TITLE SHEET
      COMMON OATIME(2),OECMAL,NRMANG,NSAVEO,NYEARS,PLNOPT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5I,SAVE,SEORN2,WEIGHT
      INTEGER OATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEORN2
      COMMON/M/ALTYR(8),BOUNO(6,8),CALDEF(8),COVOEN(8I,CUT(8I,
     1 OECIOS(2,8),OREAOY(8),ENGBAL(8),EXPK(8),EXPK1(8),FREWAT(8I,LAST1,
     2 LASUSO(8),LCOPY(14),NOYSNO(8),NEXTYR,NPLAN,NUM,NUNIT,ONTRES(8),
     3 PARAM(9),PHASE(8),PHISO(8),PREWEO(8),ROIST(8),ROMAX(8),RECHRG(8),
     4 REGROW(2,8),RUNUM(8),RUWT(8),SEOINC,SEEOAT(2),SEEOYR(2),
     5 SIMTM1(3,8),TCOEFF(8),TYPCUT(8)
      INTEGER ALTYR,BOUNO,OREAOY,PHASE,RUNUM,SEEOAT,SEEOYR,TYPCUT
      COMMON/TIME/CANREF,COMAX2,CONAV
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,OATE(2I,OATES(4),LINES,
     1 NAME,NOAY,RCHRGO,RO(372),WE(372),WEO,YEAR,YRTOT(3)
      INTEGER OATE,OATES,YEAR
      OIMENSION BIMNTH(6),ETO(372),PPT(372),RAO(372),TMAX(372),TMIN(372)
      EQUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118),RAO(1)),(BLOCK(1490),ETO(1)),(BLOCK(1864),
     2 COMAX),(BLOCK(1865),VEGTYP),(BLOCK(1866),TRSHLO),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),OCOMAX),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEKOAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
      INTEGER PEKOAT,VEGTYP
      WRITE (6,910) PLUNIT,OATIME
  910 FORMAT(*1*6A10,52X2A10/115X*ALTEREO CONOITIONS*)
      RUNUM(1) = 10H   NATURAL
      WRITE (6,920) (RUNUM(I),I=1,NUNIT)
  920 FORMAT(*ORESPONSE UNIT NUMBER*10XA10,7I10)
      RUNUM(1) = 0
      WRITE (6,921) (RUWT(I),I=1,NUNIT)
  921 FORMAT(*OPERCENT OF PLAN UNIT*10X8F10.2)
      IF(NUNIT - 2) 20,10,10
   10 WRITE (6,922) (ALTYR(I),I=2,NUNIT)
  922 FORMAT(* YEAR OF CUT          *20X7I10)
      WRITE (6,923) (CUT(I),I=2,NUNIT)
  923 FORMAT(* PERCENT OF CUT       *20X7F10.2)
      WRITE (6,924) (ROIST(I),I=1,NUNIT)
  924 FORMAT(* PRECIP REOIST FACTOR*10X8F10.2)
      WRITE (6,925) (BOUNO(5,I),I=2,NUNIT)
  925 FORMAT(*    CHANGE STARTS IN  *20X7I10)
      WRITE (6,926) (BOUNO(6,I),I=2,NUNIT)
  926 FORMAT(*    CHANGE ENOS IN    *20X7I10)
      WRITE (6,927) (REGROW(1,I),I=2,NUNIT)
  927 FORMAT(* REGROWTH-AVAIL WATER*20X7F10.2)
      WRITE (6,925) (BOUNO(1,I),I=2,NUNIT)
      WRITE (6,926) (BOUNO(2,I),I=2,NUNIT)
      WRITE (6,928) (REGROW(2,I),I=2,NUNIT)
  928 FORMAT(* REGROWTH-REFLECTIVTY*20X7F10.2)
      WRITE (6,925) (BOUNO(3,I),I=2,NUNIT)
      WRITE (6,926) (BOUNO(4,I),I=2,NUNIT)
   20 WRITE (6,930) (TCOEFF(I),I=1,NUNIT)
  930 FORMAT(* TRANSMISSIVITY COEFF*10X8F10.2)
      WRITE (6,931) (COVOEN(I),I=1,NUNIT)
  931 FORMAT(* COVER OENSITY        *10X8F10.2)
      TMPMLF = (TMPMLT * 1.8) + 32.
      WRITE (6,932) COMAX,VEGTYP,TRSHLO,TMPMLF,WILTPT
  932 FORMAT(* MAXIMUM COVER DEN    *10XF10.2/
     1 * VEGETATION TYPE       *10XI10  /* REFLECTIVITY THRSHLO*10XF10.2/
     2 * MELT THRESHOLO        *10XF10.2/* WILTING POINT        *10XF10.2)
      IF(VEGTYP.NE.3) GO TO 30
      WRITE (6,940) (OECIOS(1,I),I=1,NUNIT)
  940 FORMAT(* DECIOUOUS WINTER TC *10X8F10.2)
      WRITE (6,941) (OECIOS(2,I),I=1,NUNIT)
  941 FORMAT(* OECIOUOUS WINTER CO *10X8F10.2)
      WRITE (6,942) OCOMAX
  942 FORMAT(* OECIOUOUS WNTR COMAX*10XF10.2)
   30 WRITE (6,950) (SIMTM1(2,I),I=1,NUNIT)
  950 FORMAT(*OINITIAL CONOITIONS*/* AVERAGE PACK TEMP.  *10X8F10.2)
      WRITE (6,951) (PREWEO(I),I=1,NUNIT)
  951 FORMAT(* PACK WATER EQUIV.    *10X8F10.2)
      WRITE (6,952) (RECHRG(I),I=1,NUNIT)
  952 FORMAT(* RECHARGE REOUIREMENT*10X8F10.2)
      IF(SEEOYR(1) - 9999) 40,50
   40 CALL GOATE (SEEOAT(1),OATES(1))
      CALL GDATE (SEEOAT(2),OATES(3))
      WRITE (6,960) SEEOYR,OATES,SEOINC
  960 FORMAT(*OCLOUO SEEOING FROM *I4,* TO *I4,*, OAYS *I2,*/*I2,* TO *
     1 I2,*/*I2,*, WITH A FACTOR OF *F6.2)
   50 RETURN
      END
```

Subroutine BALANC

```
      SUBROUTINE BALANC
C-----BALANCE THE REOISTRIBUTION FACTORS
      COMMON/M/ALTYP(8),BOUNO(6,8),CALOEF(8),COVOEN(8),CUT(8),
     1 OECIOS(2,8),DREAOY(8),ENGBAL(8),EXPK(8),EXPK1(8),FREWAT(8),LAST1,
     2 LASUSO(8),LCOPY(14),NDYSNO(8),NEXTYR,NPLAN,NUM,NUNIT,ONTRES(8),
     3 PARAM(9),PHASE(8),PHISQ(8),PREWEO(8),ROIST(8),ROMAX(8),RECHRG(8),
     4 REGROW(2,8),RUNUM(8),RUWT(8),SEOINC,SEEOAT(2),SEEOYR(2),
     5 SIMTM1(3,8),TCOEFF(8),TYPCUT(8)
      INTEGER ALTYR,BOUNO,OREAOY,PHASE,RUNUM,SEEDAT,SEEOYR,TYPCUT
      IF(NUNIT - 2) 10,20,20
   10 RETURN
C-----ACCUMULATE THE WEIGHTS FOR THE AREAS ON WHICH THERE IS
C----- REOISTRIBUTION WHILE CALCULATING THE REMAINING PORTION FOR THE
C----- OTHER AREAS
   20 RDSTWT = 0.0
      REMAIN = 1.0
      OO 40 N = 2,NUNIT
      IF(TYPCUT(N)) 30,40
   30 RDSTWT = RDSTWT + RUWT(N)
      REMAIN = REMAIN - (RDIST(N) * RUWT(N))
   40 CONTINUE
      IF(ABS(REMAIN).LT.0.01) REMAIN = D.0
      IF(REMAIN) 50,60,60
   50 WRITE (6,910)
  910 FORMAT(*1THE REOISTRIBUTION OF THE PRECIP TOTALS MORE THAN 100 PER
     1CENT - JOB ABORTEO*)
      CALL ABORT
C-----CALCULATE THE CORRESPONOING EFFECT ON PRECIP FOR THE NATURAL UNIT
C----- ANO THOSE WHERE REDISTRIBUTION HAS NOT SPECIFIEO
   60 REST = 1.0 - ROSTWT
      IF(REST) 70,70,80
   70 EFFECT = 0.0
      GO TO 90
   80 EFFECT = REMAIN/REST
C-----OEFINE THE REOISTRIBUTION FACTORS FOR THOSE AREAS
   90 OO 110 N = 1,NUNIT
      IF(TYPCUT(N)) 110,100
  100 ROIST(N) = EFFECT
  110 CONTINUE
      RETURN
      ENO
```

Subroutine GBOUND

```
      SUBROUTINE GBOUNO (N)
C-----GET THE BOUNOARY YEARS - (IF NOT SPECIFIEO, USE THE ASSUMEO
C----- VALUES)
      COMMON/M/ALTYR(8I,BOUNO(6,8),CALOEF(8),COVOEN(8),CUT(8I,
     1 OECIOS(2,8),OREAOY(8),ENGBAL(8I,EXPK(8),EXPK1(8),FREWAT(8I,LAST1,
     2 LASUSO(8),LCOPY(14),NOYSNO(8I,NEXTYR,NPLAN,NUM,NUNIT,ONTRES(8),
     3 PARAM(9),PHASE(8),PHISO(8),PREWEO(8),ROIST(8I,ROMAX(8I,RECHRG(8I,
     4 REGROW(2,8),RUNUM(8),RUWT(8),SEOINC,SEEOAT(2I,SEEOYR(2),
     5 SIMTM1(3,8),TCOEFF(8),TYPCUT(8)
      INTEGER ALTYR,BOUNO,OREAOY,PHASE,RUNUM,SEEOAT,SEEOYR,TYPCUT
      COMMON/TIME/CANREF,COMAX2,CONAV
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,OATE(2I,OATES(4),LINES,
     1 NAME,NDAY,RCHRGO,RO(372I,WE(372),WEO,YEAR,YRTOT(3)
      INTEGER OATE,OATES,YEAR
      OIMENSION BIMNTH(6),ETO(372),PPT(372I,RAO(372I,TMAX(372),TMIN(372)
      EOUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118I,RAO(1)),(BLOCK(1490),ETO(1)),(BLOCK(1864),
     2 COMAX),(BLOCK(1865I,VEGTYP),(BLOCK(1866I,TRSHLO),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),OCOMAX),(BLOCK(1872I,
     4 ISOTRM),(BLOCK(1873),PEKOAT),(BLOCK(1880I,BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888I,PEAKRO)
      INTEGER PEKOAT,VEGTYP
      INTEGER YRPAST
      OIMENSION ASSUMO(7,3)
C-----LOOGEPOLE PINE
      OATA ASSUMO(1,1),ASSUMO(2,1),ASSUMO(3,1),ASSUMO(4,1),ASSUMO(5,1),
     1 ASSUMO(6,1),ASSUMO(7,1)/15.,80.,0.,40.,40.,120.,0.0/
C-----SPRUCE-FIR
      OATA ASSUMO(1,2),ASSUMO(2,2I,ASSUMO(3,2I,ASSUMO(4,2I,ASSUMO(5,2),
     1 ASSUMO(6,2),ASSUMO(7,2)/30.,100.,0.,80.,80.,160.,0.0/
C-----ASPEN
      OATA ASSUMO(1,3),ASSUMO(2,3),ASSUMO(3,3),ASSUMO(4,3I,ASSUMO(5,3),
     1 ASSUMD(6,3),ASSUMO(7,3)/7.,60.,0.,20.,20.,80.,0.0/
      COMAX2 = COMAX/2.0
C-----IF THE CUT IS LESS THAN 50 PERCENT, IT IS ASSUMEO THAT THE
C----- PATCH CUT TRANSITION LEVEL OF THE FOREST IS ZERO
      IF(COMAX2 - COVUEN(N)) 10,10,20
   10 BOUNO(1,N) = ALTYR(N) - 1
      BOUNO(2,N) = BOUNO(1,N)
      BOUNO(3,N) = BOUNO(1,N)
      BOUNO(4,N) = BOUND(1,N)
      BOUNO(5,N) = BOUNO(1,N)
      BOUNO(6,N) = BOUNO(1,N)
      ROMAX(N) = 0.0
      ROIST(N) = 1.0
      TYPCUT(N) = 0
      RETURN
C-----USE THE ASSUMEO VALUES IF ALL PARAMETERS ARE BLANK
   20 OO 40 I = 1,6
      IF(PARAM(I+2)) 50,30
   30 BOUNO(I,N) = ASSUMO(I,VEGTYP)
   40 CONTINUE
      ROMAX(N) = ASSUMO(7,VEGTYP)
      GO TO 70
C-----SINCE AT LEAST ONE OF THE PARAMETERS WAS SPECIFIEO, USE THEM ALL
   50 OO 60 I = 1,6
      BOUNO(I,N) = PARAM(I+2)
C-----CERTIFY THAT THE ENOING YEARS FOLLOW THE BEGINNING YEARS
      IF(I.EO.1.OR.I.EO.3.OR.I.EO.5) GO TO 60
      IF(BOUNO(I-1,N).LT.BOUNO(I,N)) GO TO 60
      WRITE (6,910) ALTYR(N),RUNUM(N),BOUNO(1,N),BOUNO(I-1,N)
  910 FORMAT(*OMANAGEMENT PLAN CARO ERROR - YEAR*I4,*, RESPONSE UNIT*I6,
     1 *, ENOING YEAR*I4,* OOES NOT FOLLOW BEGINNING YEAR*I4,* - JOO ABO
     2RTEO*)
      CALL ABORT
   60 CONTINUE
      ROMAX(N) = PARAM(9)
C-----OEFINE PHI SOUAREO FOR THE REFLECTIVITY ANO COVER OENSITY FUNCTION
   70 PHISO(N) = (BOUNO(4,N) - BOUNO(3,N)) ** 2
C-----IF THIS IS A THINNING CUT RATHER THAN A PATCH CUT, AOJUST THE
C----- BOUNOARIES TO COMPENSATE (THIS ALLOWS THE REMOVAL OF THE
C----- OVERSTORY, BUT LEAVES A STANO WHICH, IN TERMS OF THE SIMULATION
C----- FUNCTIONS, IS ALREAOY IN THE PROCESS OF REGROWTH)
      IF(COVOEN(N)) 100,100,80
   80 YRPAST = SORT ((COVDEN(N) * PHISO(N))/COMAX) + 0.5
      DO 90 I = 1,6
   90 BOUNO(I,N) = BOUNO(I,N) - YRPAST
```

```
C-----DEFINE THE BOUNDARIES IN TERMS OF THE YEAR OF TREATMENT
  100 DO 110 I = 1,6
  110 BOUND(I,N) = BOUND(I,N) + ALTYR(N)
C-----COMPUTE THE K FOR THE INVERSE EXPONENTIAL FUNCTION REPRESENTING
C----- THE AVAILABLE SOIL WATER FACTOR
C-----GIVEN THAT TAU = M*EXP(-K*(T-TC)), AT TIME T = FULL REGROWTH, TAU
C----- BECOMES M/2.  THUS,
C----- M/2 = M*EXP(-K*(T-TC)), WHICH YIELDS
C----- 1/2 = EXP(-K*(T-TC)).  UPON TAKING THE NATURAL LOG,
C----- LN(.5) = -K*(T-TC), OR
C----- K = -LN(.5)/(T - TC)
      EXPK(N) = 0.6931471805/FLOAT(BOUND(2,N) - BOUND(1,N))
C-----COMPUTE THE K FOR THE INVERSE EXPONENTIAL FUNCTION REPRESENTING
C----- THE PRECIP REDISTRIBUTION
C-----GIVEN THAT RHO = RHO(MAX) * EXP (-K1*(T-TC)), AT TIME T = FULL
C----- REGROWTH, RHO MUST APPROACH ZERO (ASSUME 1 PERCENT).  HENCE,
C----- .01 = RHO(MAX) * EXP (-K1*(T-TC)), OR
C----- .01/RHO(MAX) = EXP(-K1*(T-TC)).  UPON TAKING THE NATURAL LOG,
C----- LN(.01/RHO(MAX)) = -K1*(T-TC), OR
C----- K1 = -LN(.01/RHO(MAX))/(T-TC)  (WATCH FOR RHO(MAX) = 0)
      IF(RDMAX(N)) 130,120,130
  120 BOUND(5,N) = ALTYR(N) - 1
      BOUND(6,N) = ALTYR(N) - 1
      RETURN
  130 EXPK1(N) = - ALOG(0.01/ABS(RDMAX(N)))/FLOAT(BOUND(6,N)-BOUND(5,N))
      TYPCUT(N) = 1
      RETURN
      END
```

Subroutine TRENDS

```
      SUBROUTINE TRENDS
C-----DETERMINE THE EFFECTS OF THE TIME TREND(S)
      COMMON/M/ALTYR(8),BOUND(6,8),CALDEF(8),COVDEN(8),CUT(8),
     1 DECIDS(2,8),DREADY(8),ENGBAL(8),EXPK(8),EXPK1(8),FREWAT(8),LAST1,
     2 LASUSO(8),LCOPY(14),NDYSNO(8),NEXTYR,NPLAN,NUM,NUNIT,ONTRES(8),
     3 PARAM(9),PHASE(8),PHISQ(8),PREWEQ(8),RDIST(8),RDMAX(8),RECHRG(8),
     4 REGROW(2,8),RUNUM(8),RUWT(8),SEDINC,SEEDAT(2),SEEDYR(2),
     5 SIMTM1(3,8),TCOEFF(8),TYPCUT(8)
      INTEGER ALTYR,BOUND,DREADY,PHASE,RUNUM,SEEDAT,SEEDYR,TYPCUT
      COMMON/TIME/CANREF,CDMAX2,CONAV
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRGD,RO(372),WE(372),WED,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETD(372),PPT(372),RAD(372),TMAX(372),TMIN(372)
      EQUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(1490),ETD(1)),(BLOCK(1864),
     2 CDMAX),(BLOCK(1865),VEGTYP),(BLOCK(1866),TRSHLD),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),DCDMAX),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEKDAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
      INTEGER PEKDAT,VEGTYP
      IF(NUNIT - 2) 10,20,20
   10 RETURN
   20 DO 170 N = 2,NUNIT
C-----AVAILABLE SOIL WATER ADJUSTMENT (ACCOUNTS FOR INCREASED CANOPY
C----- DENSITY AND ROOTING DEPTH)
C-----REGROW(1,N) WILL BE -CONAV-
      IF(YEAR - BOUND(1,N)) 30,30,40
C-----THE CUT AREA IS STILL TO BE CONSIDERED  AS AN OPENING
   30 REGROW(1,N) = 1.0
      GO TO 70
   40 IF(BOUND(2,N) - YEAR) 50,50,60
C-----REGROWTH IS COMPLETE AS FAR AS THIS FACTOR IS CONCERNED
   50 REGROW(1,N) = 0.5
      GO TO 70
C-----REGROWTH HAS OCCURRED, BUT IS NOT COMPLETE
   60 REGROW(1,N) = EXP (-EXPK(N) * (FLOAT(YEAR - BOUND(1,N))))
      WRITE (17,910) YEAR,RUNUM(N),REGROW(1,N)
  910 FORMAT(* AFTER THE GROWING SEASON OF WATER YEAR*I4,* ON RESPONSE U
     1NIT*I6,*, THE AVAILABLE WATER FACTOR IS*F5.2)
C-----CANOPY REFLECTIVITY ADJUSTMENT AND COVER DENSITY
C-----REGROW(2,N) WILL BE -CANREF-
   70 IF(BOUND(4,N) - YEAR) 80,90,90
C-----REGROWTH IS COMPLETE AS FAR AS THE CANOPY REFLECTIVITY IS
C----- CONCERNED
   80 REGROW(2,N) = 1.0 - (0.5 * EXP(-1.609437912 * COVDEN(N)/CDMAX))
      GO TO 120
C-----REGROWTH HAS OCCURRED, BUT IS NOT COMPLETE
C-----GIVEN THAT RF = RFO * EXP (-OMEGA*CDMAX*T**2/PHI**2), AT TIME T =
C----- PHI,  RF = RFO * EXP (-OMEGA*CDMAX).  AT TIME PHI, THE MAXIMUM
C----- COVER DENSITY HAVE BEEN REACHED.  HENCE, RF = 0.1 (RFO IS A
C----- CONSTANT 0.5), WHICH YIELDS
C----- 0.1 = 0.5 * EXP (-OMEGA * CDMAX), OR
C----- 0.2 = EXP (-OMEGA*CDMAX).  UPON TAKING THE NATURAL LOG,
C----- LN(0.2) = -OMEGA * CDMAX, WHICH YIELDS
C----- OMEGA = - LN(0.2)/CDMAX.  SUBSTITUTION PRODUCES
C----- RF = 0.5*EXP (-1.609*T**2/PHI**2).
C----- THE VARIABLE -CANREF- IS DEFINED TO BE 1 - RF
   90 IF(YEAR - BOUND(3,N)) 100,100,110
C-----THE CUT AREA IS STILL AN OPENING
  100 REGROW(2,N) = 0.5
      GO TO 120
  110 TBYPHI = (FLOAT(YEAR - BOUND(3,N))**2)/PHISQ(N)
      REGROW(2,N) = 1.0 - (0.5 * EXP (-1.609437912 * TBYPHI))
      COVDEN(N) = CDMAX * TBYPHI
      TCOEFF(N) = TC (COVDEN(N))
      WRITE (17,920) YEAR,RUNUM(N),REGROW(2,N),COVDEN(N)
  920 FORMAT(* AFTER THE GROWING SEASON OF WATER YEAR*I4,* ON RESPONSE U
     1NIT*I6,*, THE CANOPY REFLECTIVITY FACTOR IS*F5.2,*, COVER DENSITY
     2IS*F5.2)
      IF(VEGTYP.NE.3.AND.VEGTYP.NE.4) GO TO 120
      DECIDS(2,N) = DCDMAX * TBYPHI
      DECIDS(1,N) = TC (DECIDS(2,N))
      WRITE (17,930) DECIDS(2,N)
  930 FORMAT(*  WITH A WINTER COVER DENSITY OF*F5.2)
C-----REDISTRIBUTION
  120 IF(YEAR - BOUND(5,N)) 130,140,140
C-----MAXIMIZE REDISTRIBUTION
  130 RDIST(N) = 1.0 + RDMAX(N)
      GO TO 170
  140 IF(BOUND(6,N) - YEAR) 150,150,160
C-----REGROWTH IS COMPLETE
  150 RDIST(N) = 1.0
      TYPCUT(N) = 0
      GO TO 170
C-----ADJUST THE REDISTRIBUTION
  160 RDIST(N) = 1.0 + (RDMAX(N) * EXP(-EXPK1(N) * FLOAT(YEAR-BOUND(5,N)
     1)))
      WRITE (17,940) YEAR,RUNUM(N),RDIST(N)
  940 FORMAT(* AFTER THE GROWING SEASON OF WATER YEAR*I4,* ON RESPONSE U
     1NIT*I6,*, THE PRECIP REDISTRIBUTION FACTOR IS*F5.2)
  170 CONTINUE
C-----BALANCE THE REDISTRIBUTION FACTORS
      CALL BALANC
      RETURN
      END
```

Program SEDMOD

```
      OVERLAY (OLAYS,2,3)
      PROGRAM SEDMOD
C-----SEDIMENT YIELD MODEL
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,PLNOPT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
      INTEGER DATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
      COMMON/S/AVSOIL(11),DECLIN(11),NROADS,RATNRM(11),ROADMI(11),
     1 ROADW(11),TANCUT(11),TANFIL(11),TANRHO(11),YRCNST(11)
      INTEGER YRCNST
      COMMON/UTILTY/BLOCK(1889),CHANGR,CHANGW,DATE(2),DATES(4),LINES,
     1 NAME,NDAY,RCHRGD,RO(372),WE(372),WED,YEAR,YRTOT(3)
      INTEGER DATE,DATES,YEAR
      DIMENSION BIMNTH(6),ETD(372),PPT(372),RAD(372),TMAX(372),TMIN(372)
      EQUIVALENCE (BLOCK(2),TMAX(1)),(BLOCK(374),TMIN(1)),(BLOCK(746),
     1 PPT(1)),(BLOCK(1118),RAD(1)),(BLOCK(1490),ETD(1)),(BLOCK(1864),
     2 CDMAX),(BLOCK(1865),VEGTYP),(BLOCK(1866),TRSHLD),(BLOCK(1867),
     3 TMPMLT),(BLOCK(1868),WILTPT),(BLOCK(1871),DCDMAX),(BLOCK(1872),
     4 ISOTRM),(BLOCK(1873),PEKDAT),(BLOCK(1880),BIMNTH(1)),
     5 (BLOCK(1886),PEAKWE),(BLOCK(1888),PEAKRO)
      INTEGER PEKDAT,VEGTYP
      DIMENSION LCOPY(14),NCOL(165),ONELIN(11),SEDNAT(165,11),
     1 SEDINC(165,11)
      INTEGER CODE(11),POINT(121),YEARS(165)
C-----EQUIVALENCE ARRAYS TO SAVE STORAGE REQUIREMENTS
      EQUIVALENCE (BLOCK,SEDNAT),(RO,NCOL),(WE,YEARS)
      DATA CODE/1H1,1H2,1H3,1H4,1H5,1H6,1H7,1H8,1H9,1HA,1HB/
C-----COPY THE DESCRIPTION OF THE STRATEGY
      REWIND 18
      GO TO 3
    1 WRITE (6,903) LCOPY
  903 FORMAT(13A10,A6)
    3 READ (18,903) LCOPY
      IF(EOF(18)) 5,1
    5 REWIND 18
      END FILE 18
      REWIND 12
C-----DEFINE THE COLUMN COUNTER AND THE YEARS
      DO 10 I = 1,NYEARS
      NCOL(I) = 0
   10 READ (12,906) YEARS(I)
  906 FORMAT(2XI3)
C-----CALCULATE THE ACCUMULATED SEDIMENT FOR THE DISTURBED AREA AS
C----- THOUGH IT REMAINED IN ITS NATURAL STATE, THEN CALCULATE THE
C----- INCREASE
      DO 50 I = 1,NROADS
      CONST = (ROADW(I)/2.0) * TANRHO(I)
      DISTRB = 0.121 * ROADMI(I) * (ROADW(I) +
     1 (CONST/(TANFIL(I) - TANRHO(I))) +
     2 (CONST/(TANCUT(I) - TANRHO(I))))
C-----PLACE THIS YEAR IN THE TABLE
      DO 20 J = 1,NYEARS
      K = J
      IF(YRCNST(I) - YEARS(J)) 20,30
   20 CONTINUE
C-----CALCULATE THE VALUES FOR THE FIRST YEAR, THEN THE REMAINING YEARS
   30 SEDNAT(K,I) = DISTRB * RATNRM(I)
      CONST = DISTRB * AVSOIL(I)
      SEDINC(K,I) = CONST * (1.0 - EXP(-DECLIN(I)))
      NCOL(K) = I
      L = K + 1
      IF(L.GT.NYEARS) GO TO 45
      DECTIM = DECLIN(I)
      RATTIM = SEDNAT(K,I)
      DO 40 J = L,NYEARS
      SEDNAT(J,I) = SEDNAT(J-1,I) + RATTIM
      DECTIM = DECTIM + DECLIN(I)
      SEDINC(J,I) = CONST * (1.0 - EXP(-DECTIM))
      NCOL(J) = I
   40 CONTINUE
   45 IF(I.EQ.1) GO TO 50
      L = I - 1
      DO 46 J = K,NYEARS
      SEDNAT(J,I) = SEDNAT(J,I) + SEDNAT(J,L)
   46 SEDINC(J,I) = SEDINC(J,I) + SEDINC(J,L)
   50 CONTINUE
   60 IPASS = 1
      NAMSED = 10HCUMULATIVE
C-----PRINT THE COMBINED AMOUNTS, THEN THE INCREASE OVER NATURAL
C----- CONDITIONS
   70 DO 120 I = 1,NYEARS,55
      WRITE (6,910) PLUNIT,DATIME,NAMSED
  910 FORMAT(*1*6A10,52X2A10/113XA10,* SED YIELD*/*0*/* YEAR*/)
      N1 = I
      N2 = I + 54
      IF(N2.GT.NYEARS) N2 = NYEARS
      DO 110 N = N1,N2
      IF(NCOL(N)) 90,80
   80 WRITE (6,920) YEARS(N)
  920 FORMAT(1X15,15X11F10.0)
      GO TO 110
   90 J1 = NCOL(N)
      DO 100 J = 1,J1
  100 ONELIN(J) = SEDNAT(N,J) + SEDINC(N,J)
      WRITE (6,920) YEARS(N),(ONELIN(J),J=1,J1)
  110 CONTINUE
  120 CONTINUE
```

```
C-----PRINT THE INCREASE OVER NATURAL CONDITIONS
      DO 160 I = 1,NYEARS,55
      WRITE (6,930) PLUNIT,DATIME,NAMSED
  930 FORMAT(*1*6A10,52X2A10/* EFFECTS OF TREATMENT COMPARED WITH NATURA
     1L CONDITIONS )DECREASE INDICATED BY -)*33XA10,* SED YIELD*/*C*/
     2 * YEAR*/)
      N1 = I
      N2 = I + 54
      IF(N2.GT.NYEARS) N2 = NYEARS
      DO 150 N = N1,N2
      IF(NCOL(N)) 140,130
  130 WRITE (6,920) YEARS(N)
      GO TO 150
  140 J1 = NCOL(N)
      WRITE (6,925) YEARS(N),(SEDINC(N,J),J=1,J1)
  150 CONTINUE
  160 CONTINUE
C-----IF THE ANNUAL TOTALS HAVE PRINTED, GO ON TO THE PLOTS.  IF NOT,
C----- SET THEM UP AND GO BACK TO PRINT THEM
      IF(IPASS) 170,210
  170 IPASS = 0
      NAMSED = 10H    ANNUAL
C-----COMPUTE THE ANNUAL TOTALS
      N2 = NYEARS
      N1 = NYEARS - 1
      DO 200 I = 2,NYEARS
      IF(NCOL(N1)) 180,70
  180 J1 = NCOL(N1)
      IF(NCOL(N1).EQ.NCOL(N2)) GO TO 185
      J2 = J1 + 1
      SEDNAT(N2,J2) = SEDNAT(N2,J2) - SEDNAT(N1,J1)
      SEDINC(N2,J2) = SEDINC(N2,J2) - SEDINC(N1,J1)
  185 DO 190 J = 1,J1
      SEDNAT(N2,J) = SEDNAT(N2,J) - SEDNAT(N1,J)
  190 SEDINC(N2,J) = SEDINC(N2,J) - SEDINC(N1,J)
      N2 = N1
      N1 = N1 - 1
  200 CONTINUE
      GO TO 70
C-----PLOT THE ANNUAL INCREASES
  210 WRITE (6,930) PLUNIT,DATIME,NAMSED
      WRITE (6,940)
  940 FORMAT(*0*35X*INCREASE*/* YEAR 0*12(10H.........+))
      DO 260 I = 1,NYEARS
      DO 220 J = 2,121
  220 POINT(J) = 1H
      POINT(1) = 1H.
      J1 = NCOL(I)
      IF(J1 - 1) 250,230,230
  230 DO 240 J = 1,J1
      K = (SEDINC(I,J)*0.1) + 1.5
      IF(K.GE.1.AND.K.LE.121) POINT(K) = CODE(J)
  240 CONTINUE
C-----PRINT THE LINE OF PLOT
  250 WRITE (6,950) YEARS(I),POINT
  950 FORMAT(1XI4,1X121A1)
  260 CONTINUE
C-----RETURN TO THE MAIN OVERLAY
      END
```

Program OLDNEW

```
      OVERLAY (OLAYS,3,0)
      PROGRAM OLDNEW
C-----COPY -SAVOLD- TO -SAVNEW-
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,PLNOPT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
      INTEGER DATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
      DIMENSION BLOCK(1889),ID(9)
      CALL CORE (-1)
C-----WHEN AN END OF FILE IS SENSED ON AN ID READ, COPYING IS COMPLETE
      REWIND 14
   10 CALL GETREC (14,ID,9,IEND)
      IF(IEND) 60,20
   20 CALL PUTREC (15,ID,9)
C-----COPY ALL YEARS
   30 CALL GETREC (14,BLOCK,1889,IEND)
      IF(IEND) 50,40
   40 CALL PUTREC (15,BLOCK,1889)
      GO TO 30
   50 END FILE 15
      GO TO 10
   60 CONTINUE
      CALL CORE (0)
C-----RETURN TO THE MAIN OVERLAY
      END
```

Program COMPLN

```
      OVERLAY (OLAYS,4,0)
      PROGRAM COMPLN
C-----COMBINE THE MANAGEMENT PLANS INTO ONE PRINTOUT FOR A PLANNING UNIT
C----- AND ADD THE DATA TO THE REGIONAL FILE
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,PLNOPT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
      INTEGER DATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
      COMMON/P/NAME(2,15),NCOL(165),NPLAN,NUM(12),NVAR,OUT(165,12),
     1 VAR(15),YEAR(165)
      INTEGER YEAR
      DIMENSION LCOPY(14)
      INTEGER DATES(24)
      DATA NAME(1,1),NAME(2,1)/10H    GENERA,10HTED RUNOFF/
      DATA NAME(1,2),NAME(2,2)/10H          PRE,10HCIPITATION/
      DATA NAME(1,3),NAME(2,3)/10H  EVAPOTRA,10HNSPIRATION/
      DATA NAME(1,4),NAME(2,4)/10HCHANGE IN ,10HRECH. RED./
      DATA NAME(1,5),NAME(2,5)/10H CHANGE IN,10H PACK W.E./
      DATA NAME(1,6),NAME(2,6)/10H   APR 16-,10H30 GEN R O/
      DATA NAME(1,7),NAME(2,7)/10H    MAY 1-,10H15 GEN R O/
      DATA NAME(1,8),NAME(2,8)/10H   MAY 16-,10H30 GEN R O/
      DATA NAME(1,9),NAME(2,9)/10H   JUNE 1-,10H15 GEN R O/
      DATA NAME(1,10),NAME(2,10)/10H  JUNE 16-,10H30 GEN R O/
      DATA NAME(1,11),NAME(2,11)/10H   JULY 1-,10H15 GEN R O/
      DATA NAME(1,12),NAME(2,12)/10H          ,10H  PEAK W E/
      DATA NAME(1,13),NAME(2,13)/10H    DATE O,10HF PEAK W E/
      DATA NAME(1,14),NAME(2,14)/10H      PEAK,10H 7-DAY R O/
      DATA NAME(1,15),NAME(2,15)/10HDATE, PEAK,10H 7-DAY R O/
      CALL CORE (-1)
C-----COPY THE MANAGEMENT STRATEGY DESCRIPTION
      REWIND 18
      IF(PLNOPT(5).EQ.0.AND.PLNOPT(6).EQ.0.AND.PLNOPT(7).EQ.0.AND.
     1 PLNOPT(8).EQ.0.AND.PLNOPT(9).EQ.0) GO TO 9
      GO TO 6
    3 WRITE (6,900) LCOPY
  900 FORMAT(13A10,A6)
    6 READ (18,900) LCOPY
      IF(EOF(18)) 9,3
    9 CONTINUE
C-----PRINT THE INDICATED VARIABLES
      DO 180 NVAR = 1,15
      IF(NVAR.GT.5.AND.PLNOPT(NVAR+4).EQ.0) GO TO 180
      REWIND 12
C-----READ THE FIRST RECORD
      READ (12,910) NUM(1),YEAR(1),VAR
  910 FORMAT(I2,I3,3X(5F6.2)
      OUT(1,1) = VAR(NVAR)
      NCOL(1) = 1
      NPLAN = 1
C-----FILL THE FIRST COLUMN
      DO 30 I = 2,NYEARS
      READ (12,910) MPLAN,IYEAR,VAR
C-----IF THIS IS STILL THE SAME PLAN, STORE THE INFORMATION
   10 IF(MPLAN - NUM(1)) 30,20
   20 YEAR(I) = IYEAR
      OUT(I,NPLAN) = VAR(NVAR)
      NCOL(I) = 1
   30 CONTINUE
C-----A MAXIMUM OF -NYEARS- YEARS MAY BE SUMMARIZED
      READ (12,910) MPLAN,IYEAR,VAR
      IF(EOF(12)) 150,40
   40 IF(MPLAN - NUM(1)) 80,50
   50 WRITE (6,920) NYEARS
  920 FORMAT(*0A MAXIMUM OF*I4,* YEARS MAY BE SUMMARIZED - THE BALANCE A
     1RE IGNORED*)
   60 READ (12,910) MPLAN,IYEAR,VAR
      IF(EOF(12)) 150,70
   70 IF(MPLAN - NUM(NPLAN)) 80,60
C-----FILL THE NEXT COLUMN (UP TO 12)
   80 IF(NPLAN - 12) 100,90,90
   90 WRITE (6,930)
  930 FORMAT(*0A MAXIMUM OF 12 PLANS MAY BE SUMMARIZED - THE BALANCE ARE
     1 IGNORED*)
      GO TO 150
  100 NPLAN = NPLAN + 1
      NUM(NPLAN) = MPLAN
C-----FIND THE FIRST YEAR AND STORE IT
      DO 110 N = 1,NYEARS
      IF(IYEAR - YEAR(N)) 110,120
  110 CONTINUE
      WRITE (6,940) MPLAN,IYEAR
  940 FORMAT(*0MANAGEMENT PLAN*I4,* STARTS WITH YEAR*I4,* WHICH WAS NOT
     1PART OF THE ORIGINAL TIME SPAN - JOB ABORTED*)
      CALL ABORT
  120 OUT(N,NPLAN) = VAR(NVAR)
      NCOL(N) = NCOL(N) + 1
C-----FILL THE REMAINDER OF THE COLUMN
      N = N + 1
      IF(N - NYEARS) 130,130,60
  130 DO 140 I = N,NYEARS
      READ (12,910) MPLAN,IYEAR,VAR
      OUT(I,NPLAN) = VAR(NVAR)
      NCOL(I) = NCOL(I) + 1
  140 CONTINUE
C-----GO BACK TO READ THE NEXT PLAN
      GO TO 60
C-----WRITE THE INFORMATION ON THE REGIONAL FILE
  150 IF(NVAR.GT.5) GO TO 156
      DO 155 I = 1,NYEARS
      N = NCOL(I)
      WRITE (13,945) YEAR(I),DECMAL,OUT(I,1),OUT(I,N),WEIGHT,NVAR
  945 FORMAT(I3,F3.2,3F10.5,I1)
  155 CONTINUE
C-----PRINT THE ARRAYS IF SPECIFIED
  156 IF(PLNOPT(NVAR+4).EQ.0) GO TO 180
      IF(PLNOPT(NVAR+4).EQ.2) GO TO 175
      DO 170 I = 1,NYEARS,55
      WRITE (6,950) PLUNIT,DATIME,NAME(1,NVAR),NAME(2,NVAR)
  950 FORMAT(*1*6A10,52X2A10/113X2A10)
      WRITE (6,960) (NUM(N),N=1,NPLAN)
  960 FORMAT(*0   PLAN NUMBER*I5,11I10)
      WRITE (6,970)
  970 FORMAT(* YEAR*/)
      N1 = I
      N2 = I + 54
      IF(N2.GT.NYEARS) N2 = NYEARS
      IF(NVAR.EQ.13.OR.NVAR.EQ.15) GO TO 165
      DO 160 N = N1,N2
      J1 = NCOL(N)
      WRITE (6,980) YEAR(N),(OUT(N,J),J=1,J1)
  980 FORMAT(1XI5,5X12F10.2)
  160 CONTINUE
      GO TO 170
C-----CONVERT THE DATES FROM THE PSEUDO-JULIAN FORMAT
  165 DO 167 N = N1,N2
      J1 = NCOL(N)
      J2 = 1
      DO 166 J = 1,J1
      K = OUT(N,J)
      CALL GDATE (K,DATES(J2))
      J2 = J2 + 2
  166 CONTINUE
      J2 = J2 - 1
      WRITE (6,990) YEAR(N),(DATES(J),J=1,J2)
  990 FORMAT(1XI5,5X12(5XI2,*/*I2))
  167 CONTINUE
  170 CONTINUE
      IF(NVAR.LE.5.AND.PLNOPT(NVAR+4).EQ.1) GO TO 180
```

```
---COMPUTE THE DIFFERENCES BETWEEN THE NATURAL AND TREATED CONDITIONS
75 CALL DIFFER
80 CONTINUE
   CALL CORE (0)
---RETURN TO THE PRIMARY OVERLAY
   END
```

broutine DIFFER

```
   SUBROUTINE DIFFER
---COMPUTE ANO PRINT THE OIFFERENCES CAUSEO BY THE TREATNENTS
   COMMON OATIME(2),OECMAL,NRMANG,NSAVEO,NYEARS,PLNOPT(19),PLUNIT(6),
  1 RECOVR,REGION(B),REGOPT(5),SAVE,SEORN2,WEIGHT
   INTEGER OATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVC,SEORN2
   COMMON/P/NAME(2,15),NCOL(165),NPLAN,NUM(12),NVAR,OUT(165,12),
  1 VAR(15),YEAPI165)
   INTEGER YEAR
   OINENSION IOUT(12)
   INTEGER OOO(6)
   DATA OOO/62,154,155,217,279,372/
   DO 110 I = 1,NYEARS,55
   WRITE (6,910) PLUNIT,OATIME,NANE(1,NVAR),NANE(2,NVAR)
10 FORMAT(*1*6A10,52X2A10/* EFFECTS OF TREATNENT CONPARED WITH NATURA
  1L CONDITIONS (DECREASE INDICATEO BY -)*33X2A10)
   WRITE (6,920) (NUM(N),N=1,NPLAN)
20 FORMAT(*0    PLAN NUNBER*I5,11I10)
   WRITE (6,930)
30 FORMAT(* YEAR*/)
   N1 = I
   N2 = I + 54
   IF(N2.GT.NYEARS) N2 = NYEARS
   DO 100 N = N1,N2
   J1 = NCOL(N)
   IF(J1 - 1) 20,10
---NO TREATMENT
10 WRITE (6,940) YEAR(N)
40 FORMAT(1XI5,15X11F10.2)
   GO TO 10C
---GET THE DIFFERENCES
20 IF(NVAR.EO.13.OR.NVAR.EQ.15) GO TO 40
   DO 30 J = 2,J1
30 OUT(N,J) = OUT(N,J) - OUT(N,1)
   WRITE (6,940) YEAR(N),(OUT(N,J),J=2,J1)
   GO TO 100
---OATES
40 I1 = OUT(N,1)
   DO 90 J = 2,J1
   I2 = OUT(N,J)
   IOUT(J) = I2 - I1
---CHECK FOR OOD OAYS BETWEEN THEN
   IF(IOUT(J)) 50,90,70
---I1 IS LARGER
50 DO 60 K = 1,6
   IF(I2.LE.OOO(K).ANO.OOO(K).LE.I1) IOUT(J) = IOUT(J) + 1
60 CONTINUE
   GO TO 90
---I2 IS LARGER
70 DO 80 K = 1,6
   IF(I1.LE.OOO(K).AND.OOO(K).LE.I2) IOUT(J) = IOUT(J) - 1
80 CONTINUE
90 OUT(N,J) = IOUT(J)
   WRITE (6,950) YEAR(N),(IOUT(J),J=2,J1)
50 FORMAT(1XI5,15X11I10)
00 CONTINUE
10 CONTINUE
---PLOT THE OIFFERENCES
   WRITE (6,910) PLUNIT,OATIME,NANE(1,NVAR),NAME(2,NVAR)
   IF(NVAR.EO.13.OR.NVAR.EO.15) GO TO 120
   WRITE (6,960)
60 FORMAT(*0*35X*OECREASE*52X*INCREASE*)
   CALL PLOTD (10.0)
   RETURN
20 WRITE (6,970)
70 FORMAT(*G*36X*EARLIER*52X*LATER*)
   CALL PLOTD (1.0)
   RETURN
   END
```

broutine PLOTD

```
   SUBROUTINE PLOTO (SCALE)
---PLOT THE OIFFERENCES
   COMMON DATIME(2),OECMAL,NRNANG,NSAVEO,NYEARS,PLNOPT(19),PLUNIT(6),
  I RECOVR,REGION(B),REGOPT(5),SAVE,SEORN2,WEIGHT
   INTEGER DATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEORN2
   COMMON/P/NAME(2,15),NCOL(165),NPLAN,NUN(12),NVAR,OUT(165,I2),
  1 VAR(15),YEAR(165)
   INTEGER YEAR
   INTEGER CODE(11),POINT(121)
   OATA CODE/1H1,1H2,1H3,1H4,1H5,1H6,1H7,1HB,1H9,1HA,1HB/
   WRITE (6,910)
10 FORMAT(* YEAR *,6(10H-.........),1H0,6(10H.........+))
   DO 50 I = 1,NYEARS
   DO 10 J = 1,121
10 POINT(J) = 1H
   POINT(61) = 1H.
   J1 = NCOL(I)
   IF(J1 - 1) 20,40
---SCALE AND TRANSLATE THE OIFFERENCES, THEN STORE THE CODE
20 DO 30 J = 2,J1
   K = (OUT(I,J)*SCALE) + 61.5
   IF(K.GE.1.AND.K.LE.121) POINT(K) = CODE(J-1)
30 CONTINUE
---WRITE THE LINE
40 WRITE (6,920) YEAR(1),POINT
20 FORMAT(1X15,121A1)
50 CONTINUE
   END
```

Program COMRGN

```
      OVERLAY IOLAYS,5,0)
      PROGRAM GOMRGN
C-----CONBINE THE PLANNING UNITS INTO A REGION
      CONNON OATINE(2),OECMAL,NRNANG,NSAVEO,NYEARS,PLNOPT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEORN2,WEIGHT
      INTEGER OATIME,PLNOPT,PLUNIT,RECCVR,REGICN,REGOPT,SAVE,SEORN2
      OINENSION OUT(165,10),WT(5)
      INTEGER YEAR(165)
      OINENSION NAME(2,5)
      OATA NAME(1,1),NANE(2,1)/10H    GENERA,10HTEO RUNOFF/
      OATA NAME(1,2),NAHE(2,2)/10H       PRE,10HCIPITATION/
      OATA NANE(1,3),NAME(2,3)/10H  EVAPOTRA,10HNSPIRATION/
      OATA NAME(1,4),NANE(2,4)/10HCHANGE IN ,10HRECH. REQ./
      OATA NANE(1,5),NAME(2,5)/10H CHANGE IN,10H PACK W.E./
      CALL CORE (-1)
      REWINO 13
      OO 5 I = 1,NYEARS
    5 REAO (13,910) YEAR(I)
      REWINO 13
      OO 10 I = 1,5
   10 WT(I) = 0.0
      OO 20 J = 1,10
      OO 20 I = 1,165
   20 OUT(I,J) = 0.0
C-----REAO THE FIRST RECORO OF A VARIABLE FOR A PLANNING UNIT
   30 READ (13,910) IYEAR,UNALT,ALT,WEIGHT,NVAR
  910 FORMAT(I3,3X3F10.5,I1)
      IF(EOF(13)) 60,40
C-----ACCUNULATE THE WEIGHT
   40 WT(NVAR) = WT(NVAR) + WEIGHT
      IF(IYEAR.NE.YEAR(1)) GO TO I50
C-----ACCUMULATE THE WEIGHTEO VALUES
      NVAR5 = NVAR + 5
      OUT(1,NVAR) = OUT(1,NVAR) + (UNALT * WEIGHT)
      OUT(1,NVAR5) = OUT(1,NVAR5) + (ALT * WEIGHT)
      OO 50 I = 2,NYEARS
      REAO (13,910) IYEAR,UNALT,ALT
      IF(IYEAR.NE.YEAR(I)) GO TO 150
      OUT(I,NVAR) = OUT(I,NVAR) + (UNALT * WEIGHT)
      OUT(I,NVAR5) = OUT(I,NVAR5) + (ALT * WEIGHT)
   50 CONTINUE
      GO TO 30
C-----PRINT EACH VARIABLE AS NEEOEO
   60 OO 140 NVAR = 1,5
      IF(REGOPT(NVAR).EQ.0) GO TO 140
      IF(WT(NVAR)) 70,140
   70 WRITE (6,920) REGION,OATIME,NAME(1,NVAR),NAME(2,NVAR)
  920 FORMAT(*1*8A10,32X2A10/* REGIONAL SUMMARY*96X2A10)
      NVAR5 = NVAR + 5
      IF(WT(NVAR).GE.0.99.ANO.WT(NVAR).LE.1.01) GO TO 78
      WRITE (6,930) WT(NVAR)
  930 FORNAT(*0- - - - N O T E - - - - THE CONBINEO WEIGHTS OF THE PLANN
     1ING UNITS IS*F5.2,* AS OPPOSEO TO THE NORMAL 1.0 - - - - N O T E -
     2 - - -*/25X*THEREFORE, ALL VALUES BELOW ARE AOJUSTEO RESULTS, MAOE
     3 TO CORRESPONO TO THE NORM*)
      OO 74 I = 1,NYEARS
      OUT(I,NVAR) = OUT(I,NVAR)/WT(NVAR)
   74 OUT(I,NVAR5) = OUT(I,NVAR5)/WT(NVAR)
   78 WRITE (6,940)
  940 FORMAT(*0*3(6X*YEAR   NATURAL   NANAGEO*10X)/)
      OO 130 I = 1,55
      IF(I - NYEARS) 80,80,140
   80 J = I + 55
      IF(J - NYEARS) 100,100,90
   90 WRITE (6,950) YEAR(I),OUT(I,NVAR),OUT(I,NVAR5)
  950 FORNAT(1X3(I10,2F10.2,10X))
      GO TO 130
  100 K = J + 55
      IF(K - NYEARS) 120,120,110
  110 WRITE (6,950) YEAR(I),OUT(I,NVAR),OUT(I,NVAR5),YEAR(J),
     1 OUT(J,NVAR),OUT(J,NVAR5)
      GO TO 130
  120 WRITE (6,950) YEAR(I),OUT(I,NVAR),OUT(I,NVAR5),YEAR(J),
     1 OUT(J,NVAR),OUT(J,NVAR5),YEAR(K),OUT(K,NVAR),OUT(K,NVAR5)
  130 CONTINUE
  140 CONTINUE
      GO TO 160
C-----THE YEARS ON THE VARIOUS UNITS OO NOT NATGH
  150 WRITE (6,960)
  960 FORNAT(*0THE YEARS PROCESSEO ON THE VARIOUS UNITS WERE NOT CONSIST
     1ENT, SO THE REGIONAL SUNNARY IS BEING ONITTEO*)
  160 GALL GORE (0)
G-----RETURN TO THE PRINARY OVERLAY
      ENO
```

Program LSTSAV

```
      OVERLAY (OLAYS,6,0)
      PROGRAM LSTSAV
C-----LIST THE FILES ON -SAVNEW-
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,PLNDPT(19),PLUNIT(6),
     1 RECOVR,REGION(B),REGOPT(5),SAVE,SEDRN2,WEIGHT
      INTEGER DATIME,PLNDPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
      DIMENSION PLOCK(1BB9),IO(9)
      CALL CORE (-1)
      END FILE 15
      REWIND 15
      WRITE (6,910) DATIME
  910 FORMAT(*1LISTING OF FILES ON -SAVNEW- AS OF *2A10/
     1 *0*6X*FILE     NUMBER      FIRST       LAST*/
     2 5X *NUMBER      YEARS       YEAR       YEAR*10X*PLANNING UNIT ID*)
      IFILE = C
C-----GET AN ID RECORD
   10 CALL GETREC (15,ID,9,IEND)
      IF(IEND) 50,20
C-----GET THE FIRST YEAR, THEN THE LAST
   20 IFILE = IFILE + 1
      CALL GETREC (15,BLOCK,1889,IEND)
      FIRST = BLOCK(1)
   30 DLAST = BLOCK(1)
```

```
      CALL GETREC (15,BLOCK,1889,(END)
      IF(IEND) 40,30
   40 WRITE (6,920) IFILE,ID(7),FIRST,OLAST,(ID(I),I=1,6)
  920 FORMAT(*0*2I10,2F10.2,10X6A10)
      GO TO 10
   50 CONTINUE
C-----RETURN TO THE PRIMARY OVERLAY
      END
```

Program PROOF

```
      OVERLAY (OLAYS,7,0)
      PROGRAM PROOF
C-----PROOFREAD THE PARAMETER DECK
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,PLNOPT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
      INTEGER DATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
      COMMON/S/AVSOIL(11),DECLIN(11),NROADS,RATNRM(11),ROADMI(11),
     1 ROADW(11),TANCUT(11),TANFIL(11),TANRHO(11),YRCNST(11)
      INTEGER YRCNST
      DIMENSION CARD(5),DATCRD(8),IDATES(6),PARAM(9)
      CALL CORE (-1)
C-----READ THE REGION CARDS
      READ (5,910) NAME,NYEARS,SEDRN2,SAVE,RECOVR,REGOPT,REGION
  910 FORMAT(A6,4X415,5I1/8A10)
      IF(NAME.EO.6HREGION) GO TO 10
      WRITE (6,920)
  920 FORMAT(*0THE FIRST INPUT CARD IS NOT THE REGION CARD*)
      CALL PRABRT
   10 IF(NYEARS.GT.0.AND.NYEARS.LE.165) GO TO 20
      WRITE (6,930) NYEARS
  930 FORMAT(*0THE NUMBER OF YEARS (*I3,*) IS NOT BETWEEN 1 AND 165*)
      CALL PRABRT
C-----READ A PLANNING UNIT CARD
   20 READ (5,940) PLUNIT,DECMAL,INFILE,WEIGHT,(PLNOPT(I),I=1,10),
     1 PLNOPT(16),PLNOPT(18)
  940 FORMAT(6A10,F2.2,1X12,F3.2,12(1)
      IF(EOF(5)) 120,30
C-----IF THIS IS A RECOVERY DECK, COPY IT TO THE REGION FILE
   30 IF(PLUNIT(1).NE.10HRECOVERY D) GO TO 50
   40 READ (5,950) CARD
  950 FORMAT(2A10,A6,F10.5,A1)
      IF(CARD(1).EO.1CHEND OF REC) GO TO 20
C-----IF A NEW WEIGHT WAS SPECIFIED, REPLACE THE ONE ON THE CARD
      IF(WEIGHT.GT.0.0) CARD(4) = WEIGHT
      WRITE (13,950) CARD
      GO TO 40
C-----IF THIS IS A DATA DECK, COPY IT TO THE UNEDITED DATA FILE
   50 IF(PLUNIT(1).NE.10HDATA DECK ) GO TO 58
   52 READ (5,955) DATCRD
  955 FORMAT(8A10)
      IF(DATCRD(1).EO.10HEND OF DAT) GO TO 54
      WRITE (10,955) DATCRD
      GO TO 52
   54 END FILE 10
      GO TO 20
C-----DEFINE THE REMAINING OPTIONS
   58 PLNOPT(11) = PLNOPT(10)
      PLNOPT(12) = PLNOPT(10)
      PLNOPT(13) = PLNOPT(10)
      PLNOPT(14) = PLNOPT(10)
      PLNOPT(15) = PLNOPT(10)
      PLNOPT(17) = PLNOPT(16)
      PLNOPT(19) = PLNOPT(18)
C-----WRITE THE RECORD
      WRITE (19) PLUNIT,DECMAL,INFILE,WEIGHT,PLNOPT
      LAST1 = 0
C-----IF THE INPUT UNIT IS 14, THE NORMAL SIMULATION WILL NOT BE
C----- PERFORMED.  BUT IF IT IS NOT 14, READ THE STATION PARAMETERS
      IF(INFILE - 14) 60,80
   60 CALL PARAMS
C-----READ THE SPECIFIED CONDITIONS CARDS
   70 READ (5,960) NAME,PEAKWE,IDATES
  960 FORMAT(A10,10XF5.2,6X3I2,1X3I2)
      WRITE (19) NAME,PEAKWE,IDATES
      IF(NAME.EQ.10HSPECIFIED ) GO TO 70
      IF(NAME.EO.10HEND OF NAT) GO TO 80
      WRITE (6,970) NAME,PLUNIT
  970 FORMAT(*0A SPECIFIED CONDITIONS CARD WAS EXPECTED UNDER PLANNING U
     1NIT *6A10/*  BUT COL 1-10 OF THE CARD READ CONTAIN *A10)
      CALL PRABRT
C-----READ THE MANAGEMENT STRATEGY DECK
   80 READ (5,980) NAMF,NUM,NEXTYR,PARAM,SPECCO
  980 FORMAT(A10,1CX2I5,10F5.0)
      WRITE (19) NAME,NUM,NEXTYR,PARAM,SPECCO
      IF(NAME.NE.10HMANAGEMENT.AND.NAME.NE.10HROAD CONST) GO TO 110
      IF(LAST1 - NEXTYR) 90,80,100
   90 LASTI = NEXTYR
      GO TO 80
  10G WRITE (6,985) PLUNIT
  985 FORMAT(*0ON PLANNING UNIT *6A10/*  THE MANAGEMENT PLAN CARDS ARE N
     1OT IN ORDER BY YEAR*)
      CALL PRABRT
  110 IF(NAME.EO.1CHEND OF STR) GO TO 20
      WRITE (6,990) NAME
  990 FORMAT(*0A MANAGEMENT PLAN OR ROAD CONSTRUCTION CARD WAS EXPECTED
     1UNDER PLANNING UNIT*/2X6A10/*  BUT COL 1-10 OF THE CARD READ CONTA
     2IN *A10)
      CALL PRABRT
C-----PROOFREADING COMPLETE
  120 END FILE 19
      REWIND 19
      NSAVED = C
C-----GET THE DATE AND TIME OF THIS RUN
      CALL DATE (DATIME(1))
      CALL TIMF (DATIME(2))
      CALL CORE (0)
C-----RETURN TO THE MAIN OVERLAY
      END
```

Subroutine GETFMT

```
      SUBROUTINE GETFMT
C-----GET THE FORMAT-INDICES CARD AND CHECK FOR ERRORS
      INTEGER VARFMT(7)
      IERR = 0
C-----READ THE CARD
      READ (5,910) NAME,VARFMT,NFILE,IM,ID,IY,IMX,IMN,IP
  910 FORMAT(A6,6A10,A4,1X12,1X6I1)
      IF(NAME.EO.6HFORMAT) GO TO 10
      WRITE (6,920) NAME
  920 FORMAT(*0THE VARIABLE FORMAT CARD WAS EXPECTED, BUT COL 1-6 OF THE
     1 CARD READ CONTAIN *A6)
      CALL PRABRT
C-----CERTIFY THE VALIDITY OF THE INDICES - START WITH THE MONTH
   1C NAME = 1CHMONTH    75
      IF(IM.GT.0.AND.IM.LT.7) GO TO 20
      WRITE (6,930) NAME,IM
  930 FORMAT(1XA10,I6,* FORMAT CARD, INVALID INDEX - MUST BE 1 TO 6 IN I
     1NDICATED COLUMN*)
      IERR = 1
C-----DAY
   20 NAME = 10HDAY      76
      IF(ID.GT.C.AND.ID.LT.7) GO TO 30
      WRITE (6,930) NAME,ID
      IERR = 1
      GO TO 50
   30 IF(ID.NE.IM) GO TO 50
      WRITE (6,950) NAME,ID
  950 FORMAT(1XA10,I6,* FORMAT CARD, THIS INDEX HAS BEEN USED PREVIOUSLY
     1*)
      IERR = 1
C-----YEAR
   50 NAME = 10HYEAR     77
      IF(IY.GT.C.AND.IY.LT.7) GO TO 60
      WRITE (6,930) NAME,IY
      IERR = 1
      GO TO 80
   60 IF(IY.NE.IM.AND.IY.NE.ID) GO TO 80
      WRITE (6,950) NAME,IY
      IERR = 1
C-----MAXIMUM TEMPERATURE
   80 NAME = 10HMAX TEM 78
      IF(IMX.GT.0.AND.IMX.LT.7) GO TO 90
      WRITE (6,930) NAME,IMX
      IERR = 1
      GO TO 110
   90 IF(IMX.NE.IM.AND.IMX.NE.ID.AND.IMX.NE.IY) GO TO 110
      WRITE (6,950) NAME,IMX
      IERR = 1
C-----MINIMUM TEMPERATURE
  110 NAME = 10HMIN TEM 79
      IF(IMN.GT.0.AND.IMN.LT.7) GO TO 120
      WRITE (6,930) NAME,IMN
      IERR = 1
      GO TO 140
  120 IF(IMN.NE.IM.AND.IMN.NE.ID.AND.IMN.NE.IY.AND.IMN.NE.IMX) GO TO 140
      WRITE (6,950) NAME,IMN
      IERR = 1
C-----PRECIP
  140 NAME = 10HPRECIP  80
      IF(IP.GT.0.AND.IP.LT.7) GO TO 150
      WRITE (6,930) NAME,IP
      IERR = 1
      GO TO 170
  150 IF(IP.NE.IM.AND.IP.NE.ID.AND.IP.NE.IY.AND.IP.NE.IMX.AND.IP.NE.IMN)
     1 GO TO 170
      WRITE (6,950) NAME,IP
      IERR = 1
C-----CHECK FOR ERRORS
  170 IF(IERR) 190,180
  180 WRITE (19) VARFMT,NFILE,IM,ID,IY,IMX,IMN,IP
      RETURN
  190 CALL PRABRT
      END
```

Subroutine GETPOT

```
      SUBROUTINE GETPOT (LAT,ASPECT,SLOPE)
C-----DEFINE THE POTENTIAL RADIATION VALUES AND THE SLOPE/ASPECT
C----- ADJUSTMENT FACTORS (THE TABLES ARE FROM -POTENTIAL SOLAR BEAM
C----- IRRADIATION ON SLOPES- RY FRANK AND LEE, 1966.  ONLY THOSE
C----- PORTIONS OF THE TABLES PERTAINING TO THE CENTRAL ROCKY MOUNTAINS
C----- (LATITUDE 38 - 44) ARE INCLUDED.  LIKEWISE, UNMANAGEABLE SLOPES
C----- (GREATER THAN 40 PERCENT) WERE ELIMINATED
      DIMENSION L(1924)
      DIMENSION POTENT(24),SLPASP(24)
      INTEGER ASPECT,SLOPE
C*****LATITUDE 38
C-----HORIZONTAL SURFACE
      DATA (L(I),I=1,13)/
     1 1020,1004,974,930,872,802,722,639,558,485,425,383,359/
C-----N ASPECT
      DATA (L(I),I=14,65)/
     1 1022,1000,962,907,837,754,662,569,480,402,340,297,273,
     2 1013, 987,942,877,794,700,597,495,401,319,257,214,190,
     3  996, 965,913,839,746,641,530,42G,322,240,178,138,115,
     4  971, 937,879,797,695,5R1,461,346,246,165,107, 71, 53/
C-----S ASPECT
      DATA (L(I),I=66,117)/
     1 1011, 999,977,944,898,842,775,703,630,563,507,467,443,
     2  994, 986,972,949,916,873,R19,758,695,634,5R2,545,522,
     3  971, 967,96C,947,925,R95,854,R05,751,697,650,614,593,
     4  942, 943,942,93R,927,909,8RC,843,798,751,708,675,655/
C-----NNE OR NNW ASPECT
      DATA (L(I),I=118,169)/
     1 1021,1000,963,909,839,757,667,575,487,409,347,304,280,
     2 1012, 987,943,879,799,7C7,608,508,415,335,272,229,2C5,
     3  994, 965,915,843,754,653,547,442,346,264,202,161,138,
     4  969, 937,881,802,705,598,496,377,281,200,141,102, R1/
C-----SSE OR SSW ASPECT
      DATA (L(I),I=170,221)/
```

```
 1 1017, 999,977,943,896,839,771,698,625,557,501,460,437,
 2  996, 988,973,949,914,868,812,749,684,622,570,532,509,
 3  976, 972,963,948,924,890,845,792,735,679,631,596,574,
 4  951, 950,947,941,927,903,869,826,778,728,684,651,631/
-----NE OR NW ASPECT
  DATA (L(I),I=222,273)/
 1 1020,1000,963,913,846,768,680,590,504,428,366,324,299,
 2 1011, 987,947,889,815,730,636,541,452,374,312,263,245,
 3  993, 967,923,860,781,690,592,494,403,324,263,222,198,
 4  963, 941,894,827,744,649,549,450,359,281,222,182,159/
-----SE OR SW ASPECT
  DATA (L(I),I=274,325)/
 1 1014,1000,976,940,891,830,760,684,609,540,483,442,418,
 2 1003, 993,974,945,905,854,792,724,655,590,535,496,473,
 3  988, 981,967,946,913,871,817,757,693,633,581,544,521,
 4  962, 965,956,941,916,882,836,783,725,660,621,585,563/
-----ENE OR WNW ASPECT
  DATA (L(I),I=326,377)/
 1 1019,1001,968,920,857,783,700,613,529,454,394,352,327,
 2 1011, 991,956,905,840,762,676,587,502,427,366,324,300,
 3  997, 976,940,887,819,740,652,563,478,402,342,301,277,
 4  978, 957,920,866,797,718,630,540,456,381,322,281,258/
-----ESE OR WSW ASPECT
  DATA (L(I),I=378,429)/
 1 1016,1001,975,935,882,817,743,664,586,515,457,415,391,
 2 1008, 995,972,937,888,820,760,685,611,542,485,445,421,
 3  997, 986,966,935,891,837,773,703,632,566,511,471,448,
 4  983, 973,956,929,891,842,782,717,649,586,532,494,471/
-----E OR W ASPECT
  DATA (L(I),I=430,481)/
 1 1018,1001,972,928,870,801,722,639,558,485,426,384,359,
 2 1011, 994,965,927,866,797,719,638,558,486,427,385,361,
 3 1002, 984,956,914,859,792,716,636,557,486,428,387,363,
 4  996, 970,944,903,850,785,711,633,556,486,429,389,366/
*****LATITUDE 40
-----HORIZONTAL SURFACE
  DATA (L(I),I=482,494)/
 1 1022,1004,971,923,860,786,702,615,531,456,395,353,328/
-----N ASPECT
  DATA (L(I),I=495,546)/
 1 1021, 998,957,898,823,735,640,543,452,373,310,267,243,
 2 1010, 982,934,865,778,679,573,468,372,290,227,185,162,
 3  991, 958,903,825,728,619,503,391,292,210,150,111, 90,
 4  964, 928,867,780,674,556,433,316,216,137, 82, 48, 32/
-----S ASPECT
  DATA (L(I),I=547,598)/
 1 1015,1001,977,940,890,829,757,681,605,536,478,437,413,
 2 1001, 992,975,948,911,863,804,739,672,608,555,515,492,
 3  980, 975,965,949,923,888,842,788,730,673,623,586,564,
 4  954, 953,950,942,927,904,871,828,779,729,683,648,627/
-----NNE OR NNW ASPECT
  DATA (L(I),I=599,650)/
 1 1021, 998,958,899,825,739,645,549,459,380,317,274,250,
 2 1010, 982,935,868,783,687,584,481,386,305,242,200,176,
 3  990, 959,905,829,736,631,521,414,317,235,174,134,112,
 4  963, 928,869,786,685,574,459,349,252,173,114, 78, 59/
-----SSE OR SSW ASPECT
  DATA (L(I),I=651,702)/
 1 1016,1002,977,939,888,826,753,676,600,529,472,431,407,
 1 1003, 993,975,947,908,858,797,729,661,596,542,503,479,
 3  985, 979,968,949,921,882,832,775,714,655,604,567,545,
 4  961, 959,954,944,926,898,859,811,758,705,659,624,602/
-----NE OR NW ASPECT
  DATA (L(I),I=703,754)/
 1 1020, 998,960,904,833,750,659,565,477,399,337,294,269,
 2 1009, 984,941,879,801,711,613,515,424,345,283,240,216,
 3  989, 962,915,848,764,669,568,468,375,296,235,194,171,
 4  964, 935,884,814,726,628,525,423,332,254,195,156,135/
-----SE OR SW ASPECT
  DATA (L(I),I=755,806)/
 1 1017,1002,976,935,882,817,742,662,584,512,454,412,388,
 2 1008, 997,976,943,898,842,775,703,631,563,507,467,443,
 3  995, 987,971,945,909,861,803,738,671,608,554,515,492,
 4  978, 972,961,943,914,875,824,766,705,645,595,557,535/
-----ENE OR WNW ASPECT
  DATA (L(I),I=807,858)/
 1 1020,1000,964,912,845,766,679,589,502,426,364,322,297,
 2 1011, 989,951,897,827,745,655,563,475,398,337,295,271,
 3  996, 973,934,878,806,723,631,538,451,375,314,273,249,
 4  977, 954,914,857,784,700,609,516,430,354,295,255,231/
-----ESE OR WSW ASPECT
  DATA (L(I),I=859,910)/
 1 1019,1002,973,929,872,802,724,641,560,487,427,385,361,
 2 1012, 997,971,932,880,816,742,663,586,515,457,416,391,
 3 1002, 989,967,932,884,826,757,683,609,540,483,443,419,
 4  989, 978,958,928,885,832,768,698,627,561,506,466,442/
-----E OR W ASPECT
  DATA (L(I),I=911,962)/
 1 1020,1001,969,921,859,785,702,615,532,457,396,354,329,
 2 1013, 995,963,916,855,782,700,615,532,458,398,356,332,
 3 1002, 984,954,908,849,778,697,614,532,459,400,359,335,
 4  988, 972,942,898,841,772,694,612,532,460,402,361,338/
*****LATITUDE 42
-----HORIZONTAL SURFACE
  DATA (L(I),I=963,975)/
 1 1023,1003,967,915,849,769,681,591,504,427,366,323,298/
-----N ASPECT
  DATA (L(I),I=976,1027)/
 1 1020, 995,951,898,808,716,617,517,424,343,280,238,213,
 2 1007, 977,925,852,760,657,547,440,342,260,198,157,134,
 3  985, 951,992,810,708,595,476,362,262,181,122, 85, 65,
 4  957, 919,854,763,653,531,404,286,186,109, 57, 28, 14/
-----S ASPECT
  DATA (L(I),I=1028,1079)/
 1 1018,1003,976,935,980,815,739,659,580,508,449,407,383,
 2 1007, 996,976,946,904,851,788,719,649,582,526,486,462,
 3  989, 982,970,949,919,879,829,771,709,648,596,557,534,
 4  965, 962,957,945,926,898,860,813,760,705,657,620,597/
-----NNE OR NNW ASPECT
  DATA (L(I),I=1080,1131)/
 1 102 , 995,952,889,911,720,622,523,431,350,287,245,220,
 2 1017, 977,927,855,766,666,559,454,357,276,213,172,148,
 3  985, 952,895,815,717,608,495,385,288,206,146,107, 86,
 4  956, 927,957,770,664,549,432,320,224,145, 89, 55, 38/
-----SSE OR SSW ASPECT
  DATA (L(I),I=1132,1183)/
 1 1019,1003,975,934,878,811,735,654,574,502,442,401,376,
 2 1009, 997,977,945,901,846,781,709,637,570,513,473,449,
 3  993, 985,971,949,917,873,818,756,692,630,577,538,515,
 4  972, 968,961,947,925,892,848,795,738,682,633,596,573/
C-----NE OR NW ASPECT
  DATA (L(I),I=1184,1235)/
 1 1020, 996,955,895,819,732,636,540,449,369,307,264,240,
 2 1007, 980,934,869,785,691,590,489,396,316,254,212,188,
 3  986, 956,906,835,747,648,544,441,347,268,208,167,145,
 4  959, 927,874,800,708,607,500,397,305,227,170,132,111/
C-----SE OR SW ASPECT
  DATA (L(I),I=1236,1287)/
 1 1020,1003,974,930,872,802,722,639,558,484,424,382,358,
 2 1013,1000,976,939,890,829,758,682,606,536,478,437,413,
 3 1002, 992,973,944,903,851,788,719,648,582,526,486,462,
 4  986, 979,966,944,910,867,811,749,684,621,568,529,505/
C-----ENE OR WNW ASPECT
  DATA (L(I),I=1288,1339)/
 1 1020, 998,960,904,832,749,657,563,475,397,335,292,268,
 2 1017, 987,946,887,813,727,633,538,448,370,308,266,242,
 3  994, 970,929,868,792,704,609,514,425,347,286,245,221,
 4  975, 950,908,847,770,682,587,492,404,328,268,228,205/
C-----ESE OR WSW ASPECT
  DATA (L(I),I=1340,1391)/
 1 1021,1003,970,923,861,787,704,617,534,458,398,355,331,
 2 1015, 999,970,927,870,802,723,641,561,487,428,386,362,
 3 1006, 992,967,928,876,813,740,662,584,513,455,414,389,
 4  995, 982,960,926,879,821,752,678,604,535,478,437,413/
C-----E OR W ASPECT
  DATA (L(I),I=1392,1443)/
 1 1021,1001,965,914,847,768,681,591,505,428,367,324,299,
 2 1014, 994,960,909,843,766,680,591,506,430,369,327,302,
 3 1003, 984,951,902,838,762,678,591,507,432,372,330,306,
 4  990, 972,940,892,831,758,675,590,508,434,375,334,310/
C*****LATITUDE 44
C-----HORIZONTAL SURFACE
  DATA (L(I),I=1444,1456)/
 1 1024,1001,963,907,835,751,659,565,476,398,336,293,268/
C-----N ASPECT
  DATA (L(I),I=1457,1508)/
 1 1018, 991,944,877,792,696,593,490,395,314,251,208,184,
 2 1003, 971,916,838,742,635,521,411,313,230,169,129,107,
 3  980, 943,881,794,688,571,448,332,232,152, 96, 61, 43,
 4  949, 909,841,746,631,505,375,256,157, 83, 35, 11,  2/
C-----S ASPECT
  DATA (L(I),I=1509,1560)/
 1 1021,1004,974,929,870,800,719,636,554,480,419,377,352,
 2 1012, 999,977,943,897,839,771,698,624,555,497,456,431,
 3  996, 988,973,949,914,870,815,752,686,622,568,527,503,
 4  975, 971,963,948,924,892,849,797,739,681,630,591,567/
C-----NNE OR NNW ASPECT
  DATA (L(I),I=1561,1612)/
 1 1018, 991,945,878,795,700,598,496,402,321,258,215,191,
 2 1003, 972,918,842,749,644,533,425,328,246,184,144,121,
 3  980, 944,884,800,697,584,468,357,258,178,119, 82, 63,
 4  949, 910,945,753,643,524,404,292,195,119, 66, 35, 20/
C-----SSE OR SSW ASPECT
  DATA (L(I),I=1613,1664)/
 1 1021,1004,973,928,868,796,715,630,548,473,413,371,346,
 2 1013,1000,977,942,893,834,763,688,612,542,485,443,418,
 3  999, 991,974,948,911,863,804,737,669,604,549,509,484,
 4  981, 976,966,949,922,885,836,778,717,657,606,567,543/
C-----NE OR NW ASPECT
  DATA (L(I),I=1665,1716)/
 1 1018, 993,948,885,804,712,613,513,420,340,277,235,211,
 2 1004, 975,926,856,769,670,565,462,367,287,225,184,160,
 3  982, 950,897,822,730,627,519,414,319,240,180,141,119,
 4  953, 920,864,785,690,585,475,371,278,201,145,108, 88/
C-----SE OR SW ASPECT
  DATA (L(I),I=1717,1768)/
 1 1022,1004,971,923,861,786,702,615,531,456,395,352,327,
 2 1017,1002,975,935,881,816,740,660,581,509,449,407,382,
 3 1007, 996,974,942,896,840,772,699,625,555,498,457,432,
 4  994, 985,969,944,906,857,798,731,661,596,540,500,476/
C-----ENE OR WNW ASPECT
  DATA (L(I),I=1769,1820)/
 1 1020, 996,954,894,818,730,634,538,447,368,305,262,238,
 2 1009, 983,940,877,798,708,610,512,420,341,279,237,213,
 3  993, 966,922,857,777,685,587,488,398,319,258,217,194,
 4  973, 946,901,836,755,664,565,468,378,301,242,202,180/
C-----ESE OR WSW ASPECT
  DATA (L(I),I=1821,1872)/
 1 1022,1002,967,915,849,770,683,593,507,430,368,325,301,
 2 1018,1000,968,921,860,787,704,618,535,459,399,356,331,
 3 1010, 994,966,924,868,800,722,640,560,486,426,384,359,
 4 1001, 986,961,923,872,809,736,658,581,509,451,409,384/
C-----E OR W ASPECT
  DATA (L(I),I=1873,1924)/
 1 1021, 999,961,905,834,751,659,566,477,399,337,294,270,
 2 1014, 993,955,901,831,749,659,566,479,401,340,297,273,
 3 1004, 984,947,894,826,746,658,567,481,404,344,301,277,
 4  992, 972,937,886,820,742,656,568,483,408,348,306,282/
C-----IF ALL ARE BLANK, READ THE INFORMATION FROM CARDS
  IF(LAT.EQ.0.AND.ASPECT.EQ.3H   .AND.SLOPE.EQ.0) GO TO 330
C-----FIND THE LATITUDE IN THE TABLE
  IF(LAT - 38) 10,20,30
10 WRITE (6,910) LAT
910 FORMAT(*0LATITUDE*I3,* NOT FOUND IN RADIATION TABLE (SUBROUTINE GE
 1TRDT)*)
  CALL PRABET
C-----LATITUDE 38 (L(1) - L(481))
20 L1 = 1
  GO TO 90
30 IF(LAT - 40) 10,40,50
C-----LATITUDE 40 (L(482) - L(962))
40 L1 = 482
  GO TO 90
50 IF(LAT - 42) 10,60,70
C-----LATITUDE 42 (L(963) - L(1443))
60 L1 = 963
  GO TO 90
70 IF(LAT - 44) 10,80,10
C-----LATITUDE 44 (L(1444) - L(1924))
80 L1 = 1444
C-----FIND THE ASPECT
90 IF(ASPECT.NE.3HN  ) GO TO 100
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      L2 = L1 + 13
      GO TO 210
  100 IF(ASPECT.NE.3HS   ) GO TO 110
      L2 = L1 + 65
      GO TO 210
  110 IF(ASPECT.NE.3HNNE.AND.ASPECT.NE.3HNNW) GO TO 120
      L2 = L1 + 117
      GO TO 210
  120 IF(ASPECT.NE.3HSSE.AND.ASPECT.NE.3HSSW) GO TO 130
      L2 = L1 + 169
      GO TO 210
  130 IF(ASPECT.NE.3HNE .AND.ASPECT.NE.3HNW ) GO TO 140
      L2 = L1 + 221
      GO TO 210
  140 IF(ASPECT.NE.3HSE .AND.ASPECT.NE.3HSW ) GO TO 150
      L2 = L1 + 273
      GO TO 210
  150 IF(ASPECT.NE.3HENE.AND.ASPECT.NE.3HWNW) GO TO 160
      L2 = L1 + 325
      GO TO 210
  160 IF(ASPECT.NE.3HESE.AND.ASPECT.NE.3HWSW) GO TO 170
      L2 = L1 + 377
      GO TO 210
  170 IF(ASPECT.NE.3HE  .AND.ASPECT.NE.3HW  ) GO TO 180
      L2 = L1 + 429
      GO TO 210
  180 IF(ASPECT.EQ.3H   ) GO TO 190
      WRITE (6,920) ASPECT
  920 FORMAT(*0ASPECT *A3,* IS INVALID*)
      CALL PRABRT
C-----NO ASPECT IMPLIES A HORIZONTAL SURFACE
  190 IF(SLOPE.EQ.0) GO TO 200
      WRITE (6,930) SLOPE
  930 FORMAT(* WITH A SLOPE OF*I3,*, AN ASPECT MUST BE SUPPLIED, BUT NON
     1E WAS FOUND*)
      CALL PRABRT
  200 L2 = L1
      GO TO 310
C-----FIND THE SLOPE WITHIN THE TABLE
  210 IF(SLOPE) 230,220
  220 WRITE (6,940) ASPECT
  940 FORMAT(*0WITH AN ASPECT OF *A3,*, A ZERO SLOPE IS INVALID*)
      CALL PRABRT
  230 IF(SLOPE - 10) 240,310,250
  240 WRITE (6,950) SLOPE
  950 FORMAT(*0SLOPE*I3,* IS INVALID*)
      CALL PRABRT
  250 IF(SLOPE - 20) 240,260,270
  260 L2 = L2 + 13
      GO TO 310
  270 IF(SLOPE - 30) 240,280,290
  280 L2 = L2 + 26
      GO TO 310
  290 IF(SLOPE - 40) 240,300,240
  300 L2 = L2 + 39
C-----STORE THE VALUES AT THE HORIZONTAL SURFACE AND COMPUTE THE
C----- PERCENTAGE WHICH IS INCIDENT TO THE SLOPE
  310 L1 = L1 - 1
      L2 = L2 - 1
      DO 320 I = 1,13
      J = I + 11
      POTENT(J) = L(L1+I)
      SLPASP(J) = FLOAT(L(L2+I))/POTENT(J)
  320 CONTINUE
      GO TO 340
C-----READ THE CARDS RATHER THAN USING THE TABLE
  330 READ (5,960) NAME,(POTENT(I),I=12,24),NAME1,(SLPASP(I),I=12,24)
  960 FORMAT(A10,5X13F5.0/A10,5X13F5.2)
      IF(NAME.EQ.10HPOTENTIAL .AND.NAME1.EQ.10HSLOPE/ASPE) GO TO 340
      WRITE (6,970) NAME,NAME1
  970 FORMAT(*0SINCE THE LATITUDE, ASPECT AND SLOPE WERE NOT SPECIFIED,
     1THE -POTENTIAL RAD- AND -SLOPE/ASPECT- CARDS WERE EXPECTED.*/
     2 *0HOWEVER, COL 1-10 OF THE TWO CARDS CONTAIN -*A10,*- AND -*A10,
     3 *-.*)
      CALL PRABRT
C-----FILL THE LOWER PORTION OF THE ARRAYS
  340 DO 350 I = 1,11
      POTENT(I) = POTENT(24-I)
      SLPASP(I) = SLPASP(24-I)
  350 CONTINUE
      WRITE (19) POTENT,SLPASP
      RETURN
      END
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Subroutine PARAMS

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      SUBROUTINE PARAMS
C-----READ THE PARAMETER DECK
      COMMON DATIME(2),DECMAL,NRMANG,NSAVED,NYEARS,PLNOPT(19),PLUNIT(6),
     1 RECOVR,REGION(8),REGOPT(5),SAVE,SEDRN2,WEIGHT
      INTEGER DATIME,PLNOPT,PLUNIT,RECOVR,REGION,REGOPT,SAVE,SEDRN2
      DIMENSION DECIDS(3),ETDALY(12),AIRTMC(4)
      INTEGER ASPECT,SLOPE,VEGTYP
C-----READ THE SUBSTATION CONSTANTS
      READ (5,920) NAME,TCOEFF,COVDEN,COMAX,VEGTYP,TRSHLD,TMPMLT,WILTPT
     1 DECIDS,LAT,ASPECT,SLOPE
  920 FORMAT(A10,10X3F5.2,4XI1,2F5.0,4F5.2,1XI2,1XA3,1XI2)
      IF(NAME.EQ.10HSUBSTATION) GO TO 20
      WRITE (6,921) PLUNIT
  921 FORMAT(*0THE SUBSTATION CONSTANTS CARD DOES NOT FOLLOW THE SUBSTA
     1ION ID CARD ENTITLED*/1X6A10)
      CALL PRABRT
C-----ENSURE THAT THE WILTING POINT IS NEGATIVE
   20 WILTPT = -ABS (WILTPT)
C-----CONVERT THE MELT THRESHOLD TO CENTIGRADE
      TMPMLT = (TMPMLT - 32.0) * 0.55555555555555
      IF(COMAX.GE.COVDEN.AND.COVDEN.GE.0.0) GO TO 30
      WRITE (6,922) PLUNIT,COVDEN,COMAX
  922 FORMAT(*0ON THE SUBSTATION ID CARD ENTITLED *6A10/* THE COVER DEN
     1ITY SPECIFIED IN COLUMNS 26-30 (*F5.2,*) IS EITHER NEGATIVE OR IT
     2IS GREATER THAN THE MAXIMUM COVER DENSITY*/*   IN COLUMNS 31-35 (
     3F5.2,*)*)
      CALL PRABRT
   30 IF(VEGTYP.EQ.1.OR.VEGTYP.EQ.2) GO TO 60
      IF(VEGTYP.EQ.3) GO TO 40
      IF(COVDEN.EQ.0.0.AND.VEGTYP.EQ.0) GO TO 60
      WRITE (6,923) VEGTYP,PLUNIT
  923 FORMAT(*0INVALID VEG TYPE (*I1,*) IN COLUMN 40 OF SUBSTATION ID C
     1RD ENTITLED *6A10/* VEGETATION TYPE = 1 (LODGEPOLE PINE), = 2 (SP
     2UCE FIR), = 3 (DECIDUOUS)*)
      CALL PRABRT
C-----DECIDUOUS FOREST - CHECK THE WINTER VALUES FOR COVER DENSITY AND
C----- TRANSMISSIVITY COEFFICIENT
   40 IF(DECIDS(3).GE.DECIDS(2).AND.DECIDS(2).GT.0.0) GO TO 60
      WRITE (6,924) PLUNIT,DECIDS(2),DECIDS(3)
  924 FORMAT(*0ON THE SUBSTATION ID CARD ENTITLED *6A10/* THE COVER DEN
     1ITY SPECIFIED IN COLUMNS 61-65 (*F5.2,*) IS EITHER NEGATIVE OR IT
     2IS GREATER THAN THE MAXIMUM COVER DENSITY*/*   IN COLUMNS 66-70 (
     1F5.2,*)*)
      CALL PRABRT
C-----READ THE INITIAL CONDITIONS CARD
   60 READ (5,930) NAME,SIMTM1,PREWED,RECHRG
  930 FORMAT(A10,10X3F5.2)
      IF(NAME.EQ.10HINITIAL CO) GO TO 70
      WRITE (6,931) PLUNIT
  931 FORMAT(*0THE INITIAL CONDITIONS CARD DOES NOT FOLLOW THE SUBSTAT
     1N CONSTANTS CARD IN THE CARDS FOLLOWING THE SUBSTATION ID CARD EN
     2TITLED*/1X6A10)
      CALL PRABRT
C-----READ THE DAILY ET VALUES
   70 READ (5,940) NAME,ETDALY
  940 FORMAT(A10,10X12F5.4)
      IF(NAME.EQ.10HDAILY ET  ) GO TO 80
      WRITE (6,941) PLUNIT
  941 FORMAT(*0THE DAILY ET VALUES CARD DOES NOT FOLLOW THE INITIAL CON
     1ITIONS CARD IN THE CARDS FOLLOWING THE SUBSTATION ID CARD ENTITL
     2*/1X6A10)
      CALL PRABRT
   80 READ (5,950) NAME,AIRTMC,SUMMER
  950 FORMAT(A10,10X5F5.3)
      IF(NAME.EQ.10HAIR TEMP C) GO TO 90
      WRITE (6,951) PLUNIT
  951 FORMAT(*0THE AIR TEMPERATURE COEFFICIENTS CARD DOES NOT FOLLOW T
     1 DAILY ET CARD IN THE CARDS FOLLOWING THE SUBSTATION ID CARD ENT
     2LED*/1X6A10)
      CALL PRABRT
   90 IF(SUMMER.LE.0.0) SUMMER = 1.0
      WRITE (19) TCOEFF,COVDEN,COMAX,VEGTYP,TRSHLD,TMPMLT,WILTPT,DECID
     1 LAT,ASPECT,SLOPE,SIMTM1,PREWED,RECHRG,ETDALY,AIRTMC,SUMMER
C-----GET THE POTENTIAL RADIATION AND THE ADJUSTMENT FACTORS
      CALL GETPOT (LAT,ASPECT,SLOPE)
C-----READ THE FORMAT-INDICES CARD
      CALL GETFMT
      RETURN
      END
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Subroutine PRABRT

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      SUBROUTINE PRABRT
C-----PRE-ABORT THE RUN
      WRITE (6,910)
  910 FORMAT(*0JOB PRE-ABORTED BY A PARAMETER DECK PROOFREADING ROUTIN
     1- NO SIMULATIONS WERE PERFORMED ON ANY OF THE PLANNING UNITS*)
      REWIND 13
      END FILE 13
      CALL ABORT
      END
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Leaf, Charles F., and Glen E. Brink.
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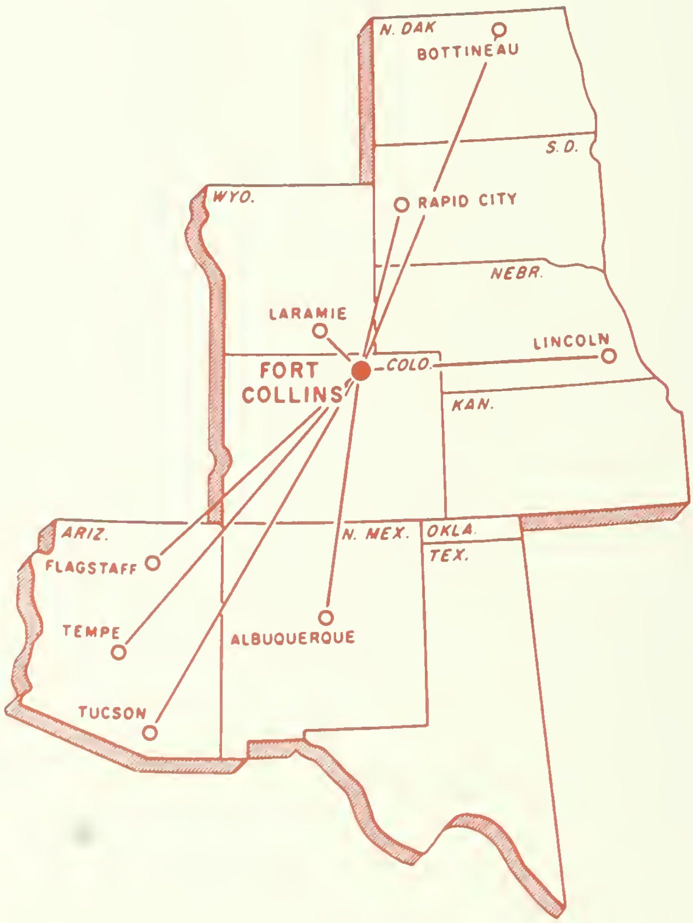
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Partial Cutting in Old-Growth Lodgepole Pine

by Robert R. Alexander

AUTHOR'S PREFACE

This publication supersedes USDA Forest Service Research Paper RM-92, "Partial cutting practices in old-growth lodgepole pine," in which I provided guidelines for initial cutting only. The revisions and improvements to the original are in response to requests by users for information on how stands should be handled after the initial harvest, and for practices needed to obtain natural regeneration after partial cutting. Other changes are the result of greater insight obtained by applying those original guidelines in field studies.

For convenient field use, the stand descriptions and cutting guides in this Research Paper were published separately in a smaller format as Research Paper RM-92A, "Partial cutting practices in old-growth lodgepole pine — Field guide to stand descriptions and cutting practices." Although it contains suggested practices for initial entry only, information in this original Field Guide is still appropriate, and can be used in conjunction with the newer guidelines published here. Copies of RM-92A are available from the Rocky Mountain Forest and Range Experiment Station, 240 West Prospect Street, Fort Collins, Colorado 80521.

Abstract

Guidelines are provided to aid the forest manager in developing partial cutting practices to maintain continuous forest cover in travel influence zones, and in areas of high recreational values or outstanding scenic beauty. These guidelines consider stand conditions, windfall risk situations, and insect and disease problems. These cutting practices may be also used in combination with small cleared openings to create the kinds of stands desirable for increased water yields, improvement of wildlife habitat, and to integrate timber production with other uses. On areas where timber production is the primary objective, clearcutting in small, dispersed units is the recommended method of harvesting trees.

About the cover:

New reproduction established after a light shelterwood cutting in lodgepole pine on the Fraser Experimental Forest, Colorado.

USDA Forest Service
Research Paper RM-136

March 1975

Partial Cutting in Old-Growth Lodgepole Pine

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

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Partial Cutting in Old-Growth Lodgepole Pine

Robert R. Alexander

From the silviculturist's point of view, clearcutting is a sound and practical way of bringing mature and overmature lodgepole pine (*Pinus contorta* Dougl.) forests under management, especially when timber production is a major objective. There are several reasons for clearcutting. Since these have been thoroughly discussed by Tackle (1961), they will only be highlighted here:

1. Lodgepole pine, a pioneer species, is shade intolerant and reproduces most satisfactorily when overstory competition is removed or drastically reduced.
2. Dwarf mistletoe (*Arceuthobium americanum* Nutt. ex Engelm.) — present in varying degrees in many mature to overmature stands — is best controlled by separating old and new stands.
3. Windfall, while variable, is always a threat to lodgepole pine forests.
4. The potential for future growth is limited because of the generally low vigor of mature and overmature stands, and the suppressed condition of many of the smaller trees.

Furthermore, many natural stands appear to be even-aged because they developed after fires, or other catastrophic disturbances.

Timber production, however, is only one of the key uses of lodgepole pine forests in the central Rocky Mountains. They occupy areas that also are important for water yield, wildlife habitat, recreation, and scenic beauty. Forest managers must consider how these areas are to be handled to meet the increasing demands of the public. The visual and environmental impacts of clearcutting for timber production are not always compatible with the objectives of other key uses. Described below are the kinds of stands that are desirable for increased water yields, improvement of wildlife habitat, preservation of the forest landscape, and maintenance of scenic values. Silvicultural practices are suggested that can be used alone or in combination with small cleared areas to maintain forest cover while gradually replacing the old stand with a healthy, vigorous new one.

FORM, STRUCTURE, AND ARRANGEMENT OF STANDS FOR KEY USES

Guidelines to aid the forest manager in developing alternatives to clearcutting in spruce-fir forests (Alexander 1973) contain similar descriptions of the kinds of stands desirable for uses other than timber production. They are repeated here for emphasis.

Water

Snowfall is the key to water yield in lodgepole pine forests. Comparisons of cut and uncut plots (8 acres in size), on the Fraser Experimental Forest in Colorado, have shown that more snow accumulated in cutover areas than under adjacent uncut stands. Accumulations were greatest on plots that were clearcut (Wilm and Dunford 1948, Hoover and Leaf 1967). The increased snow depth is not additional snow, however, but a redistribution of snow. Wind transports the snow intercepted on the surrounding trees and deposits it in the openings. Some of the increase in water equivalent in the openings is available, however, for streamflow (Hoover and Leaf 1967).

Research and experience suggest that a round or patch-shaped opening, about five to eight times tree height in diameter, is the most effective for trapping snow (Hoover 1969). In larger openings, wind is likely to dip down to the ground and blow the snow out of the openings. About one-third of the forest area in openings distributed over the watershed appears to be the best arrangement. These openings could either be maintained permanently or regenerated to new growth that would be periodically recut when trees reach about half the height of the surrounding trees. The remaining two-thirds of the area should be retained as continuous high forest, since the taller trees control snow deposition. Trees would be periodically harvested on an individual-tree basis or in small groups (one to two times tree height) to gradually replace the old with a new stand. Ultimately, the reserve stand would approach a broad-aged structure with the overstory canopy remaining at about the original height.

An alternative would be to make a light cut distributed over the entire watershed, removing about 20 to 30 percent of the basal area on an individual-tree basis or in small groups. The objective is to open up the stand enough to develop windfirmness, and salvage low-vigor and poor-risk trees. Openings five to eight times tree height can then be cut on about one-third of the area. The remaining two-thirds of the area would be retained as permanent high forests, with trees periodically removed on an individual-tree basis or in small groups.

Another alternative that would integrate water and timber production would be to harvest all of the old growth on a watershed with a series of cuts spread over a period of 120 to 160 years. At intervals of about 20 to 40 years, a portion of the area would be harvested in small openings — four to five times tree height — distributed over the watershed. The number of openings cut at each interval would depend on the size of the watershed and the length of rotation and cutting cycle selected. These openings would be regenerated so that at the end of one rotation, the watershed would contain groups of trees in several age classes from reproduction to those ready for harvest. The tallest trees may be somewhat shorter than the original overstory, but the adverse effects on snow deposition should be minimized by keeping the openings small. At the end of one rotation, the forest manager has the option of following the same procedure through the next rotation, or selecting about one-third of the openings to be maintained as snow-trapping areas and converting the remaining area into a broad-aged stand by periodically removing individual trees.

Wildlife

Timber cutting practices affect the use of lodgepole pine forests by Rocky Mountain mule deer (*Odocoileus hemionus hemionus* Rafinesque). On the Fraser Experimental Forest, deer use and abundance and selection of forage species were greater on clearcut openings than under adjacent uncut stands (Wallmo 1969, Wallmo et al. 1972). Openings three chains wide were used more than either wider or narrower openings. Forage production appears to decline about 10 years after cutting, however, as tree reproduction replaces forage species (Wallmo et al. 1972). Similar trends in forage production have also been observed on lodgepole pine clearcuts in Montana (Basile and Jensen 1971). Wallmo suggests that new openings be cut periodically.

One alternative would be to cut about one-sixth of a cutting block every 20 years in openings about four to five times tree height. Each Working Circle would be subdivided into a number of cutting blocks (of at least 300 acres) so that not all periodic cuts would be made in a single year on a Working Circle. Such periodic cutting would provide a good combination of numbers and species of palatable forage plants and the edge effect desired, while creating a several-aged forest of even-aged groups, thus integrating wildlife habitat improvement with timber production.

Natural reproduction established in cleared opening about 5 to 6 times tree height in lodgepole pine on the Fraser Experimental Forest.

Observations on the Medicine Bow National Forest in Wyoming indicate that both natural and cleared openings in lodgepole pine forests are heavily used by American elk [*Cervus canadensis canadensis* (Erxleben) Reynolds] for grazing and calving.[2] The size of opening does not appear to be critical, but openings interspersed with standing timber that can be used for ruminating, resting, and hiding are preferred. Since small openings cut in the canopy are not likely to retain a high proportion of palatable forage species for long periods of time, new openings should be cut when tree reproduction replaces forage species. Another alternative would be to extend the size of the smaller (2 acres or less) natural openings, and periodically harvest the remaining stand under some form of partial cutting.

Other wildlife, including nongame animals, living in lodgepole pine forests are affected by the way these forests are handled. In general, their habitat requirements include a combination of openings and high forests to provide food, cover, and edge. With protection from wildfires many stands have become denser, and reproduction has filled in the openings. Some reduction in stand density is needed to create or improve wildlife habitat. Small, irregular openings (about four to five times tree height) cut in the canopy at periodic intervals would open up the stand and provide the food, cover, and edge needed.

Recreation

Permanent forest cover — at least in part — is preferred in travel influence zones, and in areas of high recreational value and outstanding scenic beauty. Unfortunately, old-growth lodgepole pine stands are not likely to persist in a sound condition indefinitely. Where stand conditions and wind, insect, and disease problems permit, some form of partial cutting is one way that forest cover can be retained while at the same time replacing the old with a new stand. However, the visual impact of logging operations — haul roads, damage to residual trees, and slash and debris — must be minimized. In situations where there is no harvesting alternative to clearcutting, and the environmental impact of clearcutting is unacceptable, there is no choice but to leave the stands uncut.

To reduce the sudden and severe visual impact on the landscape viewer, openings cut in stands for timber and water production, wildlife habitat improvement, and recreation (ski runs) should be a repetition of natural shapes, visually tied together to create a balanced, unified pattern that will complement the natural landscape (Barnes 1971). This pattern is especially important for those openings in the middle and background that can be seen from distant views. The foreground should be maintained in high forests under some partial cutting system (again, where stand conditions and wind, insect, and disease problems permit).

[2] *Personal communication with A. Lorin Ward, Wildlife Biologist, Rocky Mountain Forest and Range Experiment Station, Laramie, Wyoming.*

CHARACTERISTICS OF THE TYPE

The lodgepole pine type is generally pictured as an even-aged, single-storied, overly dense forest, varying in age from place to place but uniform in age within any given stand. This characterization is valid only on those areas where favorable fire, seed, and climatic conditions once combined to produce a substantial number of seedlings (Lexen 1949). Elsewhere, lodgepole pine grows on a wide range of sites with a great diversity of stand conditions and characteristics. This diversity complicates the modification of silvicultural systems for multiple use. Lodgepole pine can occur as two-aged, single- or two-storied stands; three-aged, two- or three-storied stands; and even-aged to broad-aged, multi-storied stands (Tackle 1955). Multi-storied stands, and to a lesser extent two-and three-storied stands, generally resulted from either scattered trees that produced seed for subsequent development of the stand, or from the gradual deterioration of the old-growth associated with "normal" mortality from wind, insects, and diseases. Only rarely do multi-storied stands appear to have originated as uneven-aged stands.

Most ecologists consider the successional status of lodgepole pine to be seral if it is only a temporary occupant of the site. In those situations, stands of mixed overstory composition or with appreciable amounts of advanced reproduction of other species are not uncommon. Pine is ultimately replaced by Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir [*Abies lasiocarpa* (Hook.) Nutt.] at higher elevations, and Rocky Mountain Douglas-fir [*Pseudotsuga menziesii* var. *glauca* (Biessn.) Franco] at lower elevations. On the other hand, many lodgepole pine stands are the result of catastrophic fires, and some areas have burned so often and so extensively that they are nearly pure pine. In those situations, lodgepole pine is maintained on the area as a sub-climax because there is no seed for the normal climax species (Tackle 1961, 1964a).

In stands of pure pine of medium to high density, there is seldom any understory of reproduction, while in low-density stands there may be an understory of young trees. If this reproduction has been suppressed for a long time, it seldom responds to release. Mixed stands can be either 1) pure pine, 2) pine, spruce, and subalpine fir, or 3) pine and Douglas-fir in the overstory, and the climax species in the understory. Spruce and subalpine fir reproduction suppressed for long periods are able to respond to release and make acceptable growth.

HISTORY OF PARTIAL CUTTING

From the early 1900's to about 1945, timber harvests in the lodgepole pine type on the National Forests of the central Rocky Mountains could generally be described collectively as "partial cutting." The usual procedure was to mark stands for the "selective" removal of special products. Cutting was usually heavy because everything salable was often marked for removal. Nearly 40 years of observation, research, and experience with partial cutting provide some information on the capabilities and limitations of existing stands to maintain permanent high forest cover.

In generaly, heavy partial cutting (removal of more than 50 percent of the total basal area), and under some conditions any kind of partial cutting, was not successful in old-growth stands as a means of arresting stand deterioration. For example, residual trees on the Fraser Experimental Forest suffered heavy mortality when about 60 percent of the total basal area was removed by either individual tree selection or modified seed-tree cutting (Alexander 1966a). Similar results followed heavy partial cutting elsewhere in the central Rocky Mountains, and in the northern and Canadian Rockies (Blyth 1957, Hatch 1967, LeBarron 1952). Even where mortality was not a serious problem, heavy partial cutting often left the older, decadent stands in such poor condition that not only was there little or no growing stock available for another cut, but the stands had little appearance of permanent forest cover (Tackle 1964a).

The principal cause of mortality was usually windfall, and it generally increased as the intensity of cutting increased. Mountain pine beetle outbreaks caused heavy losses in some instances, and beetles continue to be a serious and often unpredictable threat to lodgepole pine forests. In addition, many stands were infected with dwarf mistletoe. Partially opening up the stand intensified the infection on residual trees, which in turn infected the new reproduction. These heavily infected stands are a serious lodgepole pine management problem.

Where substantial reserve volumes were left, partial cutting was successful in some instances in the sense that the residual stand did not blow down. On the Fraser Experimental Forest, windfall losses were light and other mortality negligible after partial cutting removed about 45 percent of the total basal area by a modified shelterwood cut, even though the stands were exposed to windstorms that nearly destroyed adjacent, partially cut stands with less residual basal area (Alexander 1966a). There are also numerous examples of early cuttings on many National Forests in Colorado and Wyoming where a light to moderate shelterwood cut that removed 30 to 40 percent of the total basal area did not result in excessive mortality. The openings created have regenerated to either lodgepole pine or the climax species. Where dwarf mistletoe infection in overstory trees was light, the new pine stand is not heavily infected. Similar stands have originated from open-grown trees, and from stands that were opened up by mountain pine beetle infestations.

SUSCEPTIBILITY TO WIND, DISEASE, AND INSECTS

Windfall

In the central Rocky Mountains, lodgepole pine is generally considered susceptible to windthrow, and the risk increases when the stand is opened up by partial cutting (Alexander 1966a, Mason 1915a). While the tendency to windthrow is frequently attributed to a shallow root system, the development of the root system varies with soil and stand conditions. On deep, well-drained soils, trees have a better root system than on shallow or poorly drained soils. With the same soil conditions, the denser the stand the less windfirm are individual stems, because trees that have developed together in dense stands over long periods of time mutually support each other, and do not have the roots, boles, and crowns to withstand exposure to the wind if opened up drastically. The risk of blowdown is also greater in stands with defective roots and boles. The presence of old windfalls is a good indication of lack of windfirmness. Furthermore, regardless of how stands are cut or the soil and stand conditions, the risk of blowdown is greater on some exposures than others. The following windfall risk situations based on exposure have been identified by Mason (1915b) and Alexander (1964, 1967).

Low Windfall Risk Situations:

1. Valley bottoms except where parallel to the prevailing winds, and all flat areas.
2. All lower and gentle middle north-and east-facing slopes.
3. All lower and gentle middle south-and west-facing slopes that are protected by considerably higher ground not far to windward.

Heavy windfall in lodgepole pine on the Fraser Experimental Forest after partial cutting that removed about 60 percent of the original basal area.

Moderate Windfall Risk Situations:

1. Valley bottoms parallel to the direction of prevailing winds.
2. All lower and gentle middle south- and west-facing slopes not protected to the windward.
3. Moderate to steep middle and all upper north- and east-facing slopes.
4. Moderate to steep middle south- and west-facing slopes protected by considerably higher ground not far to windward.

High Windfall Risk Situations:

1. Ridgetops.
2. Moderate to steep middle south- and west-facing slopes not protected to the windward, and all upper south- and west-facing slopes.
3. Saddles in ridgetops.

The risk of windfall in these situations is increased at least one category by such factors as poor drainage, shallow soils, and defective roots and boles. All situations become *high risk* if exposed to special topographic situations such as gaps and saddles in ridges at higher elevations to the windward that can funnel wind into the area.

Dwarf Mistletoe

Surveys in Colorado and Wyoming show that from 30 to 60 percent of the commercial lodgepole pine forests are infected to some degree by dwarf mistletoe (Hawksworth 1958). Dwarf mistletoe reduces growth and increases mortality (Hawksworth and Hinds 1964, Myers, et al. 1971). It also drastically reduces seed production in infected trees. The mortality rate depends largely on the age of the host tree when attacked. Young trees die quickly, while older trees with well-developed and vigorous crowns may not show appreciable effects for years after the intial infection. Dwarf mistletoe is most damaging in stands that have been partially opened up by cutting, mountain pine beetles, or windfall, and of least consequence on regenerated burns following catastrophic fires (Gill and Hawksworth 1964). Heavily infected old-growth stands frequently have only about half the board-foot volume of comparable uninfected stands (Hawksworth 1958).

The disease is difficult to detect in recently infected stands because trees show no abnormalities except for the inconspicuous shoots on branches and main stems. Where the parasite has been present for a long time, on the other hand, stands will have one or more heavily damaged centers characterized by many trees with witches' brooms, spike-tops, and an above-average number of snags with remnants of brooms (Gill and Hawksworth 1964).

Although optimum development is favored by a vigorous host, and the most vigorous trees in a stand suffer the most damage, the frequency of infection is usually higher on poor than good sites. Furthermore, where site index (Alexander 1966c) is 70 or greater, only the middle and lower crowns of dominants and codominants are susceptible to heavy infection, but trees in the intermediate or lower crown classes are susceptible to heavy infection throughout their crowns. Where the site index is below 70, all crown classes are susceptible to heavy infection throughout the crowns.[3] In Colorado and Wyoming, dwarf mistletoe has an altitudinal limit about 300 to 500 feet below the upper limit of commercial lodgepole pine forests. This means that in some high areas, considerable lodgepole pine lies in a dwarf mistletoe-free zone (Gill and Hawksworth 1964).

Separation of the old and new stands by clear-cutting and felling unmerchantable residual trees appears to be the best way to control dwarf mistletoe. In areas of high tree values such as recreational, administrative, and homesites, it may be possible to prune infected branches from lightly infected trees, but heavily infected trees must be cut. Partial cutting and thinning generally create ideal conditions for maximum damage and should be avoided where possible unless the infection is light. To quantify the severity of infection, Hawksworth (1961) developed the six-class mistletoe rating system. The average stand rating can be estimated by determining the percentage of trees infected in the stand. The approximate relationship of average stand rating to proportion of trees infected in several mature stands was:

Average stand mistletoe rating	Percent of trees infected
1	50
2	70
3	90
4	97
5	99
6	100

These ratings are used later in this paper under "Modifications of Cutting Practices Imposed by Disease and Insect Problems" to assist in determining which stands might be partially cut without severe damage to the residual trees.

Comandra Blister Rust

This canker disease (caused by *Cronartium comandrae* Pk.) commonly occurs in the central Rocky Mountains, but damage has been most extensive in northern Wyoming (Peterson 1962). Dead tops and flagging branches resulting from girdling are the most conspicuous symptoms (Mielke et al. 1968). The disease cannot pass directly from pine to pine but requires an intermediate host [*Comandra umbellata* (L.) Nutt.].

[3] *Personal communication with Frank G. Hawksworth, Plant Pathologist, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.*

The damage from Comandra rust is not often spectacular, but trees of all sizes and ages are susceptible (Peterson 1962). Seedlings may be killed in a relatively short time. In older trees, the time between initial infection and death may be 25 or more years because the infection enters the trunk by way of the branches, and the rate of spread is low. Under conditions favorable to the rust, stands may be heavily damaged over limited areas. In those stands, from 30 to 40% of the living and dead trees will have cankers, and about half the cankered trees will have spike-tops (Krebill 1965). Usually, however, the infection is lighter and scattered through the stand (Peterson 1962).

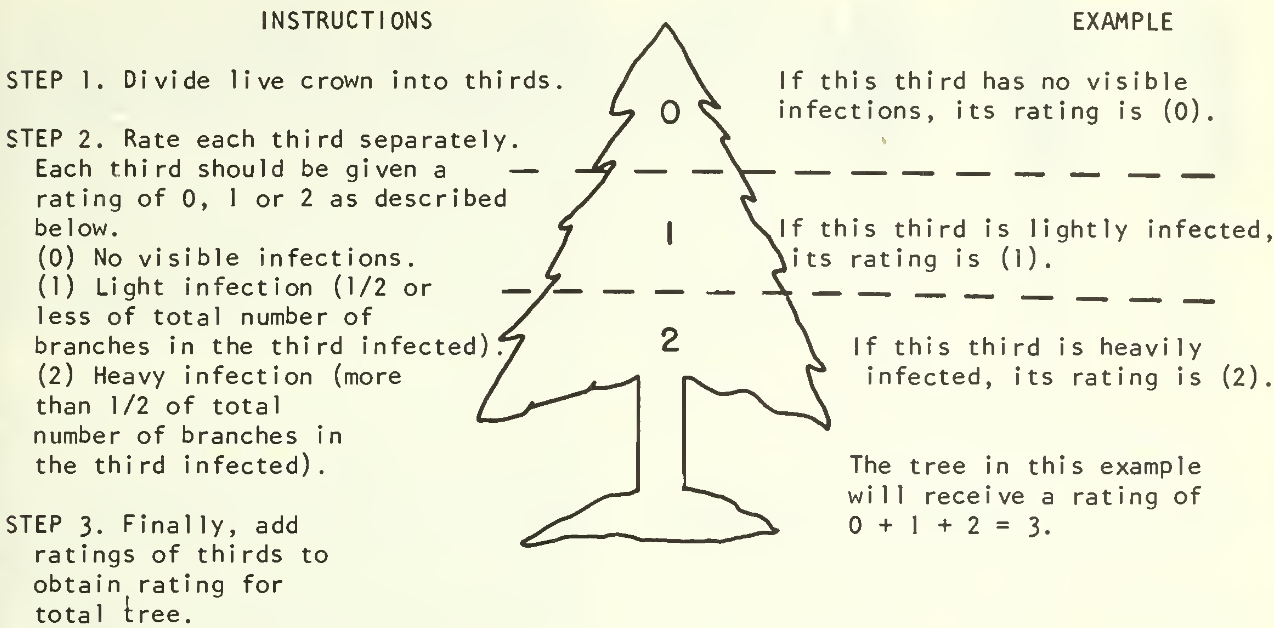
Sanitation salvage cutting is about the only practical way of controlling the disease in forest stands (Mielke et al. 1968). In areas of high tree values it may be possible to prune infected branches from lightly infected trees, but heavily infected trees should be cut. Partial cutting and thinning appear well adapted to the control or reduction of Comandra rust, even in heavily damaged stands, because the disease is not passed from pine to pine and only the trees with stem infections need to be removed.

Western gall rust (*Peridermium harknessii* Moore) occurs on lodgepole pine throughout the Rocky Mountains, but is not as distinctive as Comandra rust because most infections occur as galls on branches rather than on the trunk. Mortality in the seedling stage and loss of growth and cull are the principal forms of damage from this rust. Removal of infected trees in cultural operations is the only practical way to control gall rust damage in forests. Presence of a few galls is not sufficient cause to remove a tree. Only cankered trees need be cut (Peterson 1960).

Mountain Pine Beetle

Many species of insects infest lodgepole pine, but the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) is the most serious insect pest in mature to overmature stands in the Rocky Mountains. Epidemics have occurred throughout recorded history (Roe and Amman 1970), and extensive outbreaks are now in progress in northern Wyoming. Less extensive but severe outbreaks are underway in southern Wyoming and northern Colorado, where a large number of old-growth stands that have been protected from wildfires are now reaching a high degree of susceptibility to attack.

Mountain pine beetles feed and breed in the phloem layer. The first indications of attack are pitch tubes on the trunk where beetles have entered, and boring dust in the bark crevices and around the base of the tree. Trees successfully attacked in the summer usually begin to fade the following spring



The 6-class mistletoe rating system [Hawksworth 1961].

Needles change from green to yellow green, sorrel, and finally rusty brown before dropping off (McCambridge and Trostle 1972).

Not all stands are equally susceptible to attack. Epidemic outbreaks are usually associated with stands that contain at least some vigorous, thick-phloemed trees 14 inches in diameter and larger (Cole and Amman 1969, Roe and Amman 1970). As the larger trees are killed, the beetles must attack smaller diameter trees, and the outbreak subsides because the phloem of these trees is not thick enough to provide a food supply. Trees smaller than 6 inches d.b.h. are rarely killed.

Natural factors, such as a sudden lowering of fall temperature or prolonged subzero winter temperatures, nematodes, woodpeckers, and parasites, may reduce populations but they cannot be relied upon to control outbreaks (McCambridge and Trostle 1972). Chemical control is expensive and often is only a holding action until potentially susceptible trees can be disposed of by other means. The only alternatives left to the manager in heavily infested stands where most of the trees are 10 inches in diameter and larger are to (1) fell and salvage the infested trees, burn the green culls and unmerchantable portions of trees, and regenerate a new stand, or (2) let the infestation run its course uncontrolled. If infested stands have a good stocking of trees in the smaller diameter classes, on the other hand, partial cutting that removes the vigorous, larger trees with thick phloem appears well adapted to regulating mountain pine beetle losses.

A TREE CLASSIFICATION FOR MARKING IN PARTIALLY CUT STANDS

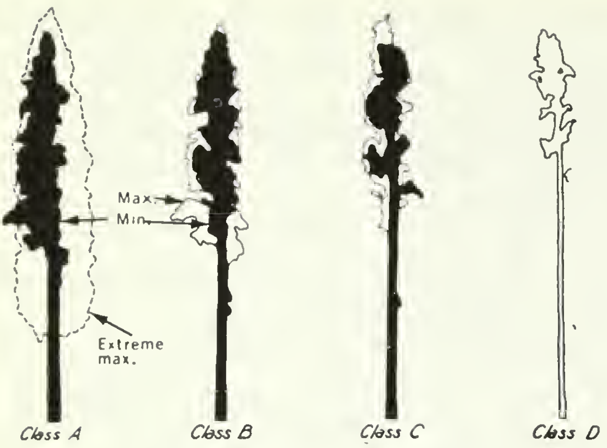
In developing partial cutting practices, knowledge of individual tree characteristics will assist in establishing marking guides. A classification scheme for lodgepole pine in Colorado and Wyoming based on the area, length, and vigor of individual tree crowns (Taylor 1939) is described below:

Vigor class A

1. Crown area: 30 percent or more of the "extreme outline" of vigor class A.
2. Crown length: 50 percent or more of the bole length.
3. Crown vigor: Dense, full, good color, pointed.

Vigor class B

2. Crown area: Usually more than 30 percent but less than 50 percent of the "extreme outline" of vigor class A.
2. Crown length: Usually more than 50 percent but usually less than 60 percent of the bole length.



Tree vigor classes [Taylor 1939].

3. Crown vigor: Moderately dense, good color, pointed or slightly rounded.

Vigor class C

1. Crown area: 15 to 30 percent of the "extreme outline" of vigor class A.
2. Crown length: 40 to 50 percent of the bole length except for trees with above average vigor, when 20 percent of the bole length is sufficient.
3. Crown vigor: Sparse, bunchy, poor color, never pointed.

Vigor class D

1. All live trees of poorer vigor than class C. Includes trees in classes A, B, and C outlines but with dead or dying tops.

Although the classification was developed more than 30 years ago, is subjective, and places many trees of old-growth stands in vigor classes C and D, it nevertheless provides useful guidelines in determining the kinds of trees that should be cut or left, depending on stand, insect and disease conditions, and management objectives.

PARTIAL CUTTING PRACTICES

Shelterwood and group selection cuttings and their modifications are applicable to old-growth lodgepole pine. These regeneration systems harvest the timber on an area in more than one step. From a silvicultural point of view these are the only acceptable options open to the manager where (1) multiple-use considerations preclude clearcutting, (2) combinations of cleared openings and high forest are required to meet the needs of various forest uses, or (3) areas are difficult to regenerate after clearcutting. However, windfall, insects, diseases, and stand conditions which vary from place to place on any area, impose limitations on how stands can be handled. Furthermore, economics of harvesting, manufacturing, and marketing wood products in the Rocky Mountains impose further limits on cutting practices. Cutting to bring old growth under management is likely to be a compromise between what is desirable and what is possible. Management, therefore, is likely to involve several cutting treatments on any one area.

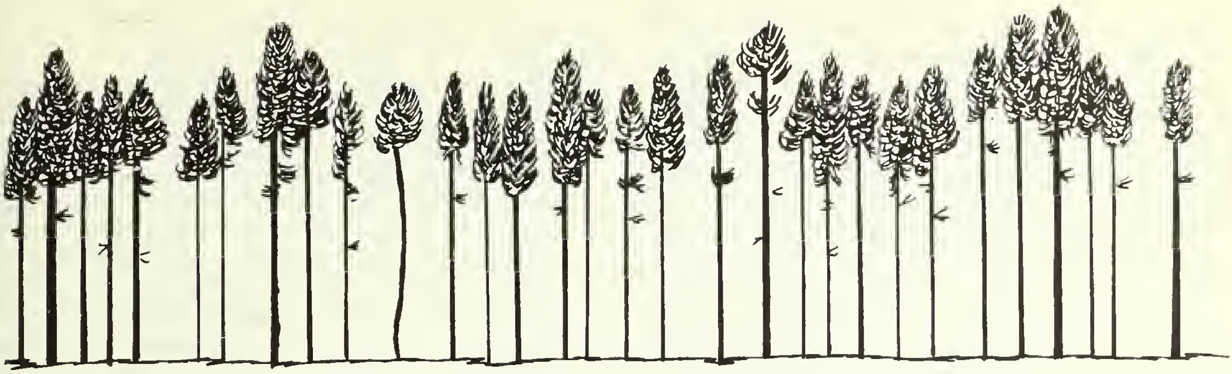
An *accurate appraisal* of the capabilities and limitations of each stand is necessary to determine cutting practices. Furthermore, partial cutting requires *careful marking* of individual trees or groups of trees to be removed, and *close supervision* of logging. The following recommended partial cutting practices are keyed to broad stand descriptions [developed largely by Tackle (1955) for the Intermountain Region and modified for central Rocky Mountain conditions] and windfall risk situations, with the objective of maintaining forest cover for various resource uses. Additional constraints imposed by insect and disease problems are considered near the end of this section. Stands are pure pine unless otherwise indicated.[4] Reproduction less than 4.5 feet tall is not considered a stand story in these descriptions.

Single-Storied Stands

Description

1. Stands may appear to be even-aged, but often contain more than one age class, occasionally may even be broad-aged.
2. Codominants form the general level of the canopy, but the difference in height between dominants, codominants, and intermediates is not as great as in spruce-fir stands.
3. If even-aged in appearance: (a) There is a small range in diameter classes and crown length. (b) Live crown length of dominants and codominants is generally short to medium (30 to 60 percent of the total tree height and boles are generally clear for 10 to 40 percent of total tree height). (c) There are few coarse-limbed trees in the stand.

[4] *In mixed stand, either less than 80 percent of the overstory basal area is lodgepole pine, or the overstory is pine with an understory of a different species.*



Single-storied stand.

4. With two or more age classes, the younger trees usually have finer branches, smaller diameters, longer live crown, and less clear bole than older trees.
5. Stocking is generally uniform.
6. A manageable stand of advanced reproduction is usually absent.[5]
7. In *mixed stands,* the overstory is either (a) pure pine or (b) pine and Engelmann spruce, subalpine fir, or Douglas-fir, with advanced reproduction of species other than pine that may or may not be a manageable stand.

Recommended Cutting Treatments

Single-storied stands are usually the least windfirm because trees have developed together over long periods of time and mutually protect each other from the wind.

Low windfall risk situations.

1. The first cut can remove about 30 percent of the basal area on an indivudal tree basis.[6] This initial entry is a *preparatory cut* that resembles the first step of a three-cut shelterwood, since it probably does not open up the stand enough for pine reproduction to become established in significant numbers. Because overstory trees are all about equally susceptible to blowdown, the general level of the canopy should be maintained by removing some trees in each overstory crown class. The cut should come from trees of C and D vigor classes, but openings larger than one tree height in diameter should be avoided by distributing the cut over the entire area. Furthermore, do not remove dominant trees that are protecting other trees to their leeward if these latter trees are to be reserved for the next cut. In *mixed stands,* if the overstory is pure pine, handle as a pure stand; if the overstory is of mixed composition, cut as much of the basal area recommended in pine as is possible to release the climax species.
2. The second entry into the stand should not be made until 5 to 10 years after the first cut to determine if the stand is windfirm. The second cut should also remove about 30 percent of the original basal area on an individual tree basis. It simulates the second or *seed cut* of a three-step shelterwood. The largest and most vigorous dominants and codominants should be reserved as a seed source in stands with the nonserotinous or intermediate cone habit,[7] but avoid cutting openings in the canopy larger than one tree height in diameter by distributing the cut over the entire area, even if it means leaving trees in the C and D vigor classes with poor seed production potential. In *mixed stands* cut as much of the recommended basal area in pine as is possible without creating openings larger than one tree height.
3. The last entry is the *final harvest* and should remove all of the remaining original overstory. It

[5] *Since any kind of cutting may destroy as much as half of the advanced reproduction, even with careful logging, at least 600 seedlings and saplings per acre of good form and vigor, and free of defect, must be present to be considered a manageable stand.*

[6] *As a practical matter, small trees that do not represent significant competition to the remainder of the stand may be excluded from the computation of the basal area.*

[7] *Lotan and Jensen (1970) classified lodgepole pine trees in the Northern Rockies and Intermountain Region as serotinous if they bore 90 percent or more closed cones, and non-serotinous if they bore 90 percent or more open cones. At least 40 percent of the trees should bear serotinous cones before a stand can be considered to have the closed-cone habit.*

should not be made until a manageable stand of reproduction has become established, but the cut should not be delayed beyond this point if timber production is the primary concern because the overwood (a) hampers the later growth of seedlings, and (b) if infected with dwarf mistletoe, will re-infect the new stand.

4. The manager also has the option of removing less than 30 percent of the basal area at any entry and making more entries, but they should not be made at more frequent intervals. The cut will be spread out and continuous high forest cover maintained for a longer period of time. *This delay is not recommended where mountain pine beetles and dwarf mistletoe impose limitations on how stands can be handled.*
5. The usual uniform arrangement of individual trees in single-storied stands is not well adapted to removing trees by *group selection cutting*. Occasionally, however, natural openings do occur when stands begin to break up. Furthermore, small openings may be desirable to meet management objectives. An alternative to removing trees on an individual basis would be to remove about 30 percent of the basal area in groups. Openings should be kept small, not more than one to two times tree height in diameter; not more than one-third of the area should be cut at any one time. *This kind of cutting should be used only in stands where insect and disease problems are minimal.*
6. The second entry into the stand should not be made until the first group of openings has been regenerated. This cut should also remove about 30 percent of the original basal area without cutting over more than an additional one-third of the area. Openings should be no closer than about one to two tree heights to the original openings.
7. The final entry should remove the remaining groups of merchantable trees. The timing of this cut depends upon the cone habit and how the manager elects to regenerate the openings. If he chooses to use natural regeneration and the stand is classified as nonserotinous or intermediate cone habit, the final harvest must be delayed until the trees in the original groups cut are large enough to provide a seed source.
8. The manager may choose to remove less than 30 percent of the basal area and cut less than one-third of the area at any one time. This will require more entries, but each new cut should not be made until the openings cut the previous entry have regenerated. Furthermore, in stands with nonserotinous or intermediate cone habit, the last groups cannot be cut until there is either an outside seed source or the manager elects to plant these openings.

Moderate windfall risk situations.

1. The first cut should be limited to a light *preparatory* cutting that removes about 20 percent of the basal area on an individual-tree basis. The objective is to open up the stand, but at the same time minimize the windfall risk to the remaining trees. Provision should be made, however, to salvage blowndowns. This type of cutting resembles a *sanitation cut* in that the lowest vigor and poorest risk trees should be removed, but it is important that the general level of the overstory canopy be maintained intact. *Mixed stands* should be handled the same as in low wind risk situations, except that less basal area will be removed.
2. The second entry can be made in about 10 years after the first cut. This entry should remove about 20 percent of the original basal area on an individual tree basis. Windfall that was salvaged after the first cut should be included in the computation of the basal area to be removed. The objective of this *preparatory cut* is to continue to develope windfirmness while preparing the stand for the seed cut. Most of the trees marked for removal should come from the smaller crown and poorer vigor classes, but maintain the general level of the canopy intact. In *mixed stands*, cut as much of the recommended basal area to be removed in pine as is possible.
3. It will require about another 10 years to determine if the stand is windfirm enough to make another entry. This will be the *seed cut* and should remove about 20 percent of the original basal area, including any windfalls since the last cutting. The largest and most vigorous dominants and codominants in *mixed stands*, and pure stands with nonserotinous or intermediate cone habit should be reserved as a seed source, but it is more important to distribute the cut over the entire area.
4. The last entry is the *final harvest*, and it should remove the remaining original overstory. It cannot be made until a manageable stand of reproduction has been established. About 40 percent of the original basal area will be removed in this cut, and if it is too heavy (10,00 bd. ft. or more per acre) to be removed in one harvest without undue damage to the reproduction, the manager must plan on a final harvest in two steps. The second step can begin as soon as skidding is finished in the first step, providing that a manageable stand of reproduction still exists.
5. The manager also has the option of removing less than 20 percent of the basal area at any entry and making more entries, but they should not be made at more frequent intervals.

Two-storied stand.

High wind risk situations.

1. The choice is limited to removing all trees or leaving the stand uncut. Cleared openings can be up to about 5 acres, interspersed with uncut areas. Cutover areas should not exceed about one-third of the total in this risk situation.

Two-Storied Stands

Description

1. Stands may appear to be two-aged, but can contain more than two age classes.
2. Top story — dominants, codominants, and intermediates — resembles a single-storied stand.
3. Second story is composed of younger trees of smaller diameter — small saw logs, poles, or saplings — than the top story, but it is always below and clearly distinguishable from the overstory. Trees in the second story are overtopped and may or may not be suppressed.
4. If more than two-aged, the overstory usually contains at least two age classes. The younger trees are finer limbed and may be smaller in diameter than the older trees. The second story may also contain more than one age class.
5. Stocking of the overstory may be irregular, but overall stocking is usually uniform.
6. A manageable stand of advanced reproduction is usually absent.
7. In *mixed stands*, the overstory is usually pure pine, but occasionally it may be pine with spruce or Douglas-fir. The second story is usually spruce and fir at the higher elevations, and Douglas-fir at the lower elevations.
8. Stocking in *mixed stands* may vary from uniform to irregular.
9. *Mixed stands* may have a manageable stand of advanced reproduction of species other than pine.

Recommended Cutting Treatments

Recommended cutting treatments are the same as for three-storied stands.

Three-Storied Stands

Description

1. Stands may appear to be three-aged, but they contain more than three age classes. Stands are seldom broad-aged, however.
2. Top story resembles a single-storied stand except that there are fewer trees.
3. The second and third stories consist of younger, smaller diameter trees. Second story may be small saw logs or large poles, while the third story is likely to be composed of small poles or saplings. Second and third stories are overtopped, and some trees may be suppressed.
4. Overall stocking is likely to be uniform, but stocking of any story may be irregular.
5. A manageable stand of advanced reproduction is usually absent.
6. In *mixed stands* the top story may be either pure pine or a mixture of pine and other species. The second story is usually spruce and subalpine fir at at the higher elevations, and Douglas-fir at the lower elevations. The second story may occasionally contain some pine, but it is rarely pure pine. The third story is almost always composed of species other than pine.
7. Stocking in *mixed stands* can vary from uniform to irregular.

Three-storied stand.

8. *Mixed stands* often have a manageable stand of advanced reproduction of species other than pine.

Recommended Cutting Treatments (Two- and Three-Storied Stands)

Trees in the top story are usually more windfirm than those in a single-storied stand. Trees in the second and third stories are usually less windfirm than trees in the top story.

Low windfall risk situations.

1. The first cut can remove up to 50 percent of the basal area in *two-storied* stands (providing not more than half of the basal area removed comes from the top story), and up to 40 percent of the basal area from *three-storied* stands. This cutting is as heavy as the first or *seed cut* of a two-cut shelterwood, but marking follows the rules for individual-tree selection. Heavier cutting may be possible in three-storied stands, but the appearance of a continous overstory is not likely to be retained. Trees removed should be in vigor classes C and D insofar as possible, but since the top story is likely to be more windfirm, selected dominants and codominants should be left even when they are in vigor classes C and D, if they do not have dead or dying tops. Avoid cutting holes in the canopy larger than one tree height in diameter by distributing the cut over the entire area. Furthermore, do not remove dominant trees that are protecting other trees to their leeward if these latter trees are to be reserved for the next cut. In *mixed stands,* if the top story or, as rarely happens, the first and second stories are pure pine, handle as a pure stand. If the top story is of mixed composition, cut as much of the basal area to be removed in pine as is possible to release the climax species, but do not cut all of the pine if it is needed to maintain the overstory.
2. The second entry should be the *final harvest* to remove the remaining original stand and release the reproduction. It cannot be made until the new stand of reproduction is established. If the residual volume is greater than about 10,000 bd. ft. per acre, the final harvest should be made in two steps to avoid undue damage to newly established reproduction. The second step can begin as soon as skidding is finished in the first step, providing that a manageable stand of reproduction still exists.
3. If there is a manageable stand of advanced reproduction, in *mixed stands,* the first cut can be an *overstory removal* if the volume is not too heavy. Otherwise, the first cut can remove 40 to 50 percent of the basal area on an individual tree basis as long as the more windfirm dominants and codominants are left. The timing of the second cut is not critical from a regeneration standpoint, providing a manageable stand of reproduction still exists after the first cut and can be saved.
4. The manager has other options to choose from. He may elect to cut less than the recommended basal area, make more entries, and spread the cut over a longer period of time by delaying the final harvest until the new stand is tall enough to create the appearance of a high forest. *This option is not recommended where mountain pine beetles and dwarf mistletoe impose limitations on how stands can be handled.*
5. In *pure* or *mixed* stands with irregular stocking that may have resulted from the breakup of single-storied stands, old beetle attacks, or windfall losses, an alternative first cut can remove about 40 percent of the basal area in a modified group selection. The group openings can be larger (two to three times tree height) than in single-

Multi-storied stand.

storied stands, but the area cutover should not exceed about one-third of the total. Openings should be irregular in shape without wind-catching indentations in the borders. *This kind of cutting is not applicable in pure stands where mountain pine beetle or dwarf mistletoe impose limitations,* because the interval between initial cutting and final harvest is likely to be too long to prevent serious mistletoe infection of new reproduction and/or loss of beetle-susceptible trees.

6. Two additional entries can be made in the stand. They should each remove about 30 percent of the original basal area in group openings up to two to three times tree height, but not more than one-third of the area should be cutover at any one time. If there is not a manageable stand of advanced reproduction, the manager must wait until the first group openings are regenerated before cutting the second series. Furthermore, in *mixed* stands, or *pure* stands with the nonserotinous or intermediate cone habit, he must either delay cutting the final groups until there is a seed source or plan on planting these openings. If there is a manageable stand of advanced reproduction, the timing between cuts is not critical from a regeneration standpoint.
7. In *mixed stands* with irregular stocking that contain a manageable stand of reproduction and the volume per acre is not too heavy, the first cut can be an *overwood removal.* If the volume is too heavy for a one-step removal, the manager should follow the recommendations for pure stands because the wind hazard is too great to permit a two-step removal in a stand that has not been previously opened up.

Moderate windfall risk situations.

1. The first entry should be a *preparatory cut* that removes not more than 30 percent of the basal area on an individual-tree basis. Predominants, and codominants and intermediates with long live crowns should be removed first. The remaining cut should then come from trees in vigor classes C and D. Maintain the general level of the canopy by not cutting holes larger than one tree height in diameter in the canopy. Provision should be made to salvage blowdowns. *Mixed stands* should be handled as in low wind risk situations, except that less basal area should be removed.
2. The second entry should not be made in less than 10 years. This cut should remove about 30 percent of the original basal area, including the salvage of any windfalls after the first cut. The second entry is the *seed cut.* The best dominants and codominants should be reserved as a seed source in stands with the nonserotinous or intermediate cone habit, but it is important that the cut be distributed over the entire area.
3. The next entry is the *final harvest* to remove the remaining merchantable volume and release the new reproduction after it has become established. However, if the residual stand has too heavy a volume, the final harvest should be made in two steps.
4. In *mixed stands* that contain a manageable stand of reproduction, and if the volume per acre is not too heavy, the first cut can be an *overwood removal.* If the volume is too heavy for a one-step removal, the manager should follow the recommendations for pure stands because the wind hazard is too great to permit a two-step removal in a stand that has not been previously opened up to develop windfirmness.

High wind risk situations.

1. The choice is limited to either removing all the trees or leaving the stand uncut. Cleared openings

can be up to about 5 acres, interspersed with uncut areas. The cutover area should not exceed about one-third of the total in this risk situation.

Multi-Storied Stands

Description

1. Stand is usually broad-aged with a wide range in diameters.
2. If stands developed from relatively few individuals following disturbance, the overstory trees are coarse-limbed. Fill-in trees are better formed and finer limbed. Vigor of the overstory trees varies from poor to good.
3. In stands that developed from deterioration of single- or two-storied stands, the overstory trees may be no limbier than the fill-in trees. Nearly all of the healthy, faster growing trees are below saw log size.
4. Stocking may be irregular.
5. A manageable stand of advanced reproduction may be present.
6. In *mixed stands,* the overstory may be pure pine or either pine, spruce, and fir at the higher elevations, or pine and Douglas-fir at lower elevations. Understory trees have the same characteristics as pure stands, except that they are likely to be of species other than pine.
7. Stocking in *mixed stands* is more likely to be irregular.
8. *Mixed stands* frequently have a manageable stand of advanced reproduction of species other than pine.

Recommended Cutting Practices

These are usually the most windfirm stands, even where they have developed from the deterioration of single- and two-storied stands. By the time they have reached their present condition, the remaining overstory trees are likely to be windfirm.

Low to moderate windfall risk situations.

1. There is considerable flexibility in harvesting these stands. All size classes can be cut, with emphasis on either the largest or smallest trees in the stand. The first cut can range from an *overwood removal* to release the younger growing stock to a *thinning from below* to improve the spacing of the most vigorous of the larger trees. Thereafter, cutting can be directed toward either even-aged or uneven-aged management. In *mixed stands* the first cut should be an overwood removal of the pine to release the climax species. The understory trees should be thinned to improve spacing.
2. Thinning should be to some specified growing stock level, which will vary with management objectives. Procedures for selecting growing stock levels are outlined by Myers et al. (1971).

High windfall risk situations.

1. The safest first cut is an overwood removal with a light thinning from below to obtain a wider spaced, more open stand that can develop windfirmness. Thereafter, cutting can be directed toward either uneven- or even-aged management.

Modifications of Partial Cutting Practices Imposed by Disease and Insect Problems

Dwarf Mistletoe

1. Cut only in stands where the average mistletoe rating is two or less (70 percent or less of the trees infected), and remove only the percentage of basal area recommended for the stand description and windfall situation. In *single-storied* stands, where site index is 70 or above, trees in the intermediate and lower crown classes should be removed first in preference to dominants and codominants. If site index is below 70, trees in all crown classes are about equally susceptible to infection. In *two-* and *three-storied* stands, as much of the first cut as is possible should come from the second and third stories because these trees are likely to be more heavily infected than the top story. In *single-, two-,* and *three-storied* stands, the final overstory removal can be delayed until the new reproduction is tall enough to provide a forest aspect. To minimize infection of new reproduction, however, the time interval should not exceed 30 years after the *regeneration cut* when the average mistletoe rating is one, or 20 years when the rating is two. Provision should be made to sanitize the young stand at the time of final harvest. In *multi-storied* stands, the safest procedure is an overwood removal with a cleaning and thinning from below.
2. In old-growth stands with an average mistletoe rating of greater than two, any partial cutting, thinning, or cleaning is likely to intensify the infection. The *safest* procedures, therefore, are to either remove all of the trees and start a new stand, or leave the stand uncut. If the manager chooses to make a partial cut for any reason, the

initial harvest should be heavy enough to be a regeneration cut. *All* residual trees must be removed within 10 years after the first cut, and provision made to sanitize the young stand at that time.

Comandra Blister Rust

Cut as many trees with stem cankers and spike-tops as possible in the first cut without removing more than the recommended basal area or cutting large openings in the canopy. Since the rate of spread in mature trees is relatively slow and the disease is not transmitted from pine to pine, leaving a few infected trees is less of a risk than opening up the stand too much.

Mountain Pine Beetle

1. If the insect is present in the stand at an endemic level, or in adjacent stands in sufficient numbers to make successful attacks, and
   a. less than the recommended percentage of basal area to be removed in the first cut is in susceptible trees: Any attacked tree and all of the most susceptible trees should be removed in the first cut. This will include most of the trees 12 inches d.b.h. and larger, and all trees 10 to 12 inches d.b.h. in vigor classes A and B. Provision should be made to salvage attacked trees, and the second cut should be made within 10 years of the first cut.
   b. more than the recommended percentage of basal area to be removed in the first cut is in susceptible trees, the manager has three options: 1) Remove all the trees. 2) Remove the recommended basal area in attacked and susceptible trees and accept the risk of future losses. 3) Leave the stand uncut. If the stand is partially cut or left uncut, some trees from 7 to 12 inches d.b.h. and most trees below 7 inches d.b.h. will survive.
2. If the stand is sustaining an infestation that is building up, and the manager chooses to either partially cut or leave the stand uncut, he must accept the risk of an outbreak that could destroy most of the merchantable stand.

Cutting to Save the Residual

In *mixed stands* and to a lesser extent pure stands, the manager must determine whether he has an acceptable stand of advanced reproduction and decide if he is going to manage it before any cutting begins. Furthermore, he must reevaluate the advanced reproduction after the final harvest and slash disposal to determine the need for supplemental stocking. The same criteria used to evaluate advanced reproduction on spruce-fir clearcuts applies here (Alexander 1973).

In partial cutting, protection of the residual from logging damage is of primary concern. The residual includes merchantable trees left after shelterwood cutting, and advanced reproduction in both shelterwood and group selection cutting where an acceptable stand is to be managed.

Protection begins with a well-designed logging plan at the time of the first cut. To minimize damage, skid roads must be layed out — about 200 feet apart depending on the topography — and marked on the ground. These skid roads should be kept narrow, and located so that they can be used to move logs out of the woods at each cut. Close supervision of logging will be required to restrict travel of skidding and other logging equipment to the skid roads.

In shelterwood cuttings, trees should be felled into openings as much as possible using a herringbone pattern that will permit logs to be pulled onto the skid roads with a minimum of disturbance. It may be necessary to deviate from the herringbone felling angle in order to drop trees into openings. If this is the case, the logs should be bucked into short lengths to reduce skidding damage. Trees damaged in felling and skidding should not be removed if they are still windfirm.

In group selection cutting, the felling pattern should be similar where there is a manageable stand of advanced reproduction. Otherwise all trees should be felled into the openings. Both shelterwood and group selection cuttings require close coordination between felling and skidding because it may be necessary to fell and skid one tree before another tree is felled.

Slash Disposal

Some treatment of logging slash and unmerchantable material will probably be needed after each cut. However, treatment should be confined to concentrations and that needed to reduce visual impact, because most equipment now available for slash disposal is not readily adaptable to working in shelterwood cuttings. Furthermore, burning slash will not only cause damage to the residual, but may destroy the seed supply in stands with serotinous cones. Skid out as much of the down sound dead and green cull material as possible for disposal at the landings or at the mill. Treatment in stands should be limited to lopping and scattering, chipping along the roadway, and hand piling and burning to minimize damage. In group selection cutting, if there is not a manageable stand of advanced reproduction, dozers equipped with brush blades can be used to concentrate slash for burning in the openings. Piles should be kept small to reduce the amount of heat generated. Furthermore, in stands with the serotinous cone habit, treatment should not be attempted until the cones have had time to dry out and open up.

REGENERATION PRACTICES

The primary purpose of the cutting practices suggested are to aid the forest manager in maintaining continuous forest cover of lodgepole pine, while minimizing the limitations to partial cutting imposed by silvical requirements, stand conditions, wind, insects, and diseases.

Nevertheless, the reductions made in the overstory canopy by removing 40 percent or more of the basal area by modified shelterwood, or openings cut in the canopy by modified group selection, are large enough to permit new reproduction to become established, if the seed supply is sufficient and the seedbed provides conditions suitable for germination and survival. Once the new reproduction has become established, the same care in logging and slash disposal suggested for protecting advanced reproduction must be exercised.

Lodgepole pine varies considerably in its cone habit, and each stand should be examined before cutting to determine serotiny. Individual trees generally bear either serotinous or nonserotinous cones; at least 40 percent of the trees should bear serotinous cones before a stand can be considered to have the closed-cone habit.

In general, throughout much of Colorado and southern Wyoming, seed is stored in closed cones that open only when exposed to relatively high temperatures (Alexander 1966b, Tackle 1961). Dispersal comes largely from cones attached to the ~~logging~~ slash or scattered on the ground. How and when the slash is treated directly influences regeneration success.

In northern Wyoming, cones generally open at maturity and seeds are dispersed by the wind in the usual manner. Most seeds will fall within about 200 feet of the source (Boe 1956, Tackle 1964b). In those situations, seed for regeneration comes from trees cut on the area, left standing on the area, or standing around the perimeter.

Scarification is usually necessary to remove heavy concentrations of duff and litter to prepare mineral soil seedbeds; it should be done during logging and slash treatment at the time of the seed cut under shelterwood and at each cut under group selection. Unless 40 percent or more of the ground surface is mineral soil after logging and slash treatment, additional seedbed preparation is needed.

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1975. Partial cutting in old-growth lodgepole pine. USDA For. Serv. Res. Pap. RM-136, 17p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

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Keywords: Forest cutting systems, *Pinus contorta*, stand condition, windfall risk, dwarf mistletoe, mountain pine beetle.

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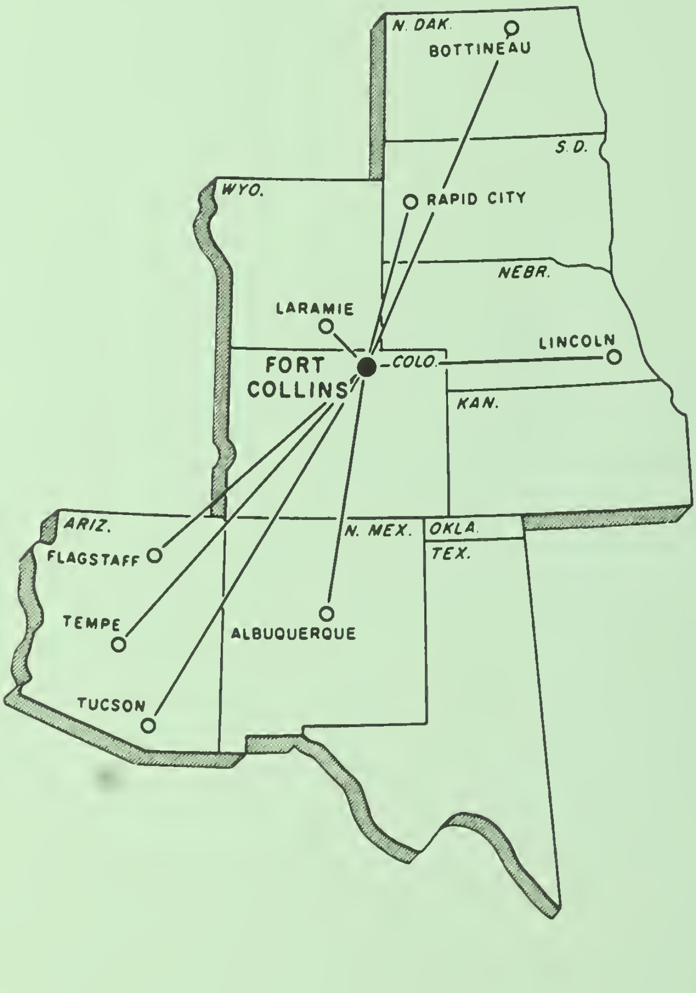
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The Status of Our Knowledge

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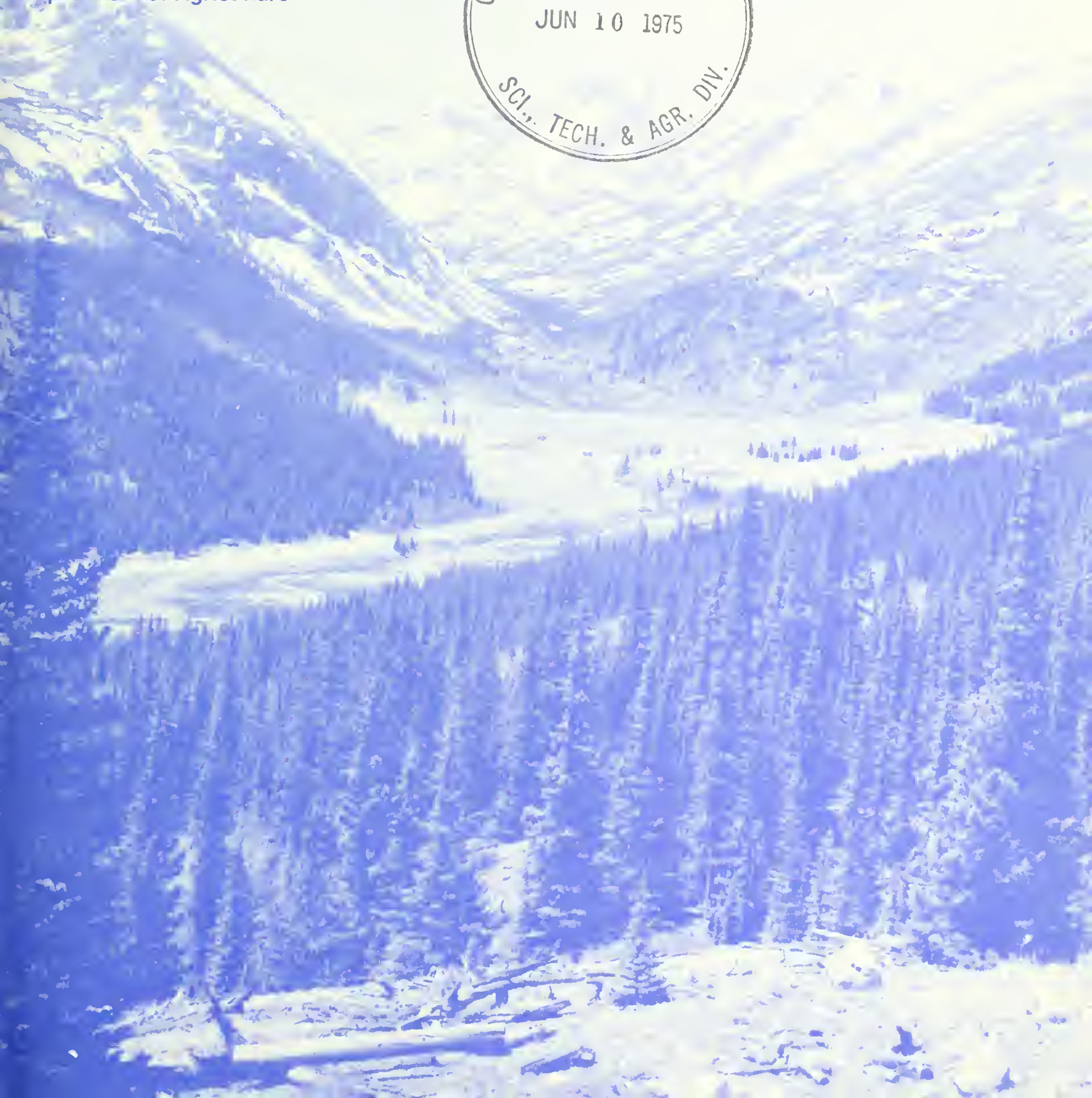

Abstract

Watershed management in the subalpine zone of Wyoming, Colorado, and New Mexico is described. Forest hydrology is briefly discussed, followed by an in-depth discussion and review of (1) field studies of the effects of watershed management practices on snow accumulation, melt, and subsequent runoff; and (2) simulation models designed to predict the hydrologic impacts of timber harvesting and weather modification. Pertinent literature is included, along with unpublished research, observations, and experience. Research needs are highlighted, and guidelines for implementing watershed management principles in land use planning are summarized.

Keywords: Forest management, simulation analysis, snowmelt, subalpine hydrology, watershed management, land use planning.

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Research Paper RM-137

February 1975

WATERSHED MANAGEMENT IN THE ROCKY MOUNTAIN SUBALPINE ZONE:

The Status of Our Knowledge

Charles F. Leaf, Principal Hydrologist
Rocky Mountain Forest and Range Experiment Station [1]

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Cover-- Research Paper RM-137

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Where severe wind effects produce ex- emely irregular patterns of snow accumula- on in forest margins and exposed parklike enings, Bartos and Rechard (1973) showed at reconnaissance snow courses can precisely

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Because there is considerable public concern for the ecologic and hydrologic consequences of weather modification, it is important to understand not only how much water yields will be increased, but also how hydrologic systems will be affected. Kahan et al. (1969) were quick to emphasize that systems modeling can play a → significant role in analyzing the impacts of increased snow accumulation on water-balance interactions. Accordingly, we have made pre-

[1] *Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University. Leaf is now privately employed in Fort Collins.*

Figure 1.—Distribution of spruce-fir and lodgepole pine forests, which comprise the subalpine zone in Wyoming, Colorado, and New Mexico.

Spruce-fir is found between 10,000 and 11,500 ft throughout the Colorado subalpine zone. Lodgepole pine is concentrated in the north-central part of the State, whereas Douglas-fir grows predominantly in the southern half.

New Mexico's subalpine forests are principally Douglas-fir and spruce-fir. Near the upper limits of its 8,000- to 9,500-ft elevational range, Douglas-fir mixes with true firs and spruce. White fir (*Abies concolor*) and aspen are commonly found within the Douglas-fir type. Spruce-fir forests occupy a relatively small area in New Mexico. They are found in the north-central part of the State at elevations between 8,500 to 12,000 ft.

Although aspen forests are common to all three States, the largest stands are found in southwestern Colorado where trees reach 24 inches in diameter at breast height (d.b.h.) and over 100 ft tall.

Alexander (1974b) summarizes current acreages of commercial subalpine forest by State and species on lands subject to management (not reserved in National Parks, Wilderness Areas, and so forth).

Geology and Soils

An excellent summary of the geology and relief of the central and southern Rocky Mountain subalpine zone is presented by Alexander (1974b), who included a number of detailed references on the geologic characteristics of the mountain ranges and plateaus shown in figure 2.

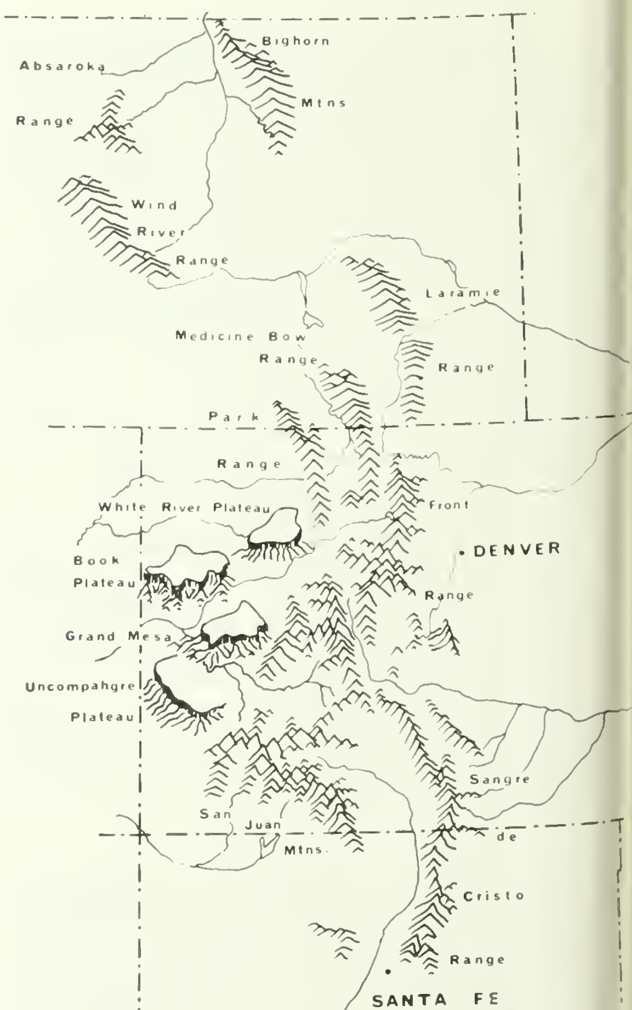


Figure 2.—Important plateaus and mountain ranges of the central and southern Rocky Mountain subalpine zone.

Soils on the subalpine watersheds vary according to the rock from which they originated. In general, the parent material consists of crystalline granite, gneiss, and schist. However, soils derived from sedimentary, basaltic, and volcanic rocks also occupy a large part of the subalpine zone. Alluvial soils occur along most streams. The parent material is generally a mixture of glacial till, glacial outwash, and recent valley fill. Included on most watersheds are bogs originating from seeps and springs which emerge on sideslopes. Soils in these areas are highly organic.

For the most part, subalpine soils are relatively deep, permeable, and capable of storing modest quantities of water from snowmelt. This feature serves to regulate streamflow during the runoff season. Exceptions occur in those areas which have experienced intensive glacial activity, as for example, in most of the Park Range of northwestern Colorado. General descriptions and typical characteristics of subalpine soils are given by Johnson and Cline (1965) and Retzer (1956, 1962).

Water Yield

The subalpine forests of Wyoming, Colorado, and New Mexico form the headwaters of six major river basins (fig. 1):

Wyoming	Colorado	New Mexico
Columbia	Colorado	Rio Grande
Colorado	Missouri	Mississippi
Missouri	Rio Grande	Colorado
Bear	Mississippi	

Water yields from the subalpine zone are of major importance to downstream users. Competition for water is extremely keen, particularly in the Colorado, Rio Grande, and Missouri River basins. Recent decisions by the courts and Federal legislation are good testimonies of the high value that users several hundred miles downstream in Los Angeles, Phoenix, and El Paso place on water which originates in the subalpine forests of Colorado and New Mexico.

The foreseeable increases in water use in areas close to the water source are also of concern to planners. Hardison (1972) has shown that natural streamflows from the subalpine zone are already 80 to 100 percent developed. Thus, future population growth, mining, oil shale, and industrial development will create acute water problems in the long run, unless water supplies are increased through conservation, water management, recycling, and efficient irrigation practices.

Opportunities to use natural flows more efficiently through interbasin diversion and storage still exist. However, new projects are being vigorously opposed by well-organized segments of an environment-conscious society.

Hydrologic Charactistics of Subalpine Forest

Water Balance

Research watersheds have provided us with considerable information about the hydrology of the subalpine zone. Some significant findings from the classic Wagon Wheel Gap experiment (Bates and Henry 1928) were;

- Little, if any, overland flow of water appeared at any season, and the quantity of eroded soil was small.
- Mean annual temperature did not exceed 35°F, and mean annual precipitation was approximately 20 inches.
- Total precipitation was about half snow and half rain. With the exception of south slopes, there was no snowmelt during winter until after early March.
- Of the total precipitation, about one-half is stored in winter snow accumulation and is released during the spring melting period.
- More than 55 percent of the total streamflow occurred from April through June.
- The difference between precipitation and runoff indicated evaporation is a fairly constant 15 inches annually.

Water-balance studies at the Fraser Experimental Forest have also given us insight into the hydrology of spruce-fir and lodgepole pine forests. In developing operational runoff forecasting methods, Garstka et al. (1958) found that water yield is 45 to 55 percent of the annual precipitation. Of this amount, 90 to 95 percent is derived from snowmelt. Typically, winter conditions keep the snowpack well below freezing until late March or April. Peak seasonal snow accumulation averages 15 inches of water equivalent, and during the melt season, the depleting snowpack is augmented by more than 5 additional inches of precipitation. Subsequent rainfall during the summer and early fall averages 8 to 10 inches. Thus, of this 28- to 30-inch input, about 12 to 15 inches becomes streamflow.[2]

[2]Records of temperature and precipitation collected over a 33-year period at the Fraser Experimental Forest have been published by Haeffner (1971). Leaf and Brink (1972a) have also summarized 29 years of streamflow from an experimental watershed in the same area.

Finally, in summarizing a 10-year hydrologic record from the Black Mesa watersheds in western Colorado, Frank[3] found that: (1) more than two-thirds of the 22 inches of precipitation during the average water year fell between October and May; and (2) spring snowmelt accounted for 99 percent of the average annual runoff, which varied from 1.4 to 6.8 inches. Moreover, he also found that summer storms are not severe, with maximum 60-minute rainfall intensities of less than 1 inch per hour, and 5-minute intensities of 4.6 inches per hour. Frank also found that, while summer storm suspended-sediment concentration can be as much as six times that sampled during snowmelt, total suspended sediment for the year is almost nine times that obtained from summer storm runoff "because of the small volume of storm runoff."

The above discussion is a good general account of hydrologic conditions in the subalpine zone, except that melting begins later in the spring in the more northern part of the region and there are small portions that receive more precipitation. For example, in the Park Range in Colorado, at elevations above 10,000 ft, precipitation is between 50 and 65 inches a year with only 20 to 30 percent falling as rain. Water yields average 25 to 45 inches. Other areas of high precipitation and runoff are Flat Tops, San Juans, and the Elk Mountains. Mean annual water balances for typical subalpine watersheds in Colorado and Wyoming are summarized in table 1.

Table 1.--Mean annual water balances (inches) for typical subalpine watersheds in Colorado and Wyoming

Watershed	Seasonal snowpack, water equivalent	Precipitation	Evapotranspiration	Runoff
COLORADO:				
Soda Creek, Routt NF	42.6	55.2	16.7	38.5
Fraser River, Arapaho NF	15.0	30.3	16.9	13.4
Wolf Creek, San Juan NF	26.2	48.0	21.0	27.0
Trinchera Creek, Sangre de Cristo Mountains	9.5	19.6	14.5	5.1
WYOMING:				
South Tongue River, Bighorn NF	15.5	29.6	15.8	13.8

Precipitation

The most accurate and complete snow survey and precipitation measurements have been made at Wagon Wheel Gap and the Fraser Experimental Forest. However, Hoover[4] has pointed out that even these records are suspect, due to the effects of wind on snow accumulation and gage catch. Because snow accumulation and rainfall in subalpine forests are strongly influenced by wind, which interacts with the vegetation and local topography, the existing system of precipitation gages and snow courses in the Rocky Mountain region can at best give only index values of areal precipitation (Meiman 1968, Hoover 1971). A possible exception is a portion of the Park Range near Steamboat Springs, Colorado, where a dense snow course network precisely measures area water equivalent (Washichek and McAndrew 1968).

If a drainage basin is freely accessible to snow measurements, studies have shown that snow input can be measured precisely. Leaf and Kovner (1971, 1972) developed guidelines for estimating total snow storage. From statistical analyses they have shown that, because of the systematic variation of the seasonal snow accumulation, little statistical efficiency can be gained from intensively sampling and extrapolating index snow courses. More precise estimates of areal snow storage can be obtained from reconnaissance snow courses—where one or two samples at most are taken at intervals along a trail which traverses the whole watershed. They have also shown that, on watersheds with uniform forest cover where snow rarely melts during the winter snow accumulation season, the natural snow accumulation can be estimated to within 5 percent of the true mean 50 samples per mi^2 widely spaced over the drainage basin. Similar conclusions can be derived from a study by Swanson (1970), who measured snow accumulation on uniformly vegetated watersheds in Alberta, Canada.

Where severe wind effects produce extremely irregular patterns of snow accumulation in forest margins and exposed parklike openings, Bartos and Rechard (1973) showed that reconnaissance snow courses can precisely

[3]*Frank, Ernest C. Hydrology of Black Mesa watersheds. (Manuscript in preparation at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

[4]*Hoover, Marvin D. The influence of forest cover on streamflow in the Central Rocky Mountains. 55 p. (Unpublished Problem Analysis, FS-RM-1602, on file at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

estimate areal snow storage, provided that sampling intensities in and near the edges of the large openings are 8 to 10 times greater than well inside the surrounding forest.

As discussed above, snow survey methods can show precisely how the seasonal snowpack is distributed on subalpine watersheds. Once the snowpack begins to melt, however, snow surveys can no longer be used to estimate precipitation input. At this point, and during the summer and fall, rain gages must be used, which in most cases give questionable results due to a host of interrelated factors. Many of these factors have been researched for several hundred years (Larson 1971). Because research using ground-based sensors has largely reaffirmed past results without producing new knowledge, Hoover (1971) suggested that new and different systems which measure precipitation above forest canopies be developed. Laser devices or particle counters, such as those developed by Schmidt and Sommerfeld (1969) and Schmidt (1971), offer promise of better precipitation measurements.

Rhea and Grant (1974) have shown that total snowfall in mountainous area can be largely explained by "systematic consideration of (a) the directionally adjusted topographic slope which potential precipitation-bearing winds must traverse on their last 20 km of approach to a given station, and (b) the number of upstream barriers which the air must pass over." The model should prove to be a highly useful tool for determining seasonal snowfall distribution in unmeasured watersheds and for snow-course network design. Another important benefit from this model is the insight it gives into the physical processes affecting mountain precipitation regimes.

Effects of Timber Harvesting on Snow Distribution

Early studies in the Rocky Mountain region included observations in the natural forest to see how virgin stands affect snow accumulation. Subsequently, plot studies were made of thinnings and patchcuttings to see how these modifications affected the snowpack.

Wilm and Dunford (1948), reporting on plot studies at the Fraser Experimental Forest, gave a comprehensive summary of watershed management concepts and potentials for changing the water cycle in subalpine forests. In their study, twenty 8-acre plots were laid out in mature lodgepole pine in 1938. After careful snowpack measurements, the plots were logged in 1940, ranging from a commercial clearcut of all trees to an uncut virgin area. The residual volume in trees larger than 9.5 inches d.b.h. was in these classes: 0; 2,000; 4,000; or 6,000 bd ft (fbm) per acre. The uncut stands contained 11,900 fbm per acre. After logging, the snowpack was again measured in 1941-43.

Harvest cutting resulted in the accumulation of more snow on the cutover plots. The highest snow accumulation was observed in the clearcut plots. Typical amounts of snow water storage observed immediately after cutting were:

Reserve volume, (fbm/acre)	Inches of water equivalent
11,900 (uncut)	10.3
6,000	11.4
4,000	12.3
2,000	12.4
0 (commercial clearcut)	13.5

The differential snow accumulation observed from this study and from similar studies that followed (Goodell 1952, Goodell and Wilm 1955) was attributed primarily to the elimination of evaporation losses from snow intercepted on the tree crowns which, it was believed, "more than offset increases in evaporation from the snowpack surface caused by removing the shelter of the forest" (Goodell and Wilm 1955).

Based on the plot results, the 714-acre Fool Creek watershed at the Fraser Experimental Forest was partially clearcut in 1954-56 in a pattern of alternate strips varying from one to six tree heights (66 to 396 ft) in width. Fifty percent of the merchantable timber volume was removed from 40 percent of the watershed area (fig. 3). In discussing 3 years of record after the timber harvest, Goodell (1959) suggested that the approximately 25 percent water-yield increase was primarily caused by reduced interception losses associated with the reduction in forest canopy.

This interpretation prevailed until the late 1950's when hydrologists began to seriously question "the conventional emphasis upon interception of snow as an important factor controlling water yield in the Colorado area" (Hoover 1960). In discussing the interception theory, Miller (1961) argued that until the basic processes are carefully studied, the belief that interception results in high evaporation losses from forest canopies is "folklore." Finally, in a reappraisal of the validity of this popular concept, Goodell (1963) summarized existing knowledge and he, too, questioned conclusions previously drawn from interception studies

Figure 3.—Fool Creek watershed, Fraser Experimental Forest. East St. Louis Creek, the 1,984-acre control watershed, is to the right of Fool Creek.

based on differential snow accumulation between uncut forest and adjacent open areas.

More recently, Hoover and Leaf (1967) reported on direct observations of snow accumulation and retention in subalpine forest. These observations indicated that mechanical removal and transport of intercepted snow are more important than vaporization. Conclusions were based on timed-sequence motion pictures of a forested slope during all daylight hours from November 6, 1963, to May 15, 1964. Photographic records during this and subsequent winters proved that snow rests on tree canopies only during periods of cloudy weather, low temperature, and frequent snowfall. Typically, after snowfall ceases, wind-generated vortexes and eddies quickly strip the snow from the trees. In less than a minute, this airborne snow is redeposited at varying distances from where it was intercepted. The sequence in figure 4 shows the obvious importance of redistribution in the subalpine zone.

These results led to the resurvey—first in 1956, and later in 1964, 1968, and 1972—of the cutting plots studied by Wilm and Dunford (1948). Young trees developed rapidly on the clearcut and 2,000-fbm reserve plots (fig. 5). By 1956, the trees averaged 5 ft in height, which placed their canopy above the snow surface. By 1968, their average height exceeded 15 ft.

In spite of vigorous regrowth and increased canopy density on the heavily cutover plots, snow storage amount changed little, if any, in the 28 years since cutting (Hoover and Leaf 1967). These results provided additional evidence that the aerodynamic effect on snow distribution, rather than reduced interception loss, is the major cause of increased snow in openings.

To get still another check, snow survey data from Fool Creek before and after treatment were analyzed to determine the effect of the treatment on a watershed basis (Hoover and Leaf 1967). As observed from the plot studies, comparisons of snowpack in the alternate forest and clearcut strips showed there was more water equivalent in the open strips:

Strip width (chains)	Uncut	Cut
	(inches of water equivalent)	
1	15.4	18.4
2	15.6	17.6
3	17.2	19.2
6	14.0	20.7

To complement the cut-uncut strip comparisons, excellent records of snow storage on Fool Creek and the calibration (East St. Louis Creek) watershed for 11 years before treatment were compared with 7 posttreatment years. Before treatment, total snow storage averaged 14.3 inches on Fool Creek and 11.8 on East St. Louis. For the 7 years observed following treatment, the average water equivalent was 14.4 inches compared with 11.4 inches on the control watershed. These results, shown graphically in figure 6, indicate that total snow storage on Fool Creek was not increased in spite of the obvious differences in snow catch between cut and uncut strips. A similar analysis of winter snow accumulation at Wagon Wheel Gap before and after timber harvesting also showed no change in areal snow storage (Hoover and Leaf 1967). In reviewing this work, Hoover (1971) stated that "If such results are typical of the effect of openings in forest stands, it explains some of the findings of conventional interception studies."

Finally, a recent comparison of snow accumulation and melt in a uniform lodgepole pine stand before and after cutting a small opening

A

B

C

Figure 4.—Significance of wind-caused snow redistribution in the subalpine zone.

A This photograph was taken during moderate snowfall that continued throughout the day of February 4, 1970, at the Fraser Experimental Forest. The storm ceased during the night.

B The most exposed trees were already bare of snow by noon on February 5, 1970. Individual vortexes look like artillery bursts on the mountainsides. Vortexes were moving rapidly eastward (from right to left), and each one was visible for less than 60 seconds.

C By 4:00 p.m. on February 5, 1970, all snow was gone from exposed tree crowns. The white patches are snow in the clearcut blocks on the upper portion of the Fool Creek watershed.

Figure 5.—New growth does not affect total snow storage in this lodgepole pine area of the Fraser Experimental Forest. This 8-acre plot, cut 28 years ago to remove all but 2,000 fbm of trees larger than 9.5 inches d.b.h., still functions as an opening with wind controlled by surrounding old-growth forest.

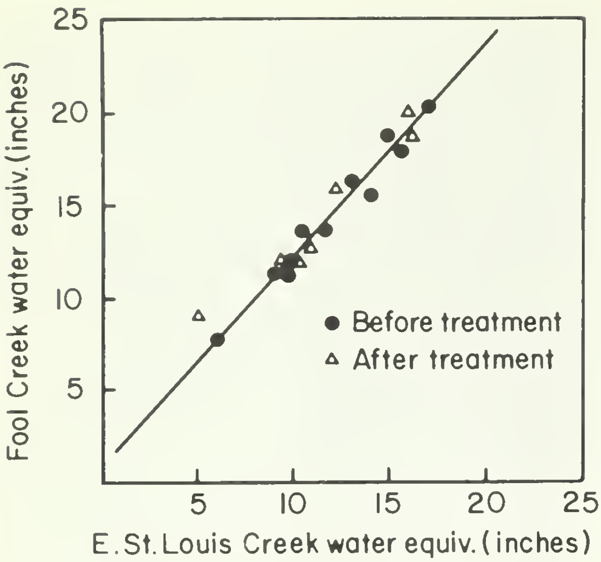


Figure 6.—Comparison of area snow storage before and after strip cutting on Fool Creek watershed.

reconfirmed the significance of redistribution (Gary 1974). Gary found that conspicuous increase in snow accumulation near the center of his opening was largely offset by a decrease in snow below the trees and downwind.

We still need more knowledge of aerodynamic processes and the hydrologic implications of interception and differential snow accumulation. The empirical results summarized above indicate that, for optimum snow accumulation, openings should be protected from wind and should not exceed eight times the height of the surrounding forest (Hoover 1969). Larger openings apparently allow wind eddies to scour the snowpack near the center. A hint of this effect was observed on the 6-chain strips on Fool Creek (fig. 7).

A more complete understanding of interception processes requires more research (Miller 1964, 1966). New work in characterizing the aerodynamic characteristics of subalpine stands (Bergen 1971) will significantly add to what we have already learned from empirical studies.

Snowmelt and Runoff

Snowmelt in relation to subalpine forest cover was studied by Bates and Henry (1928), Wilm and Dunford (1948), Garstka et al. (1958), Gary and Coltharp (1967), Leaf (1971), and Gary (1974). Typically, estimates of peak seasonal water equivalent and ablation during the melt season were derived from weekly measurements of snow courses.

At the Fraser Experimental Forest, Leaf (1971) analyzed snowmelt on two watersheds—Fool Creek (714 acres) with generally east- and west-facing aspects and Deadhorse Creek (667 acres) with north- and south-facing aspects. Leaf observed that, on Fool Creek, snowpack melt rates were generally similar on both aspects at all elevations. In contrast, snowmelt rates on Deadhorse Creek differed considerably be tween the low-elevation north and south slopes. This agrees with results of Garstka et al. (1958), who reported that, at 9,500 ft on a watershed adjacent to Deadhorse Creek, melt rates on the south slope peaked much earlier than on the opposite north slope. However, Leaf emphasized that the time lag between maximum snowmelt rates on the north and south slopes diminished with increasing elevation. Gary and Coltharp (1967) similarly observed that snowmelt rates were about the same on high-elevation north and south slopes in northern New Mexico.

In the same study, Leaf found that water-yield efficiency was highest on the Fool Creek watershed which had: (1) almost complete snow cover when seasonal snowmelt rates on all major aspects were maximum; (2) a delayed and short snow-cover depletion season; and (3) moderate recharge and evapotranspiration losses.

Water-yield efficiency in Deadhorse watershed, with low-elevation south slopes, was least. In 1969, streamflow from the drainage area on this basin below 9,850 ft was less than 30 percent of that generated from above this elevation. Fourteen years of comparative streamflow

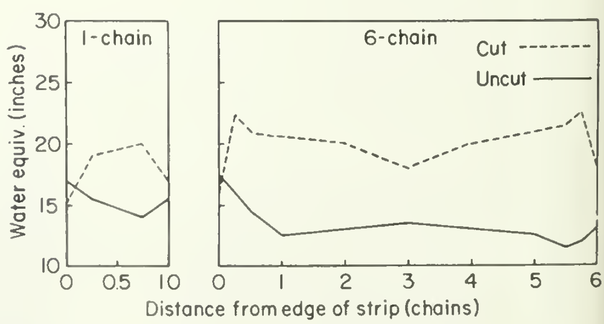


Figure 7.—Comparison of average snow accumulation in one and six tree-height strips on Fool Creek, Fraser Experimental Forest.

data indicated that water yields from the low-elevation subdrainage can vary from near zero in poor runoff years to a maximum during good years of less than 60 percent of the flow generated from the high-elevation subdrainage.

Effects of timber harvesting.—In their experiments in lodgepole pine at the Fraser Experimental Forest, Wilm and Dunford (1948) found that snow melted more rapidly in the heavily cutover stands than in the uncut forest. Moreover, they found that faster melt rates were offset by the higher snow accumulation in the cutover plots so that all the plots became bare of snow at the same time. These results have been confirmed several times in the Rocky Mountain region. The most recent study of this type is discussed by Gary (1974).

At Wagon Wheel Gap in the headwaters of the Rio Grande in Colorado, Bates and Henry (1928) observed accelerated snowmelt rates after clearcutting the aspen-mixed conifer forest from one 200-acre watershed (fig. 8). This effect was apparent in the streamflow hydrograph (fig. 9). Moreover, annual water yields were increased about 22 percent during the 7-year period that records were taken after harvest cutting.

Figure 8.—The Wagon Wheel Gap watersheds some 30 years after treatment. The regenerated forest cover on the clearcut watershed at right is aspen. The control watershed on the left is still vegetated with aspen and mixed conifers.

Timber harvesting on the 714-acre Fool Creek watershed also accelerated snowmelt rates and subsequent streamflow (fig. 10).

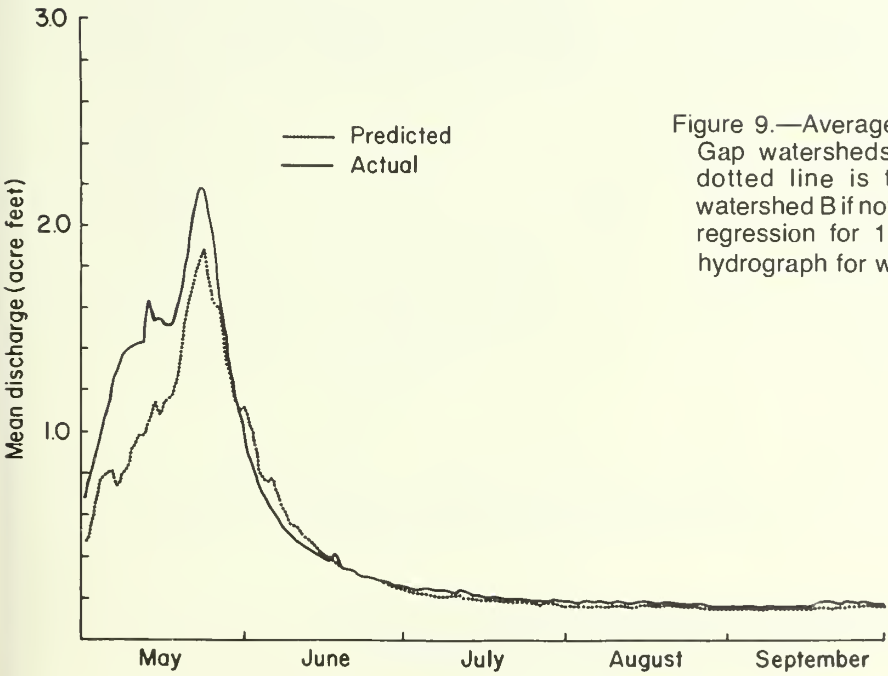


Figure 9.—Average hydrographs for Wagon Wheel Gap watersheds (Bates and Henry 1928). The dotted line is the predicted hydrograph for watershed B if not harvested, based on pre-harvest regression for 1912-19. Solid line is the actual hydrograph for watershed B after timber harvest.

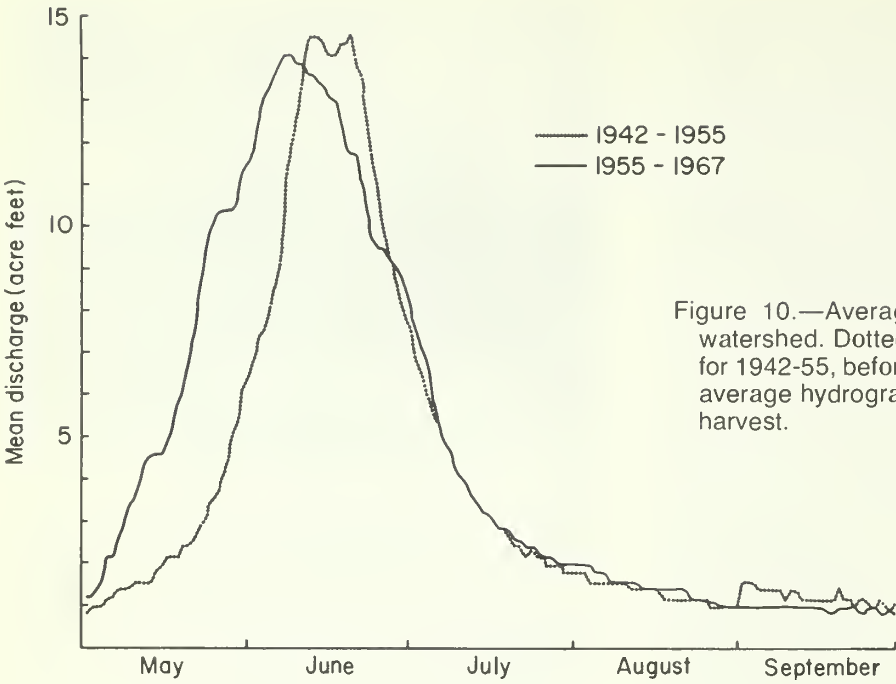


Figure 10.—Average hydrographs for Fool Creek watershed. Dotted line is the average hydrograph for 1942-55, before timber harvest. Solid line is the average hydrograph for 1955-67, following timber harvest.

Water-yield increases have averaged 3.5±0.8 inches at the 95 percent level of confidence since harvest cutting. Statistical analyses indicate that runoff increases may have begun to taper off somewhat in recent years (fig. 11).

Another significant result from this watershed study was that peak flows apparently were not significantly affected. Leaf (1970) pointed out that, for the pretreatment period from 1943 to 1955, annual peak daily flows averaged 9.7 cubic ft per second (ft^3/s), compared with an average 9.5 ft^3/s for the 1956 to 1969 postharvest periods.Finally, hydrograph comparisons indicate that recession flows were not diminished, even though timber harvesting caused higher snowmelt rates in early spring and more efficient water yield. Water yields before and after harvest cutting from Fool Creek and the East St. Louis Creek control watershed are compared in figure 12.

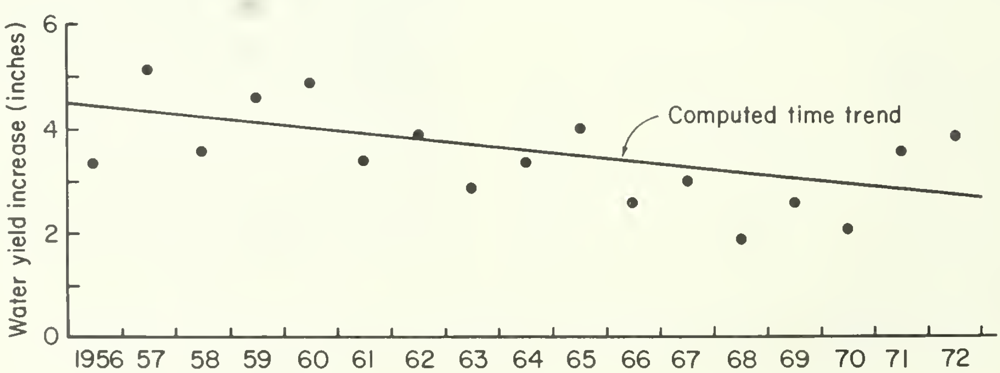


Figure 11.—Summary of increased water yields subsequent to strip cutting on Fool Creek.

Yet another illustration of increased water yields was given by Love (1955, 1960), who studied a larger 762-mi^2 watershed which drains the White River above Meeker, Colorado. In this instance, beetles killed 26 to 80 percent of the spruce-fir forest on a 226-mi^2 area. Love observed that average annual flow in the White River was increased by 25 percent. He attributed the increase to the same effects that increased water yields from Fool Creek, which included reduced interception and evapotranspiration.

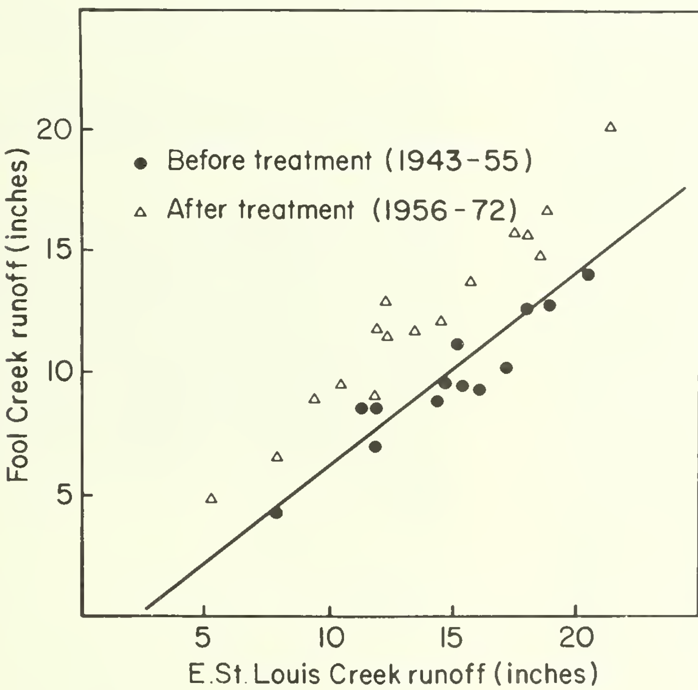
Effects of grazing.—In much of the subalpine zone, watersheds are not completely forested, but are covered with stands of spruce and aspen intermingled with extensive grassland parks. Such areas are not only important for water yield, but also for wildlife habitat, forage, and livestock production. Thus, in addition to forest hydrology, range hydrology is also important in determining the total water balance of these lands.

A considerable amount of research has been done in rangeland watershed management along the Front Range of Colorado and in central Arizona (Gary 1975). These studies covered a variety of grasses, soils, elevations, and climates, in rather low water-yielding zones. In Colorado, it was found that good plant cover on coarse and porous soils minimizes surface runoff and erosion. However, Gary(1975) has concluded that, while these studies have shown that good range management practices and revegetation of depleted land with trees, shrubs, and grass will improve watershed conditions, such measures cannot offer complete protection against intense runoff and normal geologic processes which are characteristic of the Front Range.

It should be noted that much of the early concern for protection of western Colorado mountain rangelands originated from infiltrometer studies in which artificial rainfall was applied to prewetted plots at a rate of 5 inches per hour for a 50-minute period (Turner and Dortignac 1954). These rates were approximately five times the maximum observed rainfall intensities on Black Mesa.

Frank[5] demonstrated that there was not a significant change in runoff and sediment under various intensities of cattle grazing at

[5] *Frank, Ernest C. Hydrology of Black Mesa watersheds. (Manuscript in preparation at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*



April - Sept. Runoff Increase Since Harvest

Year	Inches
1956	3.3
1957	5.2
1958	3.7
1959	4.6
1960	5.4
1961	3.4
1962	3.9
1963	2.9
1964	3.5
1965	4.0
1966	2.6
1967	3.1
1968	1.9
1969	2.5
1970	2.1
1971	3.6
1972	3.9
Mean	3.5 ±0.8*

*95 Percent level of confidence

Figure 12.—Comparison of seasonal runoff before and after strip cutting on Fool Creek watershed.

Black Mesa since: (1) virtually all of the runoff and sediment yield was produced during the snowmelt runoff season; and (2) 60-minute rainfall intensities seldom exceed 1 inch per hour. Moreover, grazing intensities on the watersheds were set up to obtain 25 to 60 percent utilization of only one range species (Idaho fescue, *Festuca idahoensis*). Therefore, it was difficult to obtain a strong indication of differences in runoff and sediment resulting from changes in ground cover. Frank's results were based on an analysis of watersheds which required rather large differences in water yield (0.6 to 2.2 inches after 10 years) before any effect could be detected.

Given the above, it would be premature to conclude that grazing does not affect water yields. On the contrary, Schuster (1964) reported that heavy grazing can decrease the amount of root material. It is reasonable to expect that any detrimental effects on root systems would reduce consumptive use and thereby increase water yields somewhat. Our knowledge as to whether or not this increase is significant requires further research.

Hydrologic Systems Analysis: Subalpine Hydrologic Simulation Model

As discussed above, a considerable body of knowledge accumulated during the past 50 years has conclusively shown that subalpine forests indeed exert a significant effect on water yields. Hoover[6] has pointed out that, in lodgepole pine and spruce-fir forests, where water is a primary resource, ". . . sufficient practical information exists to guide the first steps in applying management for increased water yield."

In spite of this position, land managers are apparently reluctant to specifically include watershed management principles in their multiple use planning—perhaps for three technical reasons: First of all, as will be discussed later, there is still a deficiency in scientific knowledge of specific processes; secondly, there is a lack of "management tools" to translate research results into management decisions; and finally, nature has so blessed much of the Rocky Mountain region with excellent water supplies during the past 20 years, that society is complacent as to the limitations of this vital resource. Nevertheless, planners have already concluded that the "thorniest problem facing energy development in the West is water" (Engineering News Record 1974). Unless alternative water sources are developed, and the present rate of use curtailed to accommodate growth and environmental needs, severe water shortages are sure to occur in the future.

[6]*Hoover, Marvin D. The influence of forest cover on streamflow in the Central Rocky Mountains. 55 p. (Unpublished Problem Analysis, FS-RM-1602, on file at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

The recent clearcutting controversy (Wyoming Study Team 1971) has made it emphatically clear that the public wants a high caliber of natural resource management. Accordingly, we must apply everything we have learned about the subalpine ecosystem —including what we have learned from watershed management research—in reaching management decisions.

Although we still have an imperfect scientific understanding of how specific hydrologic processes operate, we cannot afford to wait for new information. Rather, we must begin to use what we presently know. The systems approach, where a dynamic simulation model is built from available knowledge about separate components, is one way to incorporate research results into operational resource management. This is a technically sound procedure that has had a history of success (Forrester 1961).

Leaf and Brink (1973a, 1973b) have developed a comprehensive hydrologic model which simulates the water balance in several hydrologic subunits within a subalpine watershed on a continuous year-round basis, and compiles the results from up to 25 subunits into a "composite overview" of the entire drainage. The model has been specifically designed to simulate watershed management practices and their resultant effects on hydrologic system behavior.

The discussion which follows is intended to give a general idea of the scope of the model. Detailed flow chart descriptions and more complete hydrologic theory are presented by Leaf and Brink (1973a, 1973b), who developed the model from more than 25 years of field data collected from subalpine watersheds in the Fraser Experimental Forest. The model has also been calibrated for several representative areas throughout the Rocky Mountain region. A general flow chart of the system is shown in figure 13.

Snowmelt

Previous work in subalpine forests has shown that radiation is the major source of energy for snowmelt (Bergen and Swanson 1964). Accordingly, shortwave and longwave radiation represent the energy components available for snowmelt. Shortwave radiation to the snow or ground surface beneath the forest

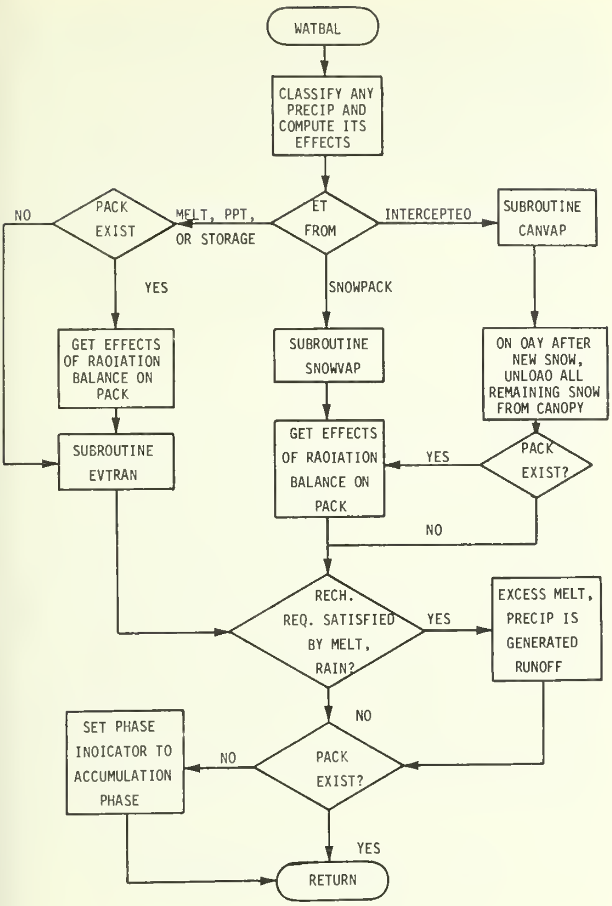


Figure 13.—Flow chart of dynamic model which simulates subalpine hydrology.

canopy is controlled by a transmissivity coefficient which varies according to forest cover characteristics. The incident shortwave radiation as measured on a horizontal surface is adjusted according to the slope and aspect of each hydrologic subunit. Longwave radiation is computed by the Stefan-Boltzmann equation.

Snowpack reflectivity varies according to precipitation form, air temperature, and the energy balance. During the winter months, temperatures within the snow cover are simulated using unsteady heat flow theory. The snowpack will yield melt water only when it has become isothermal at 0°C, and its free water-holding capacity is reached.

Interception and Evapotranspiration

We do not yet have a complete understanding of evapotranspiration on an areal basis. What we do know is summarized below:

1. Little or no evaporation from snow was observed by Wilm and Dunford (1948), who also found that nearly all evaporation took place after melting began. More recently, Hutchison (1966) reported that rapid evaporation occurred from wet soil around melting snow with possible condensation on snow surfaces. Model studies of an unripened snowpack by Bergen (1963) indicated that substantial amounts of water vapor were lost from the deepest layers of the pack, and that free convection took place within the pack during winter. Bergen also observed that evaporation from the snow surface can be relatively high during clear weather in late spring.
2. In comparing soil-moisture regimes after snowmelt in aspen and spruce, Brown and Thompson (1965) showed that both spruce and aspen remove soil moisture to 8 ft. They also observed that the rate of water use was related to available water, as did Swanson (1967, 1969). Swanson also obtained information on the diurnal and seasonal course of transpiration in subalpine forests. He found that transpiration can occur early in the melt season when there is still considerable snow cover. Using heat-pulse methods, he also observed distinct velocity profiles in the conducting tissue of tree stems. More recently, Swanson (1972) showed that heat pulse velocity (HPV) is a function of both transpiration and water stored in tree parts. When internal plant water stresses were low, HPV directly indicated transpiration rate, whereas HPV was poorly related with transpiration at higher stresses.
3. Dahms (1971), reporting on a levels-of-growing study in lodgepole pine in Oregon, observed that soil-moisture withdrawal was reduced only at the lowest stand densities. By comparing periodic annual soil-moisture withdrawal for 10 years in five levels of growing stock (1 = lowest, 5 = highest), Dahms observed a sharp decrease in soil-moisture withdrawal by the low-density stand (level 1) and no significant difference in soil-water use between levels 2 through 5. He also observed that "soil moisture was withdrawn largely from the upper part of the soil during the early part of the season. However, as the summer advanced and most of the water in the upper portion of the soil had been used, soil moisture from the deeper layers was required for transpiration demands." Soil moisture was withdrawn to a depth of more than 5 ft in August and September.
4. Finally, soil-water measurements by Dietrich and Meiman (1974) in lodgepole pine in

north-central Colorado indicate that fall soil-moisture deficits in the top 2 meters were substantially less in small patchcut openings than in the surrounding forest.

Using this background information and results from the differential snow accumulation studies discussed earlier, a "potential" evapotranspiration function was developed for the model based on the empirical Hamon equation (Hamon 1961), which requires latitude, converted to saturation vapor density. The coefficient, C, in Hamon's equation was adjusted upward to obtain an expression for potential evapotranspiration under "unlimited" solar input, assumed here as potential radiation. The evapotranspiration computed by this expression is reduced in proportion to the radiation actually received each day. The adjusted evapotranspiration is then redefined according to its source, which can include: evaporation from snow intercepted by the forest canopy; evaporation from the snowpack surface; and evapotranspiration during the growing season (presumed to begin when areal snowpack water equivalent is reduced to 5 inches).

In developing the intercepted portion of the model, it was assumed that:

- The amount of snow intercepted varies according to forest cover type and density;
- The intercepted snow rests on the canopy for only 1 day following the day of the snow event due to turbulent winds which remove snow from the crowns; and
- The residual intercepted snow which is not vaporized after that period of time is added to the snowpack.

If the source is evapotranspiration, further adjustments are made to account for available soil water in open or forested areas, and the reflectivity of open or forested areas.

Input to the watershed system is derived from snowmelt and rainfall. Once evapotranspiration requirements have been satisfied, any remaining input is used to satisfy soil mantle recharge requirements. When "field capacity" is reached, the residual input becomes water available for streamflow (generated runoff).

Hydrologic Subdivisions

A given subalpine watershed system can be subdivided into as many as 25 hydrologic subunits. Subunits can vary according to elevation, slope, aspect, and forest cover. The model is designed to output results from individual subdivisions or compute area-weighted averages to get an overall response for the entire basin. In this way, both time and spatial variations are realistically accounted for. Table 2 summarizes the environmental characteristics of 10 subunits within a 667-acre subalpine watershed at the Fraser Experimental Forest. Individual subunits average 10 percent of the total area.

Systems Analysis of Watershed Management Practices

Forrester (1961) has emphasized that the major worth of dynamic models lies in their ability to precisely predict system response

Table 2.--Environmental characteristics of Deadhorse Creek watershed, Fraser Experimental Forest (Elevation: 9,600-11,600 ft, m.s.l. General aspect: ENE Latitude: 40°N)

Units and subunits	Percent of total area	Elevation range	Slope	Aspect	Vegetation type	Cover density	Trans-missivity
		Ft	*Percent*				*Percent*
LOWER BASIN:	(37)						
Lower South	12.6	9,600-10,400	30	SSE	Lodgepole pine	40	35
Middle North	6.1	9,600-10,200	45	NNE	Lodgepole pine	40	35
Lower North	6.0	9,600-10,200	40	N	Spruce-fir	65	25
Lower East	12.4	9,600-10,600	40	SE	Lodgepole pine	45	30
UPPER BASIN:	(63)						
Upper North, Subalpine	10.3	9,800-10,600	35	NE	Spruce-fir	55	25
Upper North, Alpine	7.8	10,600-11,600	35	NE	Spruce-fir	0	100
Upper East	17.9	9,800-11,200	30	ESE	Lodgepole pine	35	40
Upper South, Forested	12.0	10,200-11,000	30	SSE	Lodgepole pine	30	40
Upper South, Teardrop	1.6	10,800-11,000	30	SSE	Lodgepole pine	0	100
Middle South	13.1	9,800-10,600	30	SSE	Lodgepole pine	25	45

from changes in one or several system components. We have used this approach to study the effects of proposed watershed management practices on undisturbed watersheds, using our best information from field studies and the model described above.

Patchcutting

Snowmelt.—In simulating a proposed cutting practice on Deadhorse Creek at Fraser, the snowmelt portion of the model has produced results similar to those observed from field studies. Leaf and Brink (1972b) assumed that 40 percent of the watershed area was uniformly patchcut in openings five tree heights in diameter. As discussed previously, research has shown that more snow accumulates in openings, but total snow storage is apparently not changed significantly following harvest cutting. Accordingly, the snowpack was increased 30 percent in the openings and decreased 20 percent in the uncut forest to simulate the timber harvest.

Apart from redistribution of the snowpack, only the forest cover density variable was adjusted in the model to represent the timber harvest system. This in turn affected the energy balance and associated hydrologic components. Leaf and Brink (1972b) assumed that "the radiation balance in the center of the clearings could be represented by the balance computed for large open areas. Thus, the energy exchanges which produce intensive melt near sunlit margins compensate for reduced snowmelt near shaded margins."

Manipulating the snowpack and forest cover parameters in the calibrated model indicates that cutting small openings in mature subalpine forest results in increased snowmelt early in the melt season and diminished snowmelt later. Although patchcutting affected the timing of snowmelt, it apparently did not significantly change the duration of the snowmelt season. Under comparable conditions, snowmelt began a few days earlier in small openings on all aspects, but in both the natural forest and cutover areas, the last snow melted at about the same time. Because melt rates in openings were higher early in the snowmelt season, results indicated that peak streamflow would not be increased appreciably, if at all, under the assumed timber harvesting alternative. Figure 14 summarizes the predicted average change in snowmelt input resulting from this practice for the 1964-71 period of record at the high-elevation north-slope and the low-elevation south-slope locations.

Water yield.—In addition to redistributing the snowpack and accelerating snowmelt runoff, the assumed timber harvesting practice

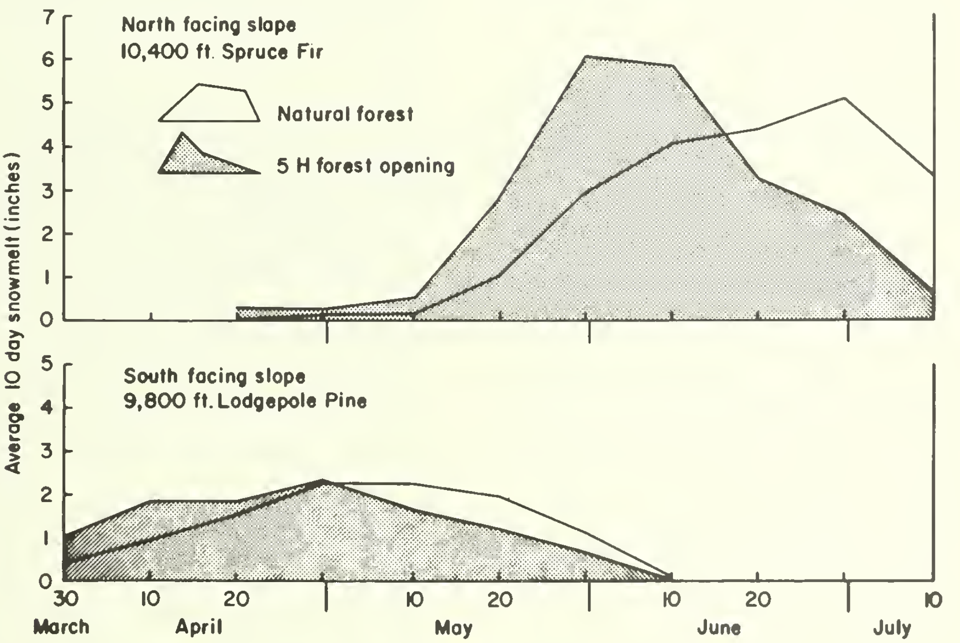


Figure 14.—Comparisons of simulated average snowmelt rates in five-tree-height openings with natural old-growth forest, 1964-71.

also affected evapotranspiration in several respects. During the snow accumulation and melt seasons, evaporation of intercepted snow was decreased in proportion to the amount of vegetation removed. However, evaporation from the snowpack in the small openings was higher, resulting in greater losses than from snow in uncut forest. Finally, evapotranspiration during the growing season was also reduced in proportion to the amount of forest cover removed. This reduced evapotranspiration resulted in lower recharge requirements over the basin. It should be emphasized that our simulation analyses failed to confirm the hypothesis that increased streamflow results from decreased interception loss. Higher evaporation losses from exposed snow surfaces in areas formerly under dense forest cover almost compensate for reduced interception losses. Thus, net input is increased less than 0.5 inch. This compares with more than 2 inches of additional streamflow resulting from the timber harvest. The combined action of redistribution and reduced evapotranspiration is the primary cause for increased water yields from subalpine forests. As Hoover and Leaf (1967) have pointed out, concentrating snowpack in openings where recharge requirements are least results in more efficient delivery of snowmelt runoff from the system.

Simulated data for 1947-71 water years (table 3) were averaged; results for this period are plotted in figure 15. (Note that, with the exception of snowpack water equivalent, all hydrologic components are plotted as 6-day means.)

The simulated average runoff increase for the 1947-71 record period, 2.1 inches, resulted from a 2.1-inch decrease in evapotranspiration losses, with no change in storage. Average recharge requirements in the fall were decreased by 1 inch. As discussed above, snowmelt timing and resultant streamflow were also changed. Figure 15(c) shows that generated runoff was increased during April, May, and the first part of June, and diminished somewhat thereafter. Because the generated flows are routed through natural storage in the watershed to produce the hydrograph, it is reasonable to expect that the recession limb of the seasonal hydrograph would not be significantly changed due to treatment. However, stream discharges would be higher on the rising limb, as observed from the Fool Creek and Wagon Wheel Gap watershed experiments (see figs. 9 and 10).

It is worth noting here that the assumption regarding the onset of transpiration, when the snowpack is melted down to 5 inches of water equivalent, accounts for the difference between the change in growing-season evapotranspiration and the change in fall recharge requirement (-1.7 inches versus -1.0 inch in table 3).

The results above refer to hydrologic changes for an entire watershed. Because hydrologic regimes of subunits within even small

Table 3.--Simulated hydrologic changes (water balance, in inches) resulting from patchcut timber harvesting, Fraser Experimental Forest (Average of 1947-71 water years)

Component	SUBALPINE FOREST (1,687-acre composite of 3 experimental watersheds)			LODGEPOLE PINE FOREST (Low elevation, south slope)			SPRUCE-FIR FOREST (High elevation, north slope)		
	Natural	Treated[1]	Change	Natural	Treated	Change	Natural	Treated	Change
					Inches				
Precipitation	30.6	30.6	0	23.5	23.5	0	30.2	30.2	0
Evapotranspiration:									
Canopy	2.0	1.0	-1.0	1.7	.8	-.9	2.2	1.1	-1.1
Snow surface	2.9	3.5	+.6	1.2	1.5	+.3	2.1	2.5	+.5
Growing season	11.6	9.9	-1.7	14.8	12.9	-1.9	9.9	8.5	-1.4
Total	16.5	14.4	-2.1	17.7	15.2	-2.5	14.2	12.1	-2.1
Recharge requirements:									
Beginning (Oct. 1)	3.4	2.4	-1.0	4.3	2.9	-1.4	3.1	2.3	-.8
End (Sept. 30)	3.4	2.4	-1.0	4.3	2.9	-1.4	3.1	2.3	-.8
Water yield	14.1	16.2	+2.1	5.7	8.2	+2.5	15.7	17.8	+2.1

[1]Figures in this column represent weighted values for both forested and nonforested areas.

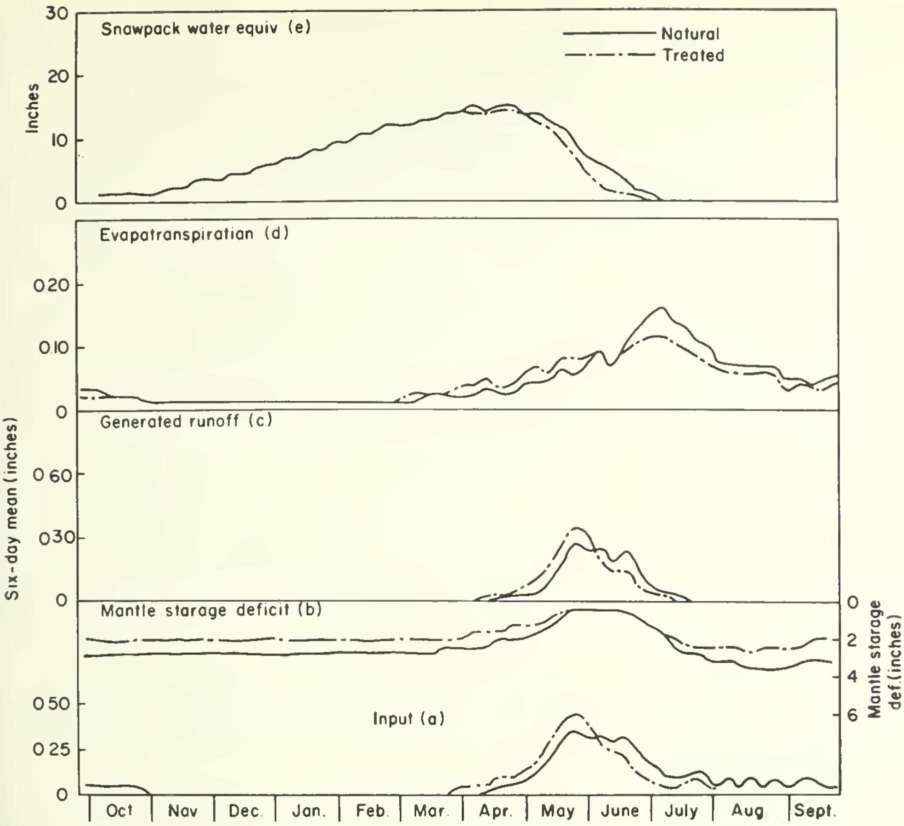


Figure 15.—Simulated average water balance for the 1947-71 water years, showing changes resulting from cutting small openings in old-growth subalpine forest (1,687-acre composite of three experimental watersheds).

forested watersheds can vary by several orders of magnitude (Leaf 1971), similar analyses were made on each subunit. Results from the low-elevation south slopes (9,000 ft) and high-elevation north slopes (10,200 ft) are also summarized in table 3.

First, it is significant that, in their natural states, the low south slopes are less than half as efficient as high north slopes in producing streamflow (24 percent versus 52 percent). At first thought, it would appear that potentials for water-yield improvement are highest in the spruce-fir forests where precipitation is greater (30.2 inches on north-slope spruce-fir versus 23.5 inches on south-slope lodgepole pine) and consumptive use is least (9.9 inches versus 14.8 inches). Apparently this is not the case, however. As seen in table 3, the changes produced in each hydrologic component are apparently the same order of magnitude on all aspects when timber is cut in small patches. Thus, the increment of increased water yield is approximately uniform over the entire basin. This result has important management implications. It implies that there is no reason to favor those areas with the highest natural water yields if the objective is to maximize streamflow from medium- to high-density stands of old-growth pine and spruce-fir.

Selection Cutting

Table 4 summarizes predicted hydrologic changes when the canopy cover density is uniformly reduced 50 percent on the entire watershed. (It was assumed that this option corresponds to removal of at least 40 percent of the timber volume.) A comparison of tables 3 and 4 shows that patchcutting apparently increases water yields considerably more than does individual-tree selection cutting—2.1 inches against 0.4 inch. In the selection-cutting option, evapotranspiration during the growing season is decreased only 0.4 inch compared to 1.7 inches for patchcutting. Moreover, fall recharge requirements are decreased by only 0.3 inch compared to 1.0 inch. Overall, the effect on snowmelt timing in the latter case is not large. Snowmelt can be accelerated or delayed when the forest canopy is reduced, depending upon aspect; however, in no case is the change in timing as large as with patchcutting.

Predicted hydrologic changes resulting from a 50 percent forest cover density reduction on north-and south-slope subunits are also summarized in table 4. In contrast to patchcutting, the selection-cut option apparently can have both postive and negative water yield effects, depending on aspect and vegetation type.

Table 4.--Simulated hydrologic changes (water balance, in inches) resulting from selection cutting, Fraser Experimental Forest (Average of 1947-71 water years)

Component	SUBALPINE FOREST (1,687-acre composite of 3 experimental watersheds)			LODGEPOLE PINE FOREST (Low elevation, south slope)			SPRUCE-FIR FOREST (High elevation, north slope)		
	Natural	Treated	Change	Natural	Treated	Change	Natural	Treated	Change
	Inches								
Precipitation	30.6	30.6	0	28.6	28.6	0	32.3	32.3	0
Evapotranspiration:									
Canopy	2.0	1.1	-.3	2.1	1.1	-1.0	2.2	1.7	-.5
Snow surface	2.9	3.8	+.9	2.1	2.8	+.7	2.4	3.7	+1.3
Growing season	11.6	11.2	-.4	14.5	14.0	-.5	9.5	9.2	-.3
Total	16.5	16.1	-.4	18.8	18.0	-.8	14.2	14.6	+.5
Recharge requirements:									
Beginning (Oct. 1)	3.4	3.1	-.3	4.1	3.9	-.2	2.8	2.4	-.4
End (Sept. 30)	3.4	3.1	-.3	4.1	3.9	-.2	2.8	2.4	-.4
Water yield	14.1	14.5	+.4	9.8	10.6	+.8	18.1	17.6	-.5

On south slopes in lodgepole pine, water yields are increased almost an inch, whereas on north slopes in spruce-fir, yields are apparently decreased as much as 0.5 inch. This decrease is primarily due to higher snowpack evaporation losses. At the higher elevations on north aspects, the longer melt season results in a 1.3-inch higher evaporation loss from snow surface compared to an 0.7-inch increase on south slopes. Reduced interception losses apparently compensate for less than half of the increased snow evaporation on north slopes, whereas on south slopes, reduced interception and increased snow evaporation are the same order of magnitude.

The simulated basinwide effects of cover density reduction are summarized according to aspect and forest cover type in table 5. It is significant that uniform canopy reduction results in less water yield in all of the response units in spruce-fir forest, whereas water yields are increased somewhat in all but two of the subunits in lodgepole pine.

Reliability of Results from Simulation Model

Most of the research in subalpine watershed management has been concerned with natural conditions or with the effects of complete removal of the forest cover. Very few studies have been made to determine the hydrologic impacts of individual-tree selection cutting. Accordingly, results obtained from the patchcutting options in the model should be considered as the most reliable. The energy and water balances of partially opened stands must be studied further before results from the

Table 5.--Simulated water yield changes resulting from a 50 percent forest cover density reduction according to aspect and forest type

Subunit and aspect	Forest cover type	Percent of area	Water-yield change
			Inches
[1]1 --SSE	Lodgepole pine	6.5	+0.8
2 --NNE	Lodgepole pine	2.4	+.3
3 --N	Spruce-fir	2.4	-.9
4 --SE	Lodgepole pine	6.9	+.5
[1]5 --NE	Spruce-fir	5.8	-.5
6 --ESE	Lodgepole pine	10.5	+.8
7 --SSE	Lodgepole pine	7.0	+1.1
8 --SSE	Lodgepole pine	9.2	+1.6
9 --NNW	Lodgepole pine	7.6	+1.0
10 --NW	Spruce-fir	7.6	-.4
11 --NNW	Spruce-fir	4.2	-.1
12 --N	Spruce-fir	4.2	-.1
13 --NNE	Lodgepole pine	12.6	-.4
14 --NE	Lodgepole pine	2.1	+.6
15 --NE	Lodgepole pine	2.1	-.2
16 --Natural open areas		8.9	0
Total for 1,687-acre composite[2]		100.0	+.4

[1]Hydrologic changes in subunits 1 and 5 are summarized in table 4.

[2]See table 4.

selection-cut options in the model can be verified. Nevertheless, selection cutting in the spruce-fir on northerly aspects may not significantly increase water yields at best; water yields may actually be decreased. In the lodgepole pine type, the model predicts that water yields can be increased provided that selection cuts are made on southerly aspects and at low elevations where the snowmelt season is short and begins relatively early in the spring. On a watershed basis, increased water yields from selectively cutting about 40 percent of the timber volume are far less than the increases generated when the same volume is removed by patchcutting. Rich (1965) observed similar results when he studied the effects of selection cutting and clearcutting in Arizona mixed conifer watersheds. Rich found that a commercial timber harvest on an individual-tree selection basis did not significantly increase water yields, whereas a moist-site clearcut increased streamflow by 46 percent.

Silviculture

It should be emphasized that the timber harvesting measures recommended for water-yield improvement are silviculturally sound and compatible with the guidelines recently developed by Alexander (1972, 1973, 1974b) for partial cutting in old-growth lodgepole pine and spruce-fir. This type of management would preserve the natural landscape by maintaining continuous forest cover in areas of high recreational value. In developing the guidelines, Alexander carefully considered: (1) stand conditions, (2) windfall risk, and (3) insects and diseases. Specific management alternatives are also recommended for integrating water and timber production which would include cutting options proposed by Alexander in combination with small cleared openings to favor increased water yields.

Weather Modification

Weather modification technology in the Rocky Mountain subalpine zone has evolved to the point where pilot projects are being started to increase water yields. One of the largest of these is the "Colorado River Basin Pilot Project," sponsored by the Division of Atmospheric Water Resources, Bureau of Reclamation.

Effects of cloud seeding have been evaluated in several ways. The most widely used approach has been statistical detection of snow accumulation and runoff increases, and much has been done in recent years to improve the power of the more classical statistical tests (Morel-Seytoux 1972).

Because there is considerable public concern for the ecologic and hydrologic consequences of weather modification, it is important to understand not only how much water yields will be increased, but also how hydrologic systems will be affected. Kahan et al. (1969) were quick to emphasize that systems modeling can play a creased snow accumulation on water-balance interactions. Accordingly, we have made preliminary studies with the Subalpine Water Balance Model to quantify the hydrologic effects of successful weather modification. These studies were based on an assumed 15 percent increase in winter snowfall between November 30 and March 31. In this case, the increased snow accumulation: (1) had little effect on evapotranspiration and soil water storage; and (2) did not extend the duration of the melt season more than 3 to 5 days. Approximately 90 percent of the increased snowpack produced streamflow. Typical results from the 15-percent-increase analyses are summarized in table 6 and figure 16. An average 2.4 inches of increased water equivalent for 1947-71 on a 667-acre subalpine watershed in central Colorado produced an average 2.2 inches of additional water yield, with a 0.2-inch increase in evapotranspiration and a negligible effect on soil-water storage. Because water-yield benefits result from the last snowmelt at a given location, the bulk of the increased runoff is released during and just after peak streamflow. This would have a tendency to broaden the snowmelt hydrograph and possibly increase peak flows (fig. 17).

The simulation model has also given some indication as to the combined effect of successful weather modification and vegetation management practices. Under this alternative, comparisons were made between the natural water balance and the resulting balance from manipulating the calibrated model to simultaneously account for: (1) patchcutting the watershed so that 40 percent of the area was in openings five tree-heights in diameter; and (2) increasing the winter snow accumulation by 15 percent. The combined effect of snowpack increase and timber harvesting (table 6) was to increase the average annual water yield from 16 percent when the snowpack was increased under no-harvest conditions to 32 percent when coupled with the simulated timber harvesting practice. Although patchcutting accelerated snowmelt, the 15 percent increase in snowpack delayed the melt process somewhat, which resulted in an insignificant change in the duration

Table 6.--Simulated hydrologic changes resulting (1) from a 15 percent snowpack increase and (2) from combined snowpack increase and timber harvesting on Deadhorse Creek, Fraser Experimental Forest (Average of 1947-71 water years)

Component	15 percent snowpack increase			Combined snowpack increase and timber harvesting		
	Natural	Treated	Change	Natural	Treated	Change
	- - - - - - - - - - *Inches* - - - - - - - - - - - -					
Precipitation	30.6	33.0	+2.4	30.6	33.0	+2.4
Evapotranspiration	16.8	17.0	+.2	16.8	14.8	-2.0
Recharge requirements:						
Beginning (Oct. 1)	3.5	3.5	0	3.5	2.4	-1.1
End (Sept. 30)	3.5	3.5	0	3.5	2.4	-1.1
Water yield	13.8	16.0	+2.2	13.8	18.2	+4.4

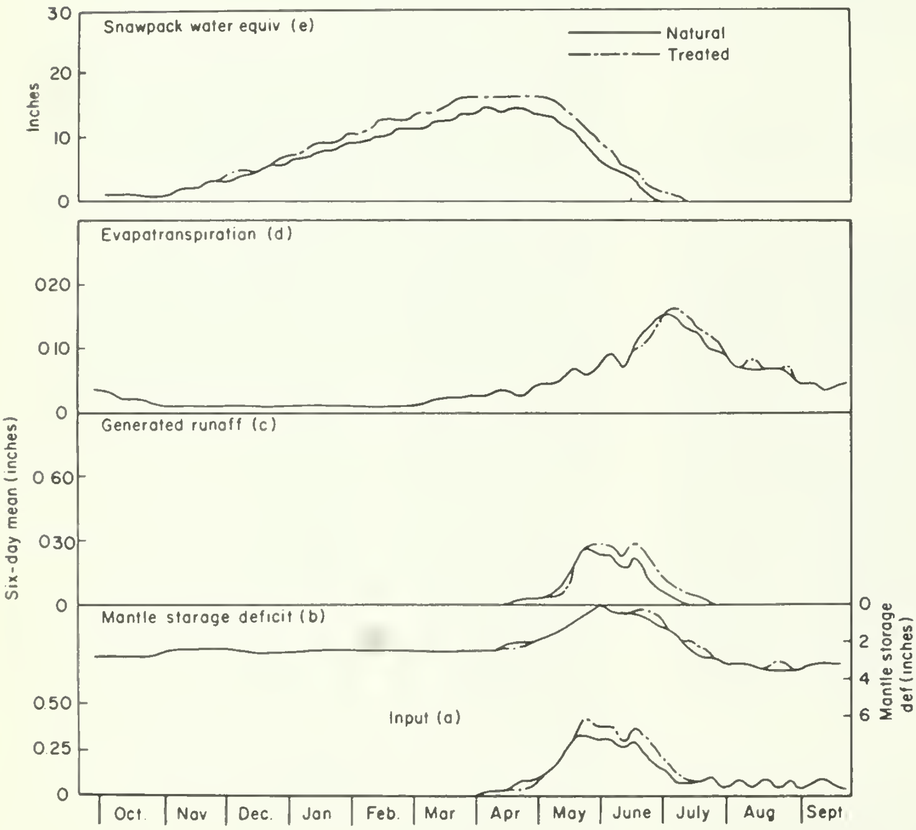


Figure 16.—Simulated average water balance for the 1947-71 water years, showing changes resulting from a 15 percent increase in winter snow accumulation on Deadhorse Creek, Fraser Experimental Forest.

of the snowmelt season. Evapotranspiration was increased from February until mid-June, but diminished thereafter with a net reduction of approximately 2 inches. Virtually all of the decreased recharge requirement of approximately 1 inch resulted from the effects of timber harvesting.

Our simulation analyses of the hydrologic effects of weather modification support recent results from field studies of tree growth and herbage production in the subalpine zone. Frank (1973) observed that a 10 percent increase in peak snowpack due to cloud seeding has "little, if any, immediate effect on the productivity and

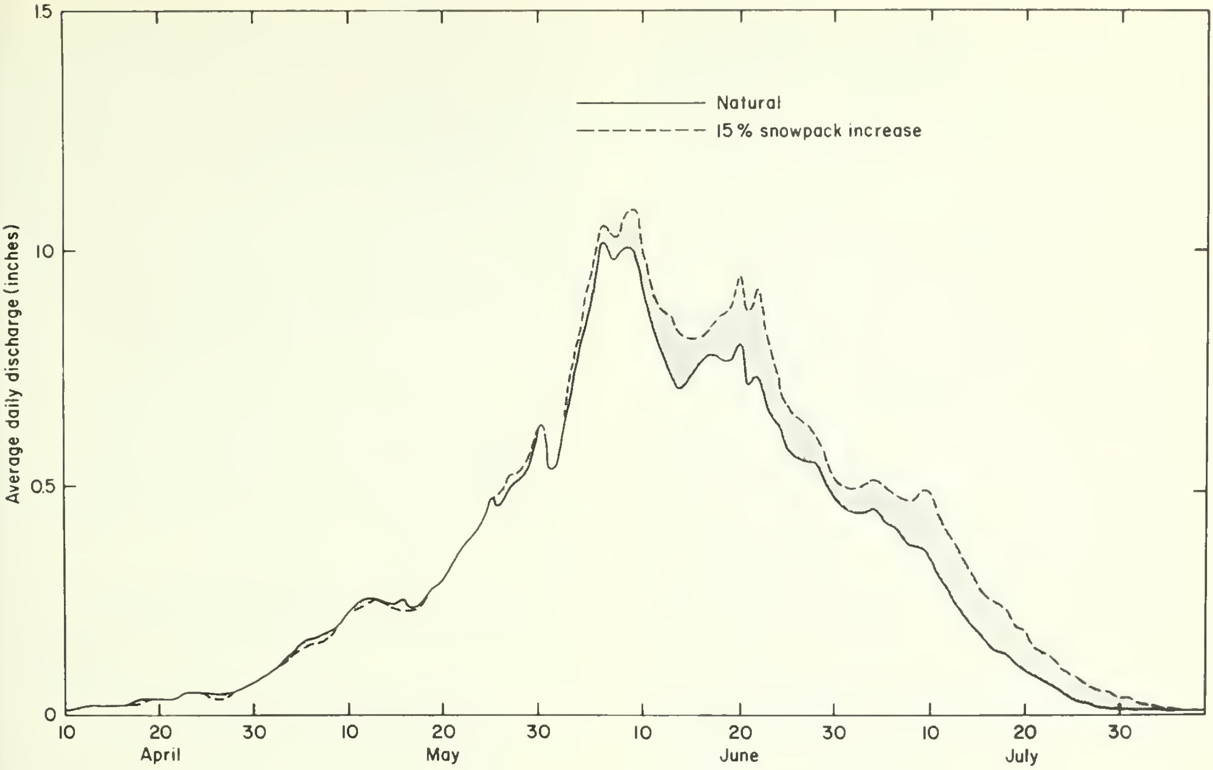


Figure 17.—Simulated hydrographs showing the average effect of a 15 percent snowpack increase on quantity and timing of streamflow for 1967-71 on Soda Creek near Steamboat Springs, Colorado.

use of mountain grasslands." Gary (1974) analyzed Engelmann spruce tree rings and snow accumulation in the Sangre de Cristo Mountains. He found that "increased snowfall will have little detrimental effect on the annual or long-term radial growth of the existing forest stands." Finally, studies of snow-cover depletion by Haeffner and Leaf (1973) have provided information on dates of final melt (last snow patches) on Bureau of Reclamation cloud-seeding project areas. Snow-cover data obtained during wet and dry years revealed that the time required to reach a given percentage of snow cover in late spring is more dependent on the magnitude of the snowpack during low runoff years than during high years. Thus, winter snow accumulation higher than normal does not delay disappearance of the last snow.

Long-term Simulation: Subalpine Land Use Model

The Subalpine Water Balance Model discussed above was designed to predict the short-term effects of timber harvesting on snowmelt and water yield. The model has recently been expanded to determine the long-term interactions between the water and timber resources with respect to partial cutting and regeneration practices in old-growth subalpine forest (Leaf and Brink 1975). This system (Subalpine Land Use Model) utilizes output from Subalpine Water Balance Model (see fig. 13).

The analytical framework of the Land Use Model is based on a "planning unit" which is defined by environmental characteristics including combinations of slope, aspect, elevation, and the species, form, and structure of the forest cover. The model is designed to simulate the hydrologic effects of timber harvesting in order to develop management strategies for planning intervals which can vary from a few years to the rotation age of subalpine forests (120 years and longer).

Because climatological observations are rarely available for the long periods of time simulated, the system has the capability to extend a sample data base by a randomized selection of water years until the desired planning interval is completed. Management strategies may subdivide a given planning unit into as many as eight distinct areas or "response units," which may be managed independently at varying points in time during the planning interval. Provision is also made so that different cutting practices may be imposed on the response units, and finally, any number of cuttings may be made on a given response unit at specified years during the planning interval.

Figure 18 shows how the Subalpine Water Balance Model is used in executing alternative management strategies. Hydrologic integrity is maintained as management strategies are formulated, since all interactions between the various response units are accounted for in time and space. The interactive effects of a new decision on ones previously implemented are simulated, as are the effects of time, as demonstrated through reforestation. Moreover, the overall hydrologic effects resulting from each management decision on the planning unit are projected to the end of the planning interval as though it were the final decision in the strategy. Thus, the singular effects of each decision can be evaluated.

The Land Use Model utilizes output from the Subalpine Water Balance Model, which simulates the water balance on a daily basis. On those areas where forest cover has been removed, the parameters which define soil water availability, forest cover density, reflectivity, interception, and snow distribution are adjusted on an annual basis by means of time-trend relationships. The procedure used in formulating each time-trend relationship was to: (1) establish plateaus, and maximum and minimum values for each hydrologic variable; (2) establish critical times at which a transition begins to occur; and (3) assume a functional relationship which determines all intermediate values.

Due to our lack of understanding of long-term hydrologic phenomena, the time-trend equations are not 'right' in any intrinsic or mathematical way. They should be considered only as relationships which represent our best estimates of how the most significant processes vary over a long period of time. We believe the time-trend relationships are plausible; however, additional research is needed before more accurate equations can be developed.

Application of simulation model.—The Subalpine Land Use Model has been used to simulate the long-term effects of a hypothetical forest and watershed management strategy on Wolf Creek, in southwestern Colorado. The planning unit selected for this example has a northwesterly aspect and an average elevation of 10,000 ft m.s.l. The average slope is 15 percent, and forest cover is spruce-fir.

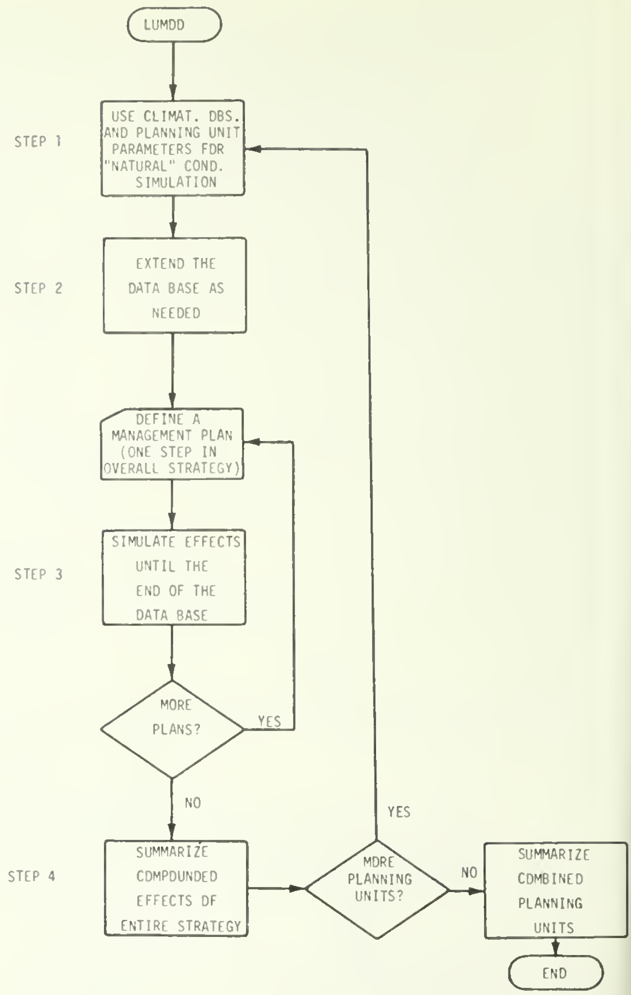


Figure 18.—Flow chart showing how Subalpine Water Balance core model is used to execute alternative management strategies.

In addition to improving water yield, the management strategy selected for this example essentially has followed recommendations by Alexander (1973), which are keyed to stand descriptions, insect and disease problems, and windfall risk situations. Under this strategy, all of the old-growth timber would be harvested in a series of patchcuts spread over a planning interval of 90 years. At intervals of 30 years, approximately one-third of the area would be harvested in small openings—five to eight times tree height—distributed over the watershed. Forest openings would be constructed in a balanced and unified pattern so as to minimize visual impact on the natural landscape.

At the end of the planning interval, all of the openings would have regenerated and the watershed would contain groups of trees in several age classes from reproduction to larger trees on the originally cutover areas. The management strategy would maintain a forest cover throughout the planning interval, and would insure regeneration of the stand from small trees on the cutover area, and from a seed source provided by mature trees surrounding the forest openings.

Projected average annual water-yield increases in 10-year increments under this management strategy for the 90-year planning interval are tabulated in table 7. The increases above the line through the data represent the overall response at any given time resulting from preceding management decisions. The data below the line reflect the singular effect of the initial patchcut on one-third of the planning unit, assuming that it was the final decision in the strategy.

Table 7.--Projected changes in water yield resulting from timber harvesting, Wolf Creek planning unit, San Juan National Forest, Colorado

Interval (Years)	Water yield increase after patchcut treatment-- I	II	III
	- - - - *Inches/year* - - - -		
0 - 10	+2.1		
11 - 20	+1.4		
21 - 30	+1.8		
31 - 40	+.72	+2.9	
41 - 50	+.34	+2.9	
51 - 60	+.11	+1.8	
61 - 70	+.19		+3.4
71 - 80	-.06		+2.1
81 - 90	+.23		+2.7

Water yields would be improved throughout the planning interval. Projected runoff increases during each treatment interval are as follows:

Treatment	Runoff increase (Percent)
I	6.8
II	9.4
III	10.1

The effect of the initial patchcut (Treatment I) would apparently persist for at least 50, and perhaps 60 or more years. Thereafter, the effect on water yield, for all practical purposes, would be negligible.

Simulation models as planning tools.—Research has shown that any management decision which leads to timber harvesting will have an impact on the water resource. Furthermore, any decision in the subalpine environment is, for all practical purposes, "for keeps." Hence, the cut-and-try approach in resource management is simply no longer acceptable. We need rational conceptual models to evaluate watershed management strategies. The comprehensive simulation models described in this report represent our first step in providing the practicing hydrologist and land manager with planning tools that utilize our best technical knowledge of fundamental hydrologic processes. One additional favorable aspect of the models is that they are no more complex than required to provide necessary information. Moreover, application of the models is not unduly restricted by data requirements. We believe that, for the most part, basic hydrologic data currently available in the Rocky Mountain region are adequate for operational use. The hydrologic impacts of the watershed management practices discussed above are but a few examples of numerous alternatives that have been simulated. The models have been tested and calibrated on several representative drainage basins in Colorado (Fraser River, Arapaho National Forest; Wolf Creek, San Juan National Forest; Trinchera Creek, Sangre de Cristo Mountains) and Wyoming (South Tongue River, Bighorn National Forest; East Fork of the Encampment River, Medicine Bow National Forest).

Erosion and Water Quality

Sediment Yield

Forest management requires roads. Unfortunately, some roads have been located too close to streams, built on too steep grades, and inadequately drained. A few obviously bad examples of road construction in the subalpine zone have caused many influential laymen to conclude that "roads are detrimental to soil stability, streamflow quality, and fisheries; that roads have adverse effects on big-game populations; and, finally, that roads are ugly" (Wyoming Forest Study Team 1971). However, several studies of the effects of careful logging and road construction on erosion and water quality indicate that this need not be the case. Research has shown that watershed erosion and damage to water quality from road construction and timber harvesting can be significantly reduced through proper planning, construction, and followup maintenance (Packer and Laycock 1969, Megahan 1972).

For example, Leaf (1970) showed that, on Fool Creek in central Colorado, road construction resulted in minimum erosion damage with apparently no reduction in water quality. The 3.3 miles of main access road were carefully located to avoid the stream channel and to minimize erosion. Timber was made accessible by an additional 8.8 miles of spur roads laid out along contours. Spur roads were provided with surface drainage and culverts at stream crossings. In 1957, after logging was completed, spurs were seeded to grass, and culverts were removed on alternate roads to reduce traffic. Routine followup maintenance is still done on the main haul road.

Sediment yield during road construction and following extensive logging on the Fool Creek watershed averaged about 200 pounds per acre, compared with an average 88 pounds per acre for this period of record (table 8). Yield decreased rapidly after 1958, despite the persistent increase in runoff caused by the harvest. Since 1958, annual sediment yield from Fool Creek has averaged 43 pounds per acre, compared with yields of from 11 to 21 pounds per acre from the undisturbed watersheds. Suspended sediment was less than 5 parts per million (p/m) during high flow periods in 1964 and 1965.

Again, these results indicated that "sediment yield need not be excessive after harvest cutting on small forested watersheds in central Colorado, provided that reasonable erosion control measures are applied during logging and road construction. Sediment yields are relatively high in the years during and immediately following these activities, but decrease rapidly in subsequent years toward preharvest levels" (Leaf 1970).

Table 8.--Annual sediment yields (pounds per acre) on Fool Creek watershed since harvest cutting and road construction (Leaf 1970)

Year	Sediment yields on--		
	Fool Creek (714 acres)	Deadhorse Creek (667 acres)	Lexen Creek (306 acres)
	Pounds/acre		
1952	[1]204		
1953	102		
1954	[2]Negligible		
1955	[2]Negligible	20	
1956	[2]166	84	32
1957	318	111	56
1958	194	10	66
1959	39	24	12
1960	63	24	11
1961	28	5	2
1962	74	62	28
1963	Negligible	4	1
1964	Negligible	7	9
1965	113	35	18
1966	25	4	7
Average	88	32	22

[1]Road construction.
[2]Timber harvest.

Sediment yield simulation model.—One of the more significant results from sediment yield studies in mountain watersheds is that most of the erosion impact is concentrated within a few years after disturbance (Leaf 1970, Megahan 1974). This time factor should not be overlooked in land use planning from both the standpoint of protection and the long-term effects on hydrologic parameters such as water quality.

Equations that require erodibility indices based on rainfall intensity may be grossly in error when applied to much of the subalpine zone, where much of the sediment yield can result from melting snow. Accordingly, a simulation model based on equations developed by Megahan (1974) was developed to predict the impacts of secondary logging road construction on erosion and sediment yields (Leaf 1974).

The primary equation in the model is a negative exponential function with a linear component containing three parameters. This equation describes the time trends in erosion and sediment yield discussed above. Numerical values of the parameters were determined, using the data summarized in table 8.

The time-trend equation is used in combination with another expression which computes the area disturbed by road construction. This equation is formulated in terms of the following watershed and engineering design parameters: (1) width of roadbed; (2) average watershed side slope; (3) number of miles of road system; and (4) angle of cut and fill. It assumes balanced cut and fill (that is, that the centerline bisects the road width). Although this is not usually the case, since the cross section can vary from total cut to total fill in actual practice, it is assumed that a sufficiently accurate index of the total area disturbed can be obtained by estimating an "effective" width and average cut and fill slope for the proposed road system. Such estimates require considerable judgment and knowledge of the topography.

Three additional assumptions were made to develop the model for predicting erosion and sediment yields:

- The model provides a better index of erosion than equations based on rainfall-derived erodibility indices. Such indices do not predict time trends, and furthermore, do not account for the effects of snowmelt.
- Onsite erosion is proportional to the area disturbed.
- The delivery ratio is constant for a given watershed size, regardless of the amount of area disturbed.

These assumptions involve complex interactions between the hydrology, geology, and soils, which need to be verified by additional study.

Because the model is formulated in terms of engineering design variables, its use should provide an indication of the probable erosion impacts of alternative road systems. The coefficients were developed from a limited amount of data obtained from a carefully constructed road system and a high standard of followup maintenance; hence, they may not be generally applicable throughout the Rocky Mountain region. They should be considered as tentative estimates until more data become available. Any application of the model should presume similar standards of construction and maintenance. The model is a subroutine of the Subalpine Land Use Model developed by Leaf and Brink (1975).

Sediment yields from subalpine ranges.—Frank[7] computed annual sediment yields from the Black Mesa watersheds in Colorado by integrating suspended sediment discharge during the runoff period. Suspended-sediment yields averaged 53 to 91 pounds per acre of herbaceous type on three watersheds. Suspected sources of sediment included the stream channels, gopher activity, and bare soil areas. All sources apparently contributed to the total load. Because these areas occupied only a small proportion of each watershed, Frank was unable to define the significance of the bare soil areas subjected to grazing by cattle "when the small sediment yield could be accounted for by a few specific areas where soil is readily available and probably removed by overland flow."

Chemical and Bacterial Water Quality

With the exception of those areas where geothermal activity and geologic conditions have mineralized the water, natural flows from the subalpine zone are as "pure as the driven snow" in comparison to low-lying areas. In general, concentrations of all the chemical components are low. The pH values are near neutral, and water temperatures are cold (0° to 7°C). Kunkle and Meiman (1967) determined the chemical composition of water in the Little South Fork of the Cache la Poudre River in Colorado; Stottlemyer (1968) and Frank[8] made similar analyses on several small watersheds at the Fraser Experimental Forest (table 9).

Effects of timber harvesting.—Research in temperate climates has shown that timber harvesting usually causes increased loss of plant

[7]*Frank, Ernest C. Hydrology of Black Mesa watersheds. (Manuscript in preparation at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

[8]*Personal communication with Ernest C. Frank, Hydrologist, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

Table 9.--Average chemical composition (in parts per million) of selected high-elevation Colorado streams

Watershed	Ca	Mg	Na	K	CO_2	HCO_3	Cℓ	PO_4	SO_4	NO_3	SiO_2
Cache la Poudre:											
Little South Fork											
1965 (Kunkle and Meiman 1967)	2.7	6.5	1.0	0.5	1.6	18.9	5.0		14.6	0.8	
Fraser Experimental Forest:											
Deadhorse and Lexen Creeks											
1965 (Stottlemyer 1968)	6.9	3.1	1.5	.6							
1971 (Frank, personal comm.)	14.5	6.0	4.5	1.0			3.0		10.0	1.0	8.0
Fool Creek											
1965 (Stottlemyer 1968)	2.1	1.1	2.0	.5							
East St. Louis Creek											
1965 (Stottlemyer 1968)	1.8	.8	1.4	.4							

nutrients. Pierce et al. (1972) reported that clearcutting a watershed in New Hampshire increased nitrate, calcium, magnesium, potassium, and sodium losses severalfold. However, little is presently known about water quality changes resulting from timber harvesting in the relatively dry, cool subalpine climate. A recent comparison of the quantity and composition of streamflow from Fool Creek and East St. Louis Creek watersheds in central Colorado has provided at least some indication of effects of timber harvesting on chemical water quality. Stottlemyer and Ralston (1968) computed the following average annual losses of cations from the two watersheds:

	Cation concentration (p/m)	Cation outflow (lb/acre)
E. St. Louis Creek	4.5	22.9
Fool Creek	6.3	28.1
Difference	+1.8	+5.2

These data are based on samples taken twice each week during a 10-week period in the summer of 1965. Unit cation outflow from Fool Creek was 5.2 pounds per acre higher than from East St. Louis. Frank[8] suggests that this small difference may not accurately reflect water quality changes 10 years after Fool Creek was logged, however, since 1965 was a high snow year. He points out that normal or deficient annual runoff might show higher differences in concentration and outflow, depending on the relative change in timing and volume of discharge.

Bacterial water quality.—Kunkle and Meiman (1967) studied bacterial water quality on the Little South Fork of the Cache la Poudre River, which they said may be considered to be representative of the subalpine zone. Many subalpine watersheds support domestic livestock and big-game through the summer months and are heavily used for recreation.

Bacterial counts were made in 1964 and 1965. In 1964, Kunkle and Meiman found an extremely wide range of total bacterial counts, which varied from several million colonies per ml down to less than 10,000 colonies per 100 ml. They observed a "strong, positive bacteria to flow relationship." High bacterial concentrations associated with grazing and recreation appeared to depend on the "flushing effect" of flooding during peak snowmelt and summer storm runoff periods. Also, they observed that the "broad seasonal trend for the coliform, fecal coliform (FC), and fecal streptococcus (FS) bacterial groups was similar: (1) low winter counts prevailed while the water was 0° C; (2) high concentrations appeared during the peak flows of June; (3) a 'post-flush' lull in counts took place as the hydrograph declined in midsummer; (4) high concentrations were found again in the late summer period of warmer temperature and low flows; and (5) counts declined with the arrival of autumn." Kunkle and Meiman also observed low bacterial concentrations in winter. Bacterial concentrations varied widely at all sampling sites. Coliforms fluctuated from zero to about 300 colonies per ml, depending on the site and season. FC and FS fluctuated less, from zero to 75 colonies per 100 ml. At the high-elevation sites, FC and FS counts were near zero, and coliform counts were less than 40.

It should be noted that very little, if any, information is available on the effects of timber harvesting on the bio-active components of water quality. In all probability, any changes in bacterial concentrations resulting from harvest cutting are considerably less than those brought about by other forms of increased human activity such as housing, mining, and recreation developments.

Conclusions

At the outset, this report addressed itself to the question: "To what extent are we able to recommend forest management practices to improve water yield and still maintain acceptable quality, quantity, and timing?" The following paragraphs highlight technical aspects of the status of our knowledge in watershed management, and summarize principles that are important for efficient multiple use management of the subalpine zone.

- Patchcutting subalpine forests results in significant redistribution of the winter snowpack. Snow accumulation patterns are optimum when openings are: (1) less than eight tree heights in diameter; (2) protected from wind; and (3) interspersed so that they are five to eight tree heights apart. Because more snow is deposited in the openings, and less snow accumulates in the uncut forest, total snow storage on headwater basins is not significantly increased.
- On all aspects, snowmelt in clearcut openings is more rapid than in the uncut forest. This accelerated melt causes streamflow to be higher on the rising limb of the hydrograph than before harvest cutting. Where

there is considerable natural regulation in the form of deep porous soils, recession flows are not changed appreciably and annual flood peaks are not significantly increased, **provided that** the forest cover on no more than 50 percent of the watershed is removed in a system of small openings.

- In central Colorado, when 40 percent of the 1- to 3-mi^2 subalpine watershed is occupied by small openings, and 60 percent is left uncut, annual water yields are increased at least 2 inches. Interception loss is decreased, but increased evaporation from snow surfaces in the openings almost compensates for the decreased interception loss so that total input is increased less than half an inch. Average recharge requirements on the basin are decreased by about 1 inch and evapotranspiration during the growing season is decreased by more than 1.5 inches. Simulation analyses indicate that, under this alternative, water-yield increases on low-elevation south aspects in lodgepole pine forest are as large as corresponding increases from high-elevation north aspects in spruce-fir. Hence, there is no reason to favor areas having the highest natural water yield if the objective is to maximize water yields from medium to dense old-growth forest.
- Due to the considerable length of time it takes for coniferous subalpine forests to grow to maturity, increased water yields from patchcutting can go essentially undiminished for perhaps 20 years and longer. It is conceivable that 30 additional years will be required before runoff increases from the initial timber harvest are completely erased.
- The **pattern** in which trees are harvested determines whether or not runoff will be increased. Streamflow increases are greatest when subalpine forests are harvested in a system of small forest openings. Simulation analyses indicate that when the forest is harvested in large clearcut blocks, or by selectively cutting individual trees, overall water-yield increases are far less than those attained if the same amount of timber volume is removed by patchcutting. When the canopy density is reduced 50 percent by selective cutting in spruce-fir forests on northerly aspects, water yields may actually be decreased. In lodgepole pine forest, water yields can be increased somewhat by selection cutting, provided that cuts are made on southerly aspects and at low elevations where the snowmelt season is short and begins relatively early in the spring.
- The timber harvesting measures recommended for maximum water yields are silviculturally sound and compatible with the guidelines recently developed from research in old-growth lodgepole pine and spruce-fir. Patchcutting would enhance wildlife habitat, and preserve the natural landscape by maintaining a high forest cover in areas where recreation and esthetics are important.
- Timber harvest measures recommended for maximum water yields should not be detrimental to water quality or excessively increase erosion, **provided that** timber harvesting is executed with proper planning, engineering, construction, and followup maintenance. Sediment yields can be relatively high immediately following road construction, but should decrease rapidly toward preharvest levels. Several studies in the Rocky Mountain and Intermountain regions document this time-trend pattern, even though soils and geology vary over a wide range of conditions. These conclusions apply only to **surface erosion,** and not to **mass erosion,** which can occur after disturbance of very steep and naturally unstable slopes.
- Results from the Subalpine Water Balance Model indicated that, in central Colorado, a 15-percent increase in snow accumulation through successful weather modification will increase water yields 16 percent in the average year. Weather modification apparently will not extend the snowmelt season more than 3 to 5 days, and apparently does not significantly affect evapotranspiration. Because water-yield benefits result from the last snowmelt at a given location, the bulk of the increased runoff is released during and just after peak streamflow. This would have a tendency to broaden the snowmelt hydrograph and possibly increase peak flows in small headwater streams. Successful augmentation of natural snowfall in combination with vegetation management practices will significantly increase water yields. In central Colorado, if 40 percent of a watershed were harvested in small patches five tree heights in diameter, water-yield increases could be doubled if the natural snowpack were also increased by 15 percent.
- Dynamic simulation models have been developed from the best information we presently have about subalpine hydrologic systems. The models have been calibrated, using data from representative watersheds in old-growth lodgepole pine and spruce-fir forests throughout the Rocky Mountain region. They have been designed to predict the short- and long-term hydrologic impacts of a broad array of watershed management practices. Hydrologic changes can be determined for intervals of time from a few years

to the rotation age of subalpine forests (120 years and longer). These predictions are based on time-trend functions which compute changes in evapotranspiration, soil water availability, forest cover density, reflectivity, interception, and snow redistribution after timber harvesting. These models produce the type of information hydrologists and land use planners need to make difficult management decisions. The ability of the models described here and other similar models to integrate complex forest and water systems makes them unique and powerful tools for evaluating the hydrologic effects of a broad array of land management alternatives.

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Watershed management in the subalpine zone of Wyoming, Colorado, and New Mexico is described. Forest hydrology is briefly discussed, followed by an in-depth discussion and review of (1) field studies of the effects of watershed management practices on snow accumulation, melt, and subsequent runoff; and (2) simulation models designed to predict the hydrologic impacts of timber harvesting and weather modification. Pertinent literature is included, along with unpublished research, observations, and experience. Research needs are highlighted, and guidelines for implementing watershed management principles in land use planning are summarized.
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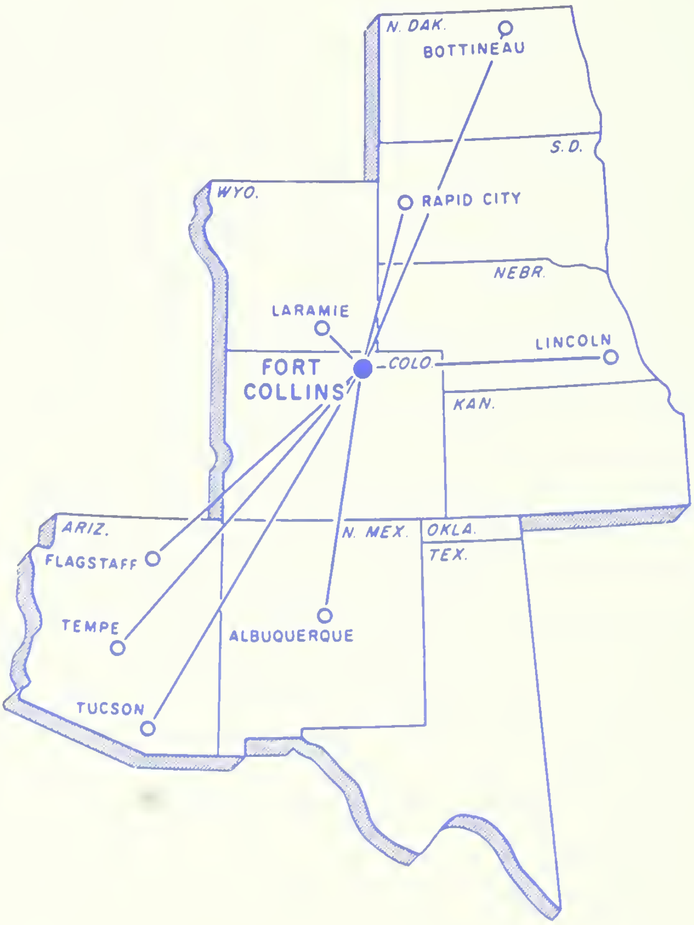
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WATER-YIELD IMPROVEMENT FROM ALPINE AREAS: The Status of Our Knowledge

M. Martinelli, Jr.

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Abstract

Snowpack management can be an effective means of improving water yields from the already productive alpine type. Due to wind and rugged terrain, the alpine snowpack is characterized by deep snowfields and bare spots. Because snow accumulates in the lee of terrain breaks or other obstacles that provide wind protection, fences upwind of natural accumulation areas effectively trap additional snow. Snowfences can also control blowing and drifting snow on highways and in avalanche-prone areas. Factors that influence the efficiency of snowfences are: (1) height, (2) density and length of fence, (3) bottom gap, (4) length and maximum depth of lee drift, (5) cumulative effect of a set of tandem fences, (6) vertical alinement, (7) terrain effects, and (8) contributing distance.

Keywords: Alpine zone, water yield, snowfences, snowpack.

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March 1975

WATER-YIELD IMPROVEMENT FROM ALPINE AREAS:
The Status of Our Knowledge

M. Martinelli, Jr., Principal Meteorologist

Rocky Mountain Forest and Range Experiment Station[1]

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

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WATER-YIELD IMPROVEMENT FROM ALPINE AREAS:
The Status of Our Knowledge

M. Martinelli, Jr.

Introduction

The demand for water in semiarid areas has always exceeded the readily available supply. This problem tends to become critical in local areas during periods of rapid population growth and expanding economy. The intricate system of reservoirs, canals, and water diversions started in the mountains of western United States during the late 1800's and greatly expanded in the 1930's and early 1940's is an engineering approach to this problem. Another approach is to manage the primary water-producing areas in a way that will enhance streamflow. As part of its national effort to improve yields from wildlands, the research branch of the USDA Forest Service decided to explore the possibilities of improving water yields from alpine areas in the Rocky Mountains. This Paper gives some of the background and summarizes the results from a series of studies carried out in the Colorado Rocky Mountains from 1955 to 1972.

The Rocky Mountain Alpine Zone

Definition and Land Forms

The "alpine zone" is that part of the mountains above the natural limit of erect tree growth. In the Rockies, tree line varies from about 10,000 ft in northern Wyoming to about 12,000 ft in southern Colorado and northern New Mexico. These elevations will vary considerably with local exposures. Land forms vary from broad, gently sloping ridge crests and plateaus to steep-sided rocky peaks and horns, depending primarily on the bedrock geology and the glacial history of the area (fig. 1). Glaciation has been extensive and patterned ground, mass soil movement, and soil frost features are prevalent (Johnson and Billings 1962).

Weather

Weather is often severe in the alpine zone (Judson 1965, Marr 1967). Winds are strong and

Figure 1.—General view of an alpine area in the Front Range of Colorado in late June. Some of the snowfields are in the lee of low trees or in nivation hollows. Others are in the lee of the main ridge crest.

persistent on the ridge crests and summits in all seasons. Summer temperatures seldom reach 70°F, and are usually in the 60°'s F. The thin atmosphere filters out little of the solar radiation and ultraviolet, so clear days have a high radiation input and present serious sunburn problems, especially when there is a fresh snow cover. Winter temperatures are cold with subzero (F) days fairly common in January and February. The alpine, however, does not experience the severe cold (−40 to −50° F) found beneath the inversion layer in high mountain valleys on clear, wind-free winter nights. The combination of cold temperatures and moderate to strong winds develop high wind-chill factors. Over three-fourths of the annual precipitation is in the form of snow. The winds move the snow from exposed places and pile it in deep drifts in all wind-sheltered spots. There is seldom any appreciable winter melt in the alpine, so the snow accumulates all winter and melts in late spring or early summer. Summer rains may be intense, but they seldom persist for long. Graupel (soft hail) and snow can be expected from many summer storms.

Vegetation

Vegetation is predominately grasses, sedges, and a wide variety of forbs and lichen. Tree species are confined to dwarf willow (*Salix* spp.) in the wet spots and to spruce (*Picea engelmannii*), fir (*Abies lasiocarpa*), and on occasion limber (*Pinus flexilis*) or bristlecone pine (*P. aristata*) on the drier sites. Coniferous trees characteristically occur in clumps or islands and are stunted, malformed, and trimmed to streamlined shapes by the wind and blowing snow. The European term **Krummholz** is often used to refer to such trees. The intricate vegetation patterns in alpine areas probably reflect local soil-moisture differences as much as anything. High-elevation westerly exposures tend to be cold deserts, since the winds keep them snow-free all winter and the summer rains quickly percolate through the porous soil or are evaporated by the wind. Plant cover on such sites is mostly prostrate and cushion-type forbs and lichen. Terrain depressions, especially on lee slopes, accumulate blowing snow and are sheltered from the drying winds. Shallow depressions are often boggy areas that typically support willow thickets. Places where deeper snowdrifts develop have such a short growing season that they usually have no more than a sparse cover of snow-tolerant forbs and many are devoid of all vegetation. For more information on alpine vegetation, see Griggs (1956), Paulsen (1960), Marr (1961), Johnson and Billings (1962), and Lewis (1970). Retzer (1962) gives a good discussion of alpine soils for a location in central Colorado.

Streamflow

Runoff data from alpine areas is scarce because there are few gaging stations, and opinions as to the amount of runoff vary considerably. Matthes (1934), for example, said after observing the sun-pitted snowfields at high elevations in the Sierra Nevada and on Mount Rainier that, "these snowfields waste away in the summer because of evaporation and contribute nothing to the streams in the valleys below." Schwan and Costello (1951), on the other hand, state, "the 3.5 percent of the surface area of Colorado in the alpine type accounts for more than 20 percent of all streamflow in the State." Other evidence comes from Lawrence's (1953) study of the Crystal River at Marble, Colorado. This basin, with over 60 percent of its area in alpine or high-elevation meadows or rock slopes, has an average annual runoff of 44 inches with wet years giving 54 inches. Unpublished data from Middle Fork Creek in Alberta[2] showed average annual runoff from this alpine basin to be 23 inches for a 6-year period with a maximum of 27 inches. On the average, streamflow from high-elevation basins peaks in early summer with about 85 percent of the annual flow between May 1 and July 31, and less than 5 percent between December 1 and March 31.

Extent

The extent of alpine type in Colorado, Wyoming, and Utah is not known exactly. Schwan and Costello (1951) estimate there are about 5 million acres in Colorado and Wyoming—about equally divided between the two States—and Lewis (1970) estimates one-fourth million acres in the Uinta Mountains of Utah. Rogers and Braun (1967) say Colorado alone has almost 4.5 million acres. A rough check on U.S. Army Map Service 1-to-240,000 scale maps gave about 1.9 million acres of alpine type in Colorado. Although the exact area of alpine type is not known, it appears to be appreciable. Hence, if techniques could be worked out for increasing the water yield from this already very productive zone, the benefits would certainly be worthwhile.

[2]Personal correspondence in 1972 with R.D. Mays, District Engineer, Inland Waters Directorate, Water Survey of Canada, Environment Canada, Calgary, Alberta.

Basic Approach to the Problem

Snowpack management is the key to water-yield improvement in most areas where snowmelt is the major source of streamflow. This is especially true in the alpine zone where grasses and grasslike species are the only significant vegetation. The possibilities of manipulating the vegetation to improve water yields—a common practice in forested areas (Leaf 1975)—is simply not practical in alpine areas.

Field observations under winter and summer conditions emphasized the importance of wind transport and deposition of snow in the high-elevation sites. The winds pick up snow from exposed places and deposit it in the lee of terrain breaks or other obstacles that provide a wind shadow. As a result, the alpine snow cover is made up of a mixture of deep snowfields and bare spots interspersed in a rather shallow general snow cover. The size and shape of the snowfields vary with the size, shape, and orientation of the barrier behind which they form. The snowfields form in the same places each year and many persist until late summer.

These observations suggested that one promising technique for improving water yields would be to use snowfences upwind of natural snowfields to increase the amount of snow held in these areas until late summer. By locating the fences so the snow they trapped piles on top of that in the natural drift, some of the deeper snowfields could be extended and others could be deepened. This increase in the amount of snow held in deep, high-elevation drifts that persist until autumn should increase the late-summer streamflow from the basin. The additional snow trapped by the fences would normally blow to lower elevation where it melts during early summer—a time of abundant streamflow. Thus, the fences, when used as outlined above, would be expected to change the timing of streamflow and not necessarily to increase total annual water yields.

Experimental Work

Early Studies and Results

An early study (Martinelli 1956) confirmed the idea that drainages with more late-lying snowfields had more late-summer streamflow than nearby drainages with fewer late-lying snowfields (table 1).

Another study (Martinelli 1965a) compared the streamflow from three drainages on the east side of the Front Range in Colorado and confirmed the importance of the alpine zone as a water producer. Both annual and July-August streamflow increased with an increase in the percentage of the total basin in alpine type (fig. 2). The water-yield potential[3] from the alpine snowfields in these drainages varied from 95 percent of total summer flow in one stream with 62 percent of its drainage basin in alpine type to 59 percent for another with only half as much alpine.

Characteristics of the alpine snowfields were studied under summer and winter conditions for several years. **Summer data** showed early summer snow depths of more than 20 ft (table 2) in the larger snowfields and snow densities of 500 to 600 KgM^{-3}. Higher densities were noted

[3]*Water yield potential was computed from weekly ablation measurements assuming a linear decrease in snow area with time, snow density of 500 KgM^{-3} and zero losses to evaporation, evapotranspiration, and ground water storage.*

Table 1.--Comparison of two drainage basins and their summer streamflow (Martinelli 1956, p. 112-116)

Item	Glacier Creek	Middle Boulder Creek
DRAINAGE CHARACTERISTICS:		
Area above 8,300 ft elevation (mi^2)	25.2	35.5
Maximum elevation on western border of watershed (ft)	14,255	12,500
Most distant point in watershed (mi)	6.75	9.5
Amount of snow, Sept. 30, 1953 (acres/mi^2)	2.5	0.83
STREAMFLOW (percent of annual):		
July 1953	20	20
August 1953	15	8
September 1953	5	2

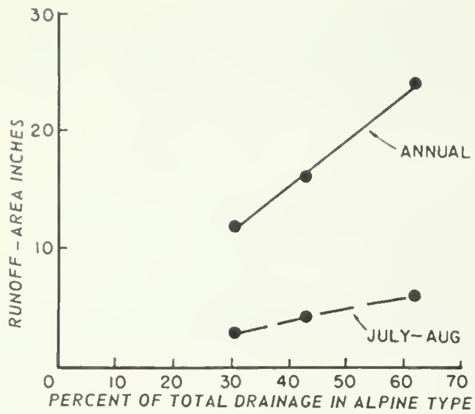


Figure 2.—Area-inches of runoff as a function of the proportion of total drainage area in alpine type in a portion of the Front Range of Colorado (Martinelli 1965a).

Table 2.--Summary of important features of the snowfields studied (Martinelli 1959)

Snowfield, aspect, and elevation	First observation: Date	Maximum snow depth	Area
		ft	*Acres*
Mount Evans			
E-- 12,500 ft	June 23, 1955	19.5	3.3
	July 3, 1956	16.7	2.3
	July 3, 1957	--	4.5
	June 26, 1958	--	2.8
Science Lodge			
S-- 11,500 ft	July 1, 1955	21.8	8.6
	June 30, 1956	16.7	8.5
Trail Ridge No. 1			
NE--12,000 ft	July 3, 1955	8.0	.5
Trail Ridge No. 2			
N-- 11,700	July 4, 1955	[1]21.5	3.8
Corona			
N-- 11,500	July 19, 1955	[1]18.8	2.6

during periods of heavy summer rain when meltwater could occasionally be seen flowing over the snow surface for short distances. Free water content in the top 1 ft (30 cm) at midday in August varied from 6 to 11 percent, depending on elevation and aspect of the site. Ablation varied from 1 to 2.8 ft (30-85 cm) of snow per week and averaged 1.9 ft (58 cm) per week for 1955 and 1956 (table 3).

The onset of ablation varies from year to year with variations in spring weather conditions, and the size of the fields varies with winter snow

Table 3.--Average ablation in inches of snow per week for several aspects and elevations, 10 to 80 readings per field (Martinelli 1959)

Month and year	12,500 ft-- E	11,500 ft-- S	11,500 ft-- N	11,700 ft-- N	12,000 ft--NE
	Ablation by elevation and aspect				
			Inches		
July					
1955	21.6	27.6	[1]28.8	26.4	28.8
1956	18.1	24.0	--	--	--
1957	19.3	--	--	--	--
1958	22.8	--	--	--	--
August					
1955	20.5	28.8	24.0	24.0	--
1956	16.9	25.2	--	--	--
1957	16.9	24.0	--	--	--
1958	[2]24.0	--	--	--	--
September					
1955	[2]16.9	--	[2]18.1	[2]15.7	--
1956	[2]16.9	[2]22.8	--	--	--

[1]Measured first 2 weeks of month only.
[2]Measured last 2 weeks of month only.

amounts. Once spring melt is firmly established, however, the reduction in snowfield area progresses at a remarkably uniform rate, regardless of the time of onset or the initial size of the field (fig. 3).

During the summer it was noticed that frozen ground extended out a short distance from the edge of the snowfields. The depth to the frozen layer increased with distance from the edge of the snow. At times melt water trapped above this frozen layer soaked the soil, giving a fluid mixture that occasionally produced miniature mudflows when disturbed. There was no doubt that the snow was producing considerable amounts of melt water. In some locations, the melt quickly disappeared into the coarse soil so there was little evidence of melt water a slight distance from the fields. Drilling crews working in a tunnel 1,600 ft below one study site reported (telephone conversation) water flowing through the tunnel roof at times that corresponded closely to the seasonal and diurnal production of melt water in the alpine snowfields above. No doubt this deep and rapid percolation of melt water contributed to the idea of heavy evaporation losses mentioned earlier.

It was also noticed that foreign material, such as soil or plant remains on the snow surface changed the melt (fig. 4). This suggested the possibility of altering the melt rate of alpine snowfields to meet management goals.

Winter observations at selected alpine sites helped confirm some of the early concepts. Weekly readings on a series of snow stakes gave

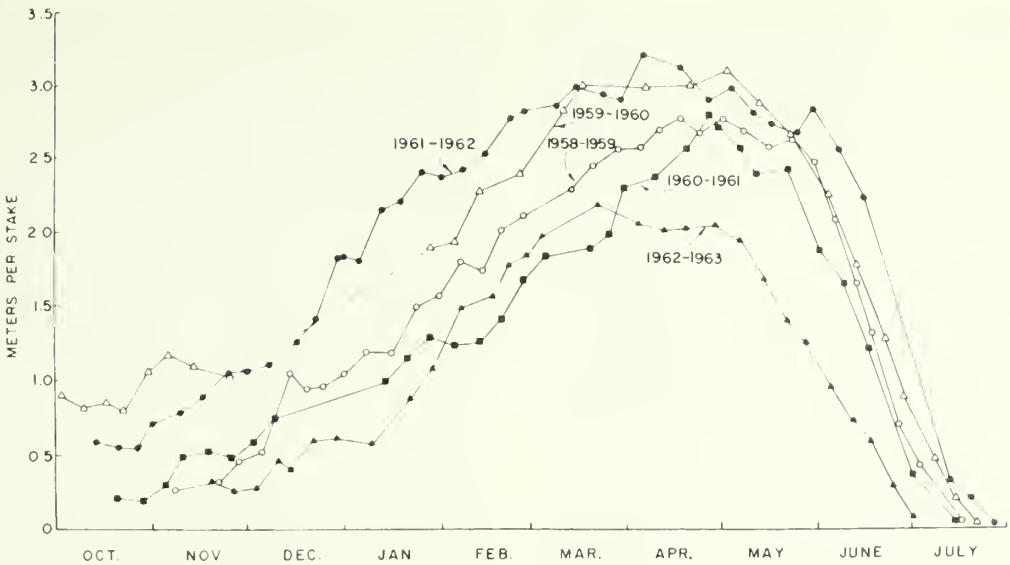


Figure 3.—Snow depths in the control area at Loveland Basin, Colorado, for 5 winters. Each point represents the average snow depth at 29 stakes (Martinelli 1965b).

information on how the alpine snowpack accumulated. The uneven depth of the pack was emphasized with some stakes seldom showing as much as 3 ft of snow, while others nearby would exceed 15 ft most years. The sequence of accumulation was also of interest. Snow accumulated first at the windward edge of the fields and built downwind rather than filling the deeper parts of the field as first casual speculation might suggest. The size and shape of the fields reflected the size and shape of the barrier behind which it formed, with the exception that very heavy or very light snow years made a difference in the size of the field. This indicated that there was insufficient blowing snow to fill some of the fields during dry years. Prior to this, it was generally felt there was enough blowing snow at most alpine sites to fill all but the largest catchments, even in relatively dry years.

Figure 4.—Soil and plant material, blown from the area in the background, accumulated in depressions in the snow. Subsequent melting lowered the surrounding snow cover more rapidly than that protected by the layers of soil, which now appear as soil-capped snow mounds.

The winter stake readings showed most of the seasonal accumulation took place in a relatively few events (table 4). Over a 5-year period, between 55 and 70 percent of the seasonal accumulation was deposited during the 5 weeks of heaviest drifting. Furthermore, between 30 and 40 percent of the seasonal accumulation took place in the 2 weeks of heaviest drifting. For 3 of the 5 years, the first major storm of the season was also the largest accumulation period of the winter. Weekly data are given because that is the way the data were taken and there was no good way to interpolate for shorter periods. In many cases, the weekly accumulation actually took place in a few days, so the true periods of heavy accumulation were even shorter than given here.

Attempts were made to develop snowdrift gages in order to learn more about the time,

Table 4.--Total snow accumulation on 29 control stakes at Loveland Basin, 12,000-ft elevation, for the five major drift periods each year, 1958-63 (Martinelli 1965b)

Major drift period	Accumulation
	ft
1958-59:	
December 5-14	[1]50.5
January 15-23	30.2
February 13-19	26.0
January 30-February 6	21.2
December 31-January 7	16.7
Total, five drift periods	144.6
Total, entire winter	267.42
	Percent of total
Five largest drift periods	54
Two largest drift periods	30
1959-60:	
September 27-October 2	87.0
February 4-13	32.8
October 22-30	24.5
February 24-March 11 (2-week period)	42.5
October 30-November 5	11.0
Total, five drift periods	197.8
Total, entire winter	286.44
	Percent of total
Five largest drift periods	69
Two largest drift periods	45
1960-61:	
December 9-23 (most between 19+23)	45.7
March 25-April 1	40.8
February 19-26	24.7
April 19-26	22.7
November 4-10	17.5
Total, five drift periods	151.4
Total, entire winter	253.45
	Percent of total
Five largest drift periods	60
Two largest drift periods	34
1961-62:	
January 5-12	46.7
September 15-22	43.8
December 22-29	39.6
March 29-April 5	28.0
February 15-23	23.5
Total, five drift periods	181.6
Total, entire winter	286.18
	Percent of total
Five largest drift periods	63
Two largest drift periods	32
1962-63:	
January 28-February 6	39.3
January 9-21	27.3
January 21-28	20.2
December 14-21	18.4
February 16-24	18.4
Total, five drift periods	123.6
Total, entire winter	196.44
	Percent of total
Five largest drift periods	63
Two largest drift periods	34

[1]Figures are total accumulation on 17 check stakes plus 12 stakes in field V. For this date, average accumulation would be 50.5/29=1.74 ft per stake.

duration, and intensity of drifting events. Several versions of storage-type drift gages were designed and tested, as well as one directional recording type. All had serious limitations and were inconvenient and awkward to use. The recording blowing snow gage recently developed by Tabler and Jairell (1971) is a mechanically improved unit that embodies several components of these earlier gages. There are basic problems, however, with all gages that trap blowing snow. It is generally agreed these problems can be avoided only by gages that measure the moving particles without trapping them. The snow particle counter developed in the Station's Alpine Snow and Avalanche Project (Schmidt and Sommerfeld 1969, Schmidt and Holub 1971, Schmidt 1971b) works on a light attenuation principle (Landon-Smith and Woodberry 1965, Sommerfeld and Businger 1965, Hollung and others 1966, Rogers and Sommerfeld 1968) that avoids all the problems associated with traps. It has been shown to be accurate and thoroughly field reliable.

Two other early studies involved field measurements of the rate of **evaporation** and **condensation** at a summer snow surface, and the change in melt rate caused by materials added to the snow. Plastic lysimeters were used to measure evaporation and condensation on a snowfield in North Boulder Creek (Martinelli 1960). There was a net gain of moisture on the snow surface during August one summer. The next July there was a net loss of about the same magnitude due to evaporation (table 5). In both cases, moisture exchange was between 2 and 3 percent of the daily melt. The average rate was +0.03 inch per day in August 1957 and −0.03 inch per day in July 1958. The difference was primarily due to weather conditions during the afternoons, since condensation dominated the nights and evaporation the mornings for both summers. Others (deQuervain 1952, West 1959, Hutchison 1966) have also confirmed this general order of magnitude for moisture exchange at a spring or summer snow surface.

The change in melt rate caused by materials added to the snow surface was studied for one summer (USDA FS 1956). Carbon black, soil, and gravel were added in thin layers to speed melt. Sawdust and soil in 3-inch layers were added to slow melt. After 19 days, the most effective treatments were the sawdust, which reduced melt 50 percent, and the carbon black, which increased it 10 percent. Only the sawdust treatment was statistically significant. The carbon black would have been more effective if it had been spread more evenly. Small patches of concentrated carbon black actually reduced melt rather than accelerated it. The small size (1 m × 1 m) and close spacing of the test plots also reduced treatment effect a bit toward the end of the experiment.

able 5.--Melt from an alpine snowfield and net moisture exchange between an alpine snow surface and the atmosphere (Martinelli 1960)

Date	Inches per day of water from-- Melt	Inches per day of water from-- Net moisture exchange	Days	Containers
			No.	*No.*
MALL CONTAINERS:				
957--				
July 30-Aug. 1	1.6394	0.0298	2.00	6
Aug. 6-8	2.2355	.0344	2.12	4
Aug. 13-15	1.2079	.0129	2.00	2
Aug. 21-23	1.8951	.0387	1.96	2
Aug. 28-29	1.0477	.0043	1.00	2
eighted average	1.6736	.0263		
958--				
July 9-18	1.5769	-.0268	8.71	3
ARGE CONTAINERS:				
957--				
Aug. 20-29	2.0798	.0535	8.96	1
Aug. 21-29	2.1163	.0420	8.29	1
eighted average	2.0973	.0480		
958--				
July 8-17	1.8336	-.0595	9.08	2

nowfences for Increasing ummer Streamflow

Since most of the above evidence confirmed he possibility of using fences to improve alpine vater yields, a series of fences were built to test he idea more directly. The first fences were common slat and wire fences, 8 to 12 ft tall, ocated upwind of five natural snowfields at an levation of 12,000 ft near Loveland Basin ski rea in Colorado. These were in a high alpine basin, 0.3 to 0.5 mile east and 500 to 600 ft below he Continental Divide. Later, four more fences vere built—three on major ridge crests and one n a windy, exposed lee slope with a gentle graient.

All fence work was based on the following ssumptions:

. In alpine areas, drifting snow accumulates to reat depths only in places that are protected rom the wind.
 Snow fills most terrain depressions before e end of winter. Once full, these areas are erodynamically smooth and trap little addional snow.
 There is no shortage of drift snow in alpine egions most years. Therefore, the depth of snow accumulations could be greatly increased if the capacity or the trapping efficiency of natural catchments could be increased.
4. There should be places in alpine regions where barriers of modest height (10 to 12 ft tall) could be combined with terrain features to increase greatly the trapping efficiency of the natural terrain.
5. If snow depths could be increased in areas where it is normally 3 to 5 m deep, the amount of snow available for summer streamflow would be increased substantially.
6. Fence effect can be measured on the basis of changes in the amount of snow in the catchment with and without the fence. Snow depths will be equated to "potential melt-water production."

As a supplement to the alpine fence studies, other snowfence experiments were started at a more accessible site on Pole Mountain, Wyoming, to test certain fence design features. The influence of gap size, new fence materials, and a "swinging panel" design on the size and location of the lee drift were studied at this grassy, windswept site. The swinging panel was an attempt to design a fence that would trap snow effectively at low to moderate windspeeds and would streamline itself during high winds to minimize structural damage. It was not very effective, so the idea was dropped. Several plastic cloth materials were tested to see how they compared to slat and wire fencing. While the cloth fences were lightweight, easy to handle, and worked well, the extra cost and the added installation and maintenance problems argued against them for many sites. Tests on the influence of gap size on the size and location of the lee drift were more productive (fig. 5). Relations were established (figs. 6, 7, 8) between gap size and the location and size of the lee drift (Martinelli 1964).

Other work at this test site (Tabler and Veal 1971) showed that windspeed reduction increased with fence height for fences 6 to 12 ft tall, but that the reduction per foot of height (windspeed reduction efficiency) was greatest for the 6-ft fence. Still other work at this site (Tabler 1968, 1971, 1973) has helped establish economic and physical criteria for designing systems of snowfences to serve a variety of needs in the alpine as well as in other vegetative types.

Results of Alpine Snowfence Studies

Fence Effect on Snow Accumulation

The long-term studies of snowfences at alpine sites showed fence effect varied greatly, even

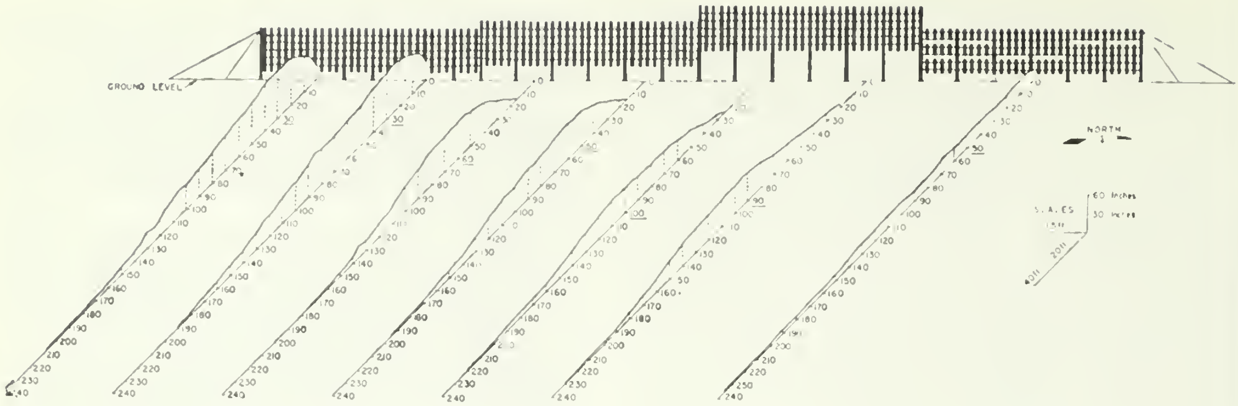


Figure 5.—Typical snowfence panel at Pole Mountain, Wyoming, at the end of the 1962-63 accumulation season. Snow depths along the profile lines are the average for four locations. The underlined figures along the probe lines mark the position of maximum snow depth. The right panel is a special design that swings open in high winds. Other panels are tests of bottom gap size. Note: There are three different scales in the diagram (Martinelli 1964).

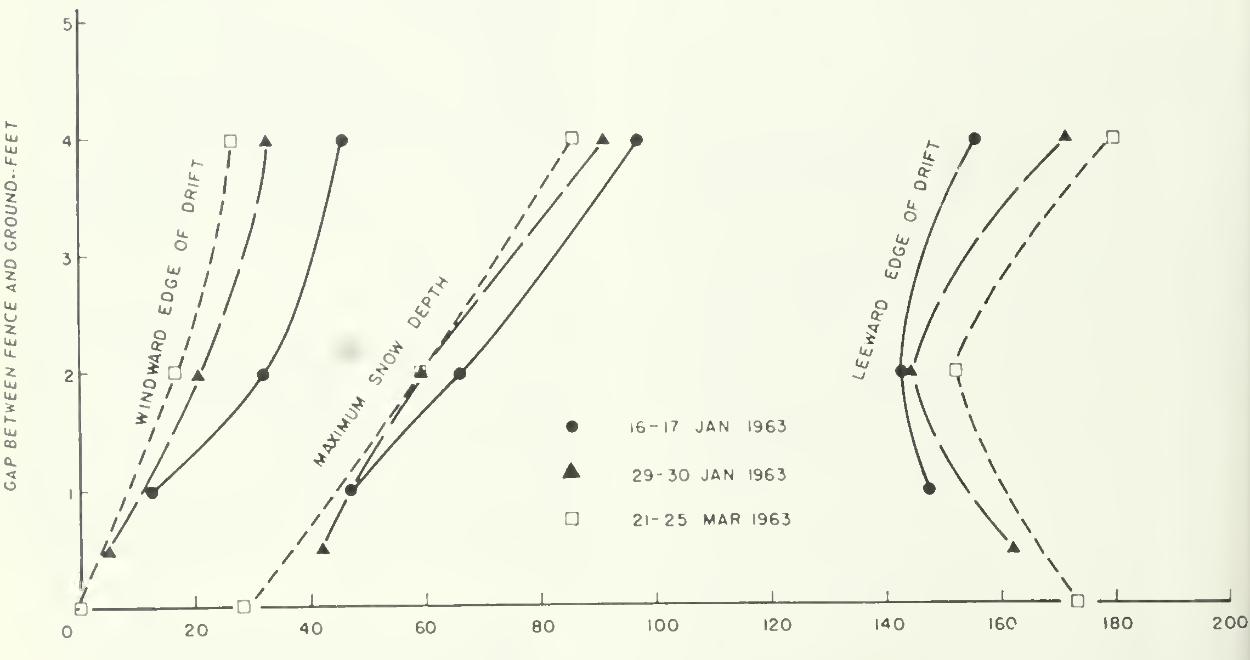


Figure 6.—Effect of size of gap on the snowdrift behind 6 ft of vertical slat snowfencing. Gap widths of 6 inches and 0 represent the gradual closing of the 1-ft gap. Points are the average of two values from each of four locations.

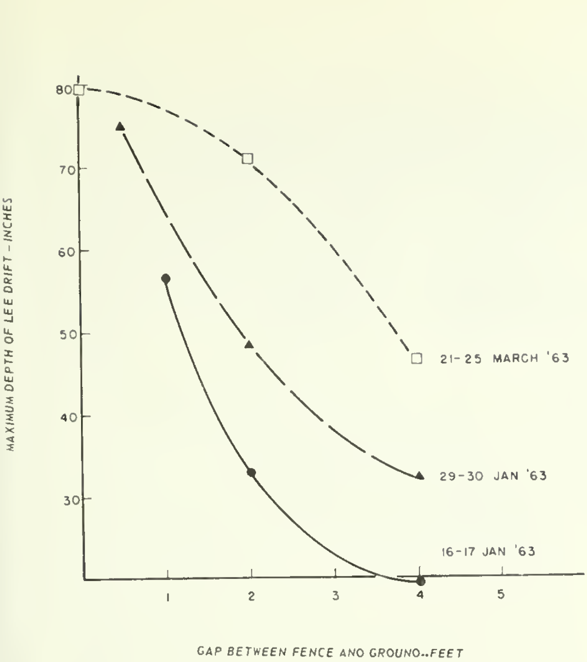


Figure 7.—Maximum snow depth in the drift behind 6 ft of slat snowfencing for various gap widths. Gap widths of 6 inches and 0 represent the gradual closing of the 1-ft gap. Points are the average of two values from each of four locations.

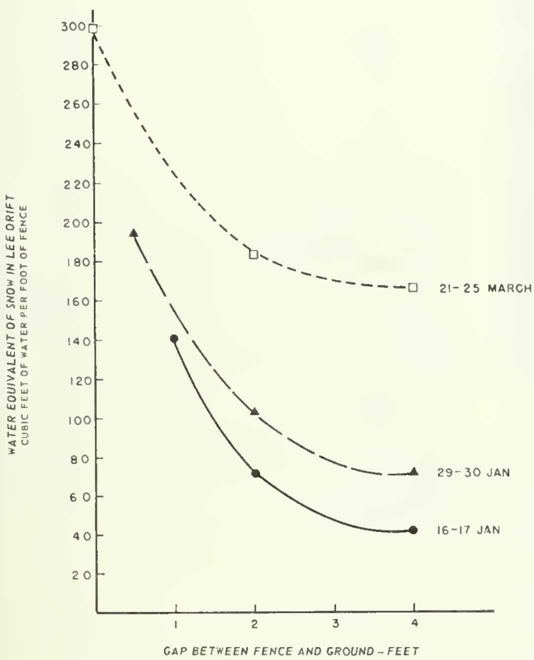


Figure 8.—Water equivalent in the drift behind 6 ft of slat snowfencing for various gap widths. Gap widths of 6 inches and 0 represent the gradual closing of the 1-ft gap. Points are the average of two values from each of four locations.

when sites were carefully selected. At three of nine study locations, fences increased the volume of late-lying snow and prolonged the melt season by several weeks. At one site, the increase in total snow accumulation was accompanied by a more rapid melt rate so that early summer runoff was increased but the melt season was not prolonged. At three more of the sites, snow depths were increased close behind the fences, but were decreased farther downwind with no net increase in the amount of snow, and at two sites the fences reduced the amount of snow caught (table 6).

At the best site, Straight Creek Pass (fig. 9), a fence 10 ft tall with a density of 42 percent and a bottom gap of 2 ft increased the total volume of snow at the start of the melt season by 1,500 ft^3 of snow per lineal foot of fence (ft^3/ft) and increased average depth by 6.5 ft. The snow behind the fence persisted about 3 weeks longer than normal (Martinelli 1973).

Maximum snow depths in the fence-induced lee drift exceeded the height of the fences (H) at most of the catchments. In general, depths varied from 0.8 to 1.5 H, but were as low as 0.5 to 0.7 H at Loveland Basin fields I and III. The deepest part of the positive fence effect was located 3 to 5 H downwind of the fence in most cases. The exceptions were Loveland Basin field II and Straight Creek, where the crests of the lee drifts were 8 to 11 H downwind of the fences.

At the better sites, 60 to 120 ft of fence was needed to produce an extra acre-foot of melt water potential at the start of the melt season. This is based on fences 10 to 12 ft tall, 40 percent fence density, bottom gaps of 2 tq 4 ft, and snow density in the lee drifts of 500 KgM^{-3} (Martinelli 1973). At such sites, the melt season was prolonged 1 to 3 weeks. In general, an extra 2 ft of snow depth on July 1 means an extra week added to the melt season.

Based on 10 years of field experience, we found that for our purposes **good fence** sites had:

1. Ridge crest locations with the deep part of the natural drift not more than 8 to 10 H to the lee.
2. Upslope or level windward approach to the fence.
3. Good orientation to prevailing drifting winds.
4. Upslope or level terrain to the lee of the accumulation area.
5. Plenty of contributing area (at least 500 ft).
6. Little natural accumulation upwind of the fence.
7. Northerly to northeasterly exposure (or terrain shadowing of any southerly exposed accumulations.)

Table 6.--Summary of changes in snow accumulation at natural snow accumulation sites after slat and wire snowfences were located at upwind edge of accumulation site

Site	Change in snow accumulation	Change in length of melt season	Change in amount of potential melt water
Straight Creek Pass	Increase	Increase (3 weeks)	Doubled
Mount Evans	Increase	Increase (1 week)	Doubled
Loveland Basin II	Increase	Increase (1-2 weeks)	Increase
Teller Mountain	Increase	No change	Increase
Loveland Basin I	No net change	No change	No change
Loveland Basin III	No net change	No change	No change
Loveland Basin VI	No net change	No change	No change
Loveland Basin IV	Decrease	Decrease (1-2 weeks)	Decrease
Glacier Mountain	Decrease	Decrease (1 week)	Decrease

Figure 9.—Straight Creek Pass snowfield, with a snowfence 10 ft high:

In February, with natural snow accumulation in foreground. Behind the fence, where person is standing, snow deposited by winds blowing from left to right is about 20 ft deep.

In August, the 6 to 7 ft of additional snow due to the fence is still obvious. Snow depth in left foreground is typical of the unfenced portion of this natural drift.

Poor sites had:

1. Downslope approach to the fence.
2. No natural catchment within 8 to 10 H of the logical fence location.
3. Upwind accumulation sites to rob snow or to throw a drift on the fence.
4. Variable wind direction during drifting.
5. Steep downslope exhaust zone that results in reverse windflow and erosion of the lee deposition.

Schmidt (1970) used pressure-gradient concepts to provide a rationale for relating fence and terrain effects to snow accumulation. He points out that the pressure gradient in the lower layers is considered zero for flow over a horizontal surface. However, local pressure gradients develop when air flows over irregular terrain or against natural or artificial barriers, such as trees or snowfences. A favorable pressure gradient exists when flow moves from high pressure to lower pressure; that is, air flowing uphill. An adverse pressure gradient exists when flow is from a lower toward a higher pressure; that is, air flowing downslope or against a barrier. When flow is along a favorable pressure gradient, velocity and shear stresses in the lower layers increase downwind and maximum shear stress is at the surface. When air flows against an adverse pressure gradient, velocity and shear stresses near the ground decrease and maximum shear stresses move up from ground level. Under extreme adverse pressure conditions, a reverse flow (rotor) develops. Since the carrying capacity of the wind is directly related to the shear stresses in the lower layers, when flow goes from a favorable to an adverse pressure gradient, velocities and shear stresses are reduced and snow tends to settle out of the airstream.

Examples of how the above concepts help explain total snow accumulation and maximum drift length observed in several terrain situations are given below (Schmidt 1970):

Case 1—A snow fence on a uniform windward slope.—The adverse pressure gradient associated with the fence is reduced by the favorable pressure gradient created by flow up the windward slope. Thus, the terrain gradient reduces both total drift accumulation and maximum drift length from those expected for a horizontal surface. Figure 10 shows that this is the case for the maximum drift length.

Case 2—A snowfence on a uniform leeward slope.—Here the adverse pressure gradient produced by the fence is added to the natural adverse pressure gradient. A larger fence effect should result in increased drift accumulation and maximum length compared to the horizontal case (fig. 10). For example, a fence 12 ft high with a 3-ft gap was located upwind of a depression in a long lee slope on Mt. Evans in Colorado. The resulting drift had a maximum length on the order of 30 times the fence height with a fairly uniform increase in depth (fig. 11a).

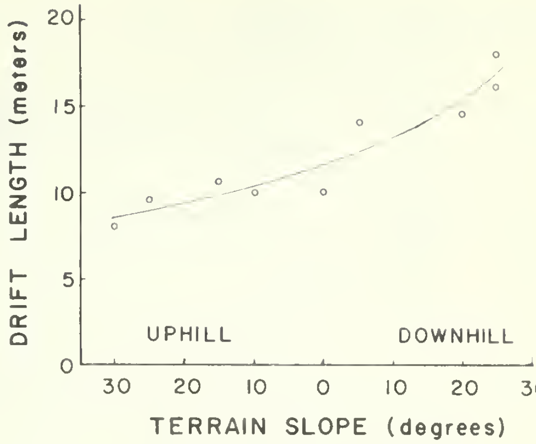


Figure 10.—Maximum drift length as a function of terrain slope (Schneider 1962).

One problem that arises from locating a fence in a natural adverse pressure region is that the fence becomes buried in the drift. This results in expensive maintenance unless the fence is designed to withstand snow settlement load.

Case 3—A snowfence located leeward from a rounded ridge crest.—The pressure gradient changes from favorable to adverse near the crest. The fence is located in an adverse pressure gradient, and the results depend on the strength of the natural adverse gradient. If the lee slope is gradual and flow does not separate, results should be similar to those of Case 2, where accumulation and length were increased and the fence became buried.

If the lee slope is steep and flow separates, the fence fixes the point of separation, and a cornice forms behind the fence. In this situation, velocities in the reverse flow are strong enough to transport snow. The drift is then shorter and contains less snow than expected for the same fence on a horizontal surface. Such a condition was

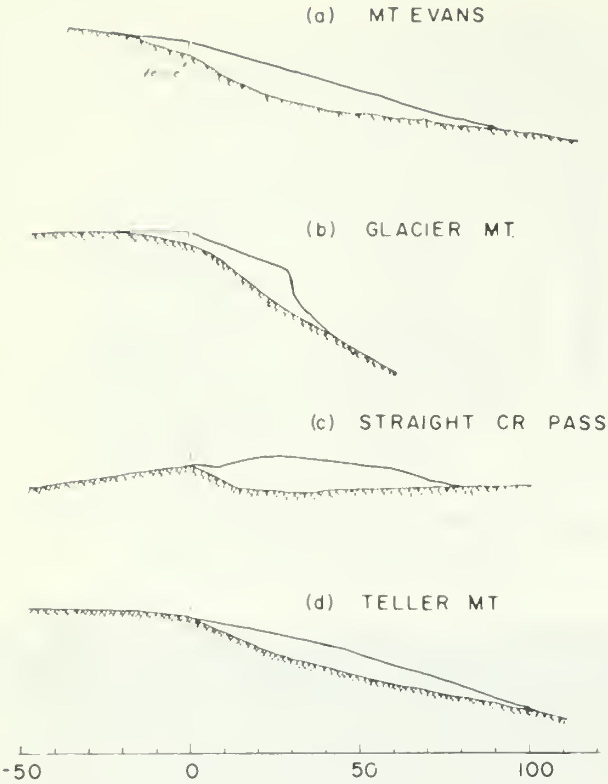


Figure 11.—Snowdrift cross sections on four irregular terrain situations, showing variations of total drift length and snow accumulation (horizontal and vertical scale equal): (a) Case 2—Mt. Evans, (b) Case 3—Glacier Mountain, (c) Case 4—Straight Creek Pass, (d) Case 5—Teller Mountain (Schmidt 1970).

examined at Glacier Mountain near Montezuma, Colorado (fig. 11b). The fence was 115ft (35m) lee of the crest and the lee slope was steep. Again the fence was buried in the drift in spite of the gap between fence and ground.

Case 4—A snowfence at a sharp ridge crest.—If a fence is located at the point where the pressure gradient changes from favorable to adverse, the fence effect is again increased by the natural adverse pressure gradient in the lee of the crest. As in Case 3, the resulting drift depends on the steepness of the lee slope; it is larger and longer if the slope is gradual, and smaller if the slope is steep enough to cause strong reverse flow. However, the favorable pressure gradient upwind of the fence maintains increasing surface shear stress, which causes snow erosion and leaves the fence free of the drift.

The drift cross section shown in figure 11c was measured at Straight Creek Pass on the Continental Divide in Colorado. The terrain depression lee of the crest filled in rapidly, and the lee slope was then gradual enough to allow a rather spectacular drift to develop.

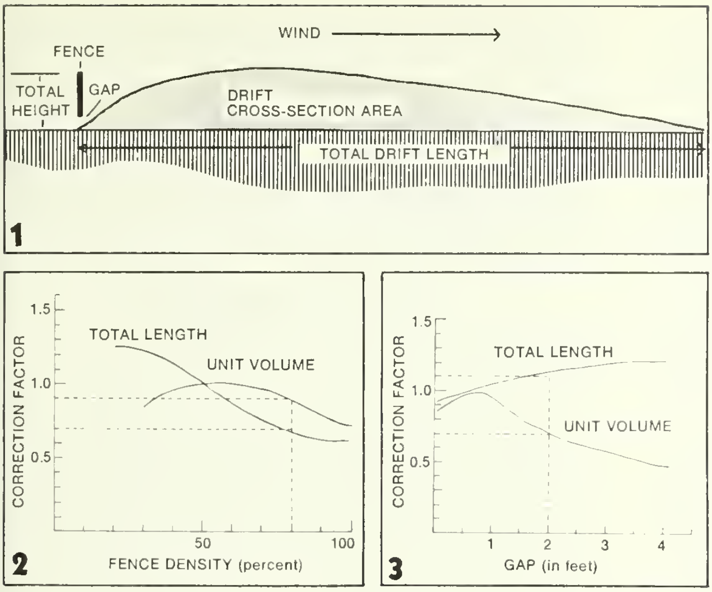
Case 5—A fence located at a break from horizontal to lee slope.—In terms of pressure gradients, this fence is located at a point where the gradient changes from zero to adverse. The fence effect is again strengthened by the natural gradient, and the results depend on the strength of the gradient. A cliff is an extreme example of this case; separation is well defined at the dropoff, and a cornice typically forms. With a more gradual lee slope, both total accumulation and maximum drift length increase. Measurements at Teller Mountain (fig. 11d) are an example of the latter situation.

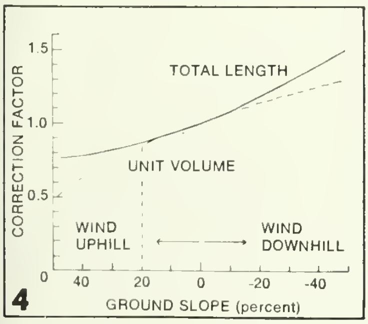
Although the configurations of terrain and snowfence locations described above are only a few of the infinite possibilities, they suggest a few generalizations to summarize this section: (a) snowfences that obstruct flow in a favorable pressure gradient yield smaller and shorter drifts than expected over horizontal terrain; (b) the effects of fences located at the change from a zero or favorable to adverse pressure gradient should increase as the gradient increases up to the point where reverse flow in the eddy begins to erode the downstream edge of the drift; and (c) fences located within an adverse pressure region should show effects that follow those given in statement (b), but the fences usually become buried in the drift.

A fair approximation of fence effect under a variety of conditions can be obtained by adjusting tabular values of accumulation volumes and drift lengths for level terrain, for slope, fence density, and size of the gap beneath the fence (fig. 12) (Schmidt 1971a).

Some Details on Snowfence Construction

Several things have been learned about building fences in windy sites subject to heavy accumulation. First, every effort must be made to keep the fence from being buried. Snow settlement forces cause extensive damage to any buried fence. Fences designed for long-term projects should be anchored to buried deadmen instead of being guyed. This reduces settlement damage to the fence and creates less clutter





1 *End view of a fence and snow drift defining total fence height, total drift length, and drift cross-section area.*

2 *Fence density factor to be multiplied by the values in Table 1, to correct for densities different from 50 percent.*

3 *Values in Tables 1 are multiplied by these correction factors when gaps other than six inches are required. (The gap is measured between the bottom of the fence and ground surface.)*

4 *For ground slopes different from zero (horizontal), the values in Table 1 are multiplied by the appropriate correction factor determined from this graph.*

Table 1.—Cross-section area and length of drifts formed by fences of various heights.

Total Fence Height (ft.)	Unit Drift Volume* (cu. ft./ft.)	Total Drift Length (ft.)
4	172	64
6	392	96
8	576	128
10	776	160
12	989	192
14	1214	224
16	1470	256

*Drift volume is expressed as the cubic feet of snow storage per lineal foot of fence. It is equal to the drift cross-section area multiplied by one foot of fence length.

Figure 12.—Principles of snowfence design to eliminate an unwanted drift, or to provide snow cover in a particular area, or to accomplish both objectives at the same time (Schmidt 1971a).

around the fence. If some type of wind barrier is needed at a site subject to burial, it is possible a rock wall, earth mound, or some other type of massive structure that could withstand the settlement forces would work better than a traditional snowfence.

Where open structures are used, there is an advantage to using horizontal rather than vertical slats (Tabler, oral communication). The horizontal slat fence has the same density for a wide variety of wind directions, whereas the vertical slat fence presents a higher density to any wind that deviates from the perpendicular. The horizontal openings at the bottom of the fence also act as bottom gaps if snow starts to accumulate at the fence.

There also seems to be some evidence that porous fences of a given density made up of large openings and large solid units are much less effective than other fences of the same overall density that have smaller openings and smaller solid units. For example, a fence with 12-inch-wide slats and 12-inch openings traps much less snow than another fence with 1½-inch openings and 1½-inch slats, even though each has a density of 50 percent. We have no good data on the size of opening where fence efficiency starts to drop off, but it appears to be somewhere between 6 inches and 12 inches.

The back braces on snowfences should attach near the top of the fence. When the attachment is midway or lower on the fence, there is a tendency for strong winds to pull the main fenceposts out of the ground and overturn the fence.

Cautions on Use of Snowfences for Snowpack Management

Before using snowfences, one must decide what the fences are expected to do. In the studies reported here, the objective was to increase the amount of snow in late-lying, high-elevation snowfields in order to increase late-summer streamflow. In other cases, it may be desirable to use snowfences to increase spring or early summer streamflow, to keep snow out of such areas as avalanche starting zones, highway or railway rights-of-way, parking lots, or selected big-game browsing areas; or to add snow to ski or snowmobile trails, snow roads, or to the area contributing water to stock ponds, or domestic water supplies. Fence location, density, bottom gap, and height can and should be changed, depending on the job the fence is expected to do.

Fences used to increase late-summer streamflow from alpine areas should be located only at selected spots and not strung indiscriminately along entire ridges or upwind of a random assortment of natural snowfields. In addition, snowfences in the alpine area of a watershed should be considered only supplemental to other water-yield improvement treatments in the timbered and riparian zones of the watershed. Care must be exercised to minimize the visual impact of fences in open areas. Wood poles and native lumber blend into the landscape better than metal structures. Quick-rusting metals are better than shiny aluminum or galvanized metal. Any type of fence in the alpine, however, is easily seen from long distances, as are the shadows cast by the fences, and both are objectionable to many people.

Fringe Benefits from the Alpine Snowfence Work

The evolution of the snowdrift meter from various types of cans and traps to an electronic counter is a significant advance. The Schmidt snow particle counter is theoretically sound and reasonably easy to use in the field. If offers the first good opportunity to gather reliable data on the flux of blowing snow. It also provided basic data for the theoretical approach to the sublimation of blowing snow (Schmidt 1972).

The wide variation in the early fence data was one of the incentives for Tabler and others to develop the contributing distance-snowdrift coefficient-fence capacity concept of fence system design that has proven so useful in the recent Wyoming Highway Department fence projects (Tabler and Schmidt 1972, Tabler 1973).

The knowledge of snowdrift patterns behind fences in irregular terrain is also being used by Colorado Division of Game, Fish and Parks in their Junction Butte Wildlife Habitat Improvement Project. In this study, fences will be used to change natural snow accumulation patterns to make more browse available on winter deer range.

Ski areas, too, find fences useful for many purposes. In some places, they provide snow for wind-eroded trails; in other places, they keep unwanted drifts from parking lots, avalanche paths, and ski trails.

Work Still to Be Done

Snowfences and Blowing Snow

Several bits of additional information are needed before complete guidelines can be developed to help land managers decide how efficiently a given area is trapping blowing snow and how much change can be expected from snowfencing.

First, we need to know the amount of blowing snow arriving at various sites in order to determine trapping efficiency. In the past, there was no way of knowing if a large accumulation of snow was due to high trapping efficiency or to unusually large amounts of blowing snow. The modified snow particle counter is expected to give a good measure of blowing snow.

Second, we need more exact information on which combinations of terrain features result in good natural accumulation sites. Schmidt's (1970) pressure-gradient concepts seem a logical starting point for developing such objective criteria based on sound physical concepts.

Third, experimental evidence is needed to sharpen the relationship between weather features and sublimation losses as given in Schmidt's (1972) theoretical model. Changes in sublimation rate due to snow particle size, humidity gradient, and the ratio of particle speed to windspeed needs to be checked.

The culmination of these efforts would be a better expression of the efficiency of various fence and terrain combinations for trapping blowing snow.

Other Snowpack Management Possibilities

Several other techniques for improving water yields from alpine areas should be tested.

- **Terrain modification** offers some interesting possibilities once we get a better feeling for the relative trapping efficiency of various terrain shapes. Many snow accumulation areas could probably be shaped into more efficient configurations with only minor damage to surrounding vegetated areas. Approach and exhaust zones in many places could perhaps be made more favorable by using earth or rock walls to trap early snows and thus produce the desired shapes for the remainder of the winter season.

- **Intentional avalanching** should be tried in selected spots. Snow could be released from the starting zones and piled in deep layers in the runout zone. If paths were chosen that loaded rapidly and had confined and sheltered runout zones, it should be possible to store the avalanche debris in or near stream channels and to carry a good deal of snow well into the summer.

- **Glacier building** during average to heavy snow years should also be investigated. The extra water stored in this way could then be used during dry years. A gravity system of spraying water from flowing streams into the air at high-elevation sheltered spots during the fall and early winter should result in massive accumulations of ice. This is a very effective way to store water for use at a later date.

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Snowpack management can be an effective means of improving water yields from the already productive alpine type. Due to wind and rugged terrain, the alpine snowpack is characterized by deep snowfields and bare spots. Because snow accumulates in the lee of terrain breaks or other obstacles that provide wind protection, fences upwind of natural accumulation areas effectively trap additional snow. Snowfences can also control blowing and drifting snow on highways and in avalanche-prone areas. Factors that influence the efficiency of snowfences are: (1) height, (2) density and length of fence, (3) bottom gap, (4) length and maximum depth of lee drift, (5) cumulative effect of a set of tandem fences, (6) vertical alinement, (7) terrain effects, and (8) contributing distance.
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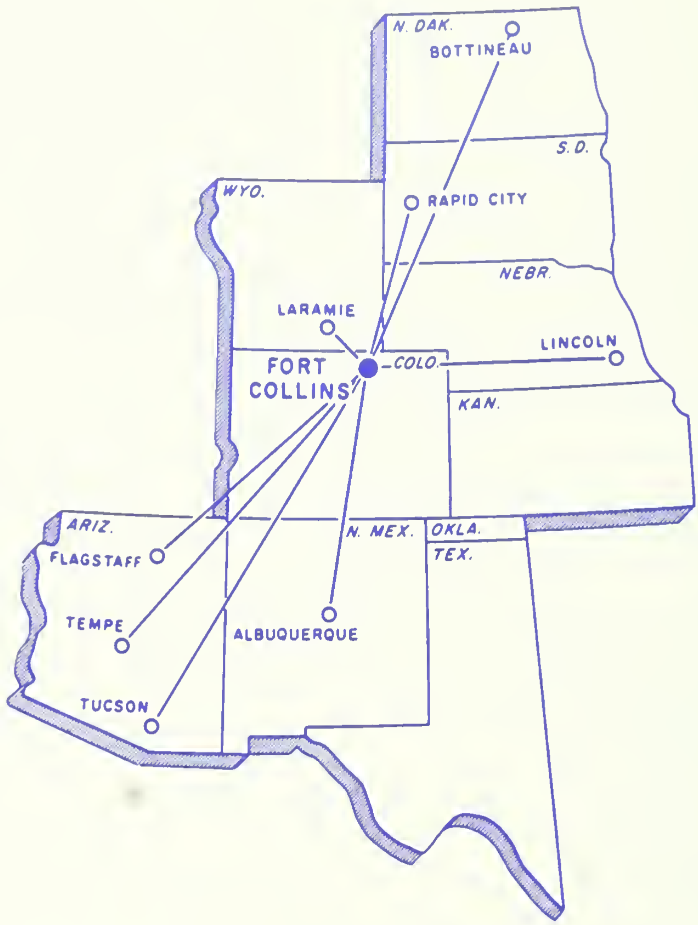
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WATERSHED MANAGEMENT PROBLEMS AND OPPORTUNITIES FOR THE COLORADO FRONT RANGE PONDEROSA PINE ZONE: The Status of Our Knowledge

Howard L. Gary

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Abstract

The east flank of the Continental Divide consists largely of open timber stands and grasslands. Soils erode easily after abuse. Precipitation ranges from 15 to 20 inches, about two-thirds from high-intensity storms from April to September.

Guidelines are provided for maintaining satisfactory watershed conditions. The 3- to 5-inch water yields are comparatively small in contrast to yields of 12 to 25 inches from the high-altitude subalpine forests, but are important to development along the Front Range. Watershed management practices can be expected to provide practical alternatives for increasing water supplies.

Keywords: Coniferous forest, forest management, range management, vegetation effects, ponderosa pine zone, watershed management, land use planning.

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WATERSHED MANAGEMENT PROBLEMS AND OPPORTUNITIES FOR THE COLORADO FRONT RANGE PONDEROSA PINE ZONE: The Status of Our Knowledge

Howard L. Gary, Hydrologist

Rocky Mountain Forest and Range Experiment Station[1]

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

Contents

WATERSHED MANAGEMENT PROBLEMS AND OPPORTUNITIES FOR THE COLORADO FRONT RANGE PONDEROSA PINE ZONE:
The Status of Our Knowledge

Howard L. Gary

The rapid and continuing economic expansion along the east slope of the southern range of the Rocky Mountains, with attendant greater use of resources, has complicated management of the Front Range watersheds.

This Paper is one of a series for the vegetation zones in the land areas for which the Rocky Mountain Forest and Range Experiment Station has research responsibility for resource management. Its purposes are to (1) summarize past studies and evaluate the status of watershed management knowledge for the Colorado Front Range pine type, and (2) indicate to what extent we are able to recommend management practices to improve water yield and still maintain acceptable quality and quantity of water and other wildland resources.

Regional Description

The Colorado Front Range, generally regarded as the eastern foothills region of the Rocky Mountains, extends from roughly southern Wyoming to Canon City, Colorado. The region is bounded on the east by plains; on the west it reaches to the crest of the Continental Divide. The low-elevation (6,000 to 9,000 ft) forests and grasslands are generally termed the ponderosa pine zone. Chief characteristics are its infertile and potentially unstable soils, and sparse tree cover. Moisture is provided mostly in late spring and midsummer by afternoon thunderstorms.

Timber cutting started more than 100 years go. Commercially valuable tree species above ,000 ft elevation are ponderosa pine (*Pinus onderosa*), lodgepole pine (*P. contorta*), Douglas-fir (*Pseudotsuga menziesii*), and some Engelmann spruce (*Picea engelmannii*). Much f the forest cover is a residual of old growth assed over in earlier cuttings, mixed with atchy stands of second growth. Aspen (*Populus tremuloides*) is also an important omponent in many young stands, particularly fter fire.

Grazing by livestock is also a major land use in certain areas. In 1950, approximately 300,000 head of cattle were grazed, some yearlong and some only a few months. Many of the valleys were farmed in the early 1900's, but have since been abandoned because of low rainfall and erosion problems.

Today, recreation use and residential development in the Front Range probably have highest impacts.

Physiography

Land features along the Front Range include ridges, mountain slopes, steep rocky canyons, foothills, narrow mountain valleys, and large openings or parks. Geologic features of this area are summarized by Marcus (1973). Soils, for the most part, developed from coarse granite rocks, alluvial deposits, sandstones, limestones, and quartzite.[2]

The most stable soils are those developed from limestone, while the most unstable are those derived from granite bedrock. The limestone and deep granite alluvium soils have the highest productive capacity, while those from granite bedrock are the least fertile and most erosive. The latter soils occur over about 90 percent of the Front Range (USDA FS 1949). Since they occupy extensive areas, much additional work is needed before we can manage them to their potential. Wet meadows cover about 2 percent of the area, and are the only highly productive grazing lands in the region.

Vegetation

As a result of the relatively abrupt ascent from the plains, the several vegetation and life zones are usually restricted to well-defined

[2]*Retzer, John L. 1949. Soils and physical conditions of Manitou Experimental Forest. 35 p. (Unpublished report on file at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

horizontal belts. On the Western Slope of the Rockies, the slopes are more gradual and cover types overlap over a considerable horizontal distance. Costello (1964) points out that the vegetation zones are also conditioned by geology, physiography, and climate, and that past grazing, logging, and mining will have a continuing effect on the vegetation.

The ponderosa pine type covers approximately 4 million acres in the Front Range of the Colorado Rockies; Statewide it is distributed principally from the Wyoming line to Trinidad, west to Mesa Verde, and north to the Uncompahgre Plateau (Costello 1964). Alexander (1974) summarized the status of our knowledge in timber management of the ponderosa pine type. The type occurs on ridges and slopes at elevations varying from 6,000 ft in the foothills to 8,500 to 9,000 ft in the mountains (fig. 1). The open ponderosa pine stands on south and west

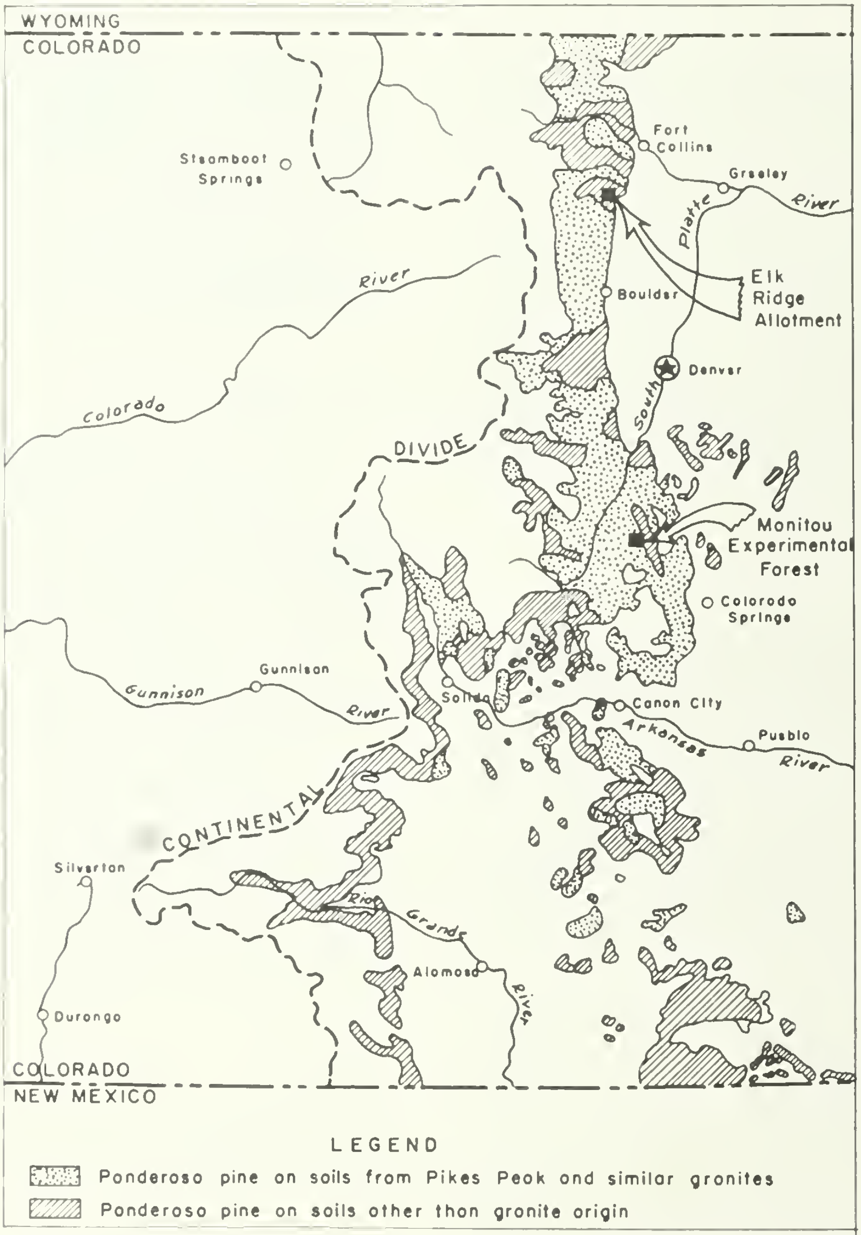

Figure 1.—Distribution of the ponderosa pine type along the Front Range of the Colorado Rockies in relation to soil origin.

slopes permit an abundance of light and the development of herbaceous understory (fig. 2). Grasslands, devoid of trees, are frequent. Meadows and streambanks often support luxuriant vegetation. On the north slopes, under denser Douglas-fir and Engelmann spruce, herbaceous plants are scarce. Shrub and broadleaved tree communities are also common throughout the pine zone. Some of the communities represent stages in secondary succession following fires and other disturbances.

Cover for the Missouri Gulch watershed (elevations from 7,500 to 9,300 ft), on the Manitou Experimental Forest, is characteristic of much of the pine zone. The areas of plant-cover types reported by Berndt (1960) were as follows:

	Area *(Acres)*	Proportion of total *(Percent)*
Lodgepole pine —Engelmann spruce	1,119	24.3
Ponderosa pine —Douglas-fir	1,372	29.8
Quaking aspen	392	8.5
Mixture	966	21.0
Brush and grass	352	7.7
Erosion pavement	316	6.9
Bare rock	83	1.8

Climate

The climate of the region is typically sub-

Figure 2.—Panoramas typical of the Front Range pine type: **A,** the North Fork of the Little Thompson watershed; **B,** the Manitou Experimental ranges.

humid, with wide diurnal and annual temperature ranges and great variation in the occurrence and distribution of rainfall. The greatest single factor controlling the climate is the Rocky Mountain range, which runs somewhat normal to the prevailing westerlies and the northwesterlies during the winter and the southeasterlies during the summer. Precipitation may be in the form of snow from late September through May, but snows commonly melt from the south exposures and valleys within days. The shallow snowpacks at the higher elevations and on the protected north exposures generally disappear by mid-May.

Precipitation through the Front Range pine zone probably averages between 15 and 20 inches. Average precipitation amounts for two centrally located and representative stations within the pine zone are:

	Estes Park	Manitou Experimental Headquarters
Elevation, ft	7,525	7,740
Years of record used	46	21
Average annual precipitation, inches	16.5	15.4

Precipitation at Estes Park has ranged from a low of 9.43 inches in 1939 to a high of 32.47 inches in 1946. The precipitation and mild temperatures are normally well distributed for plant growth throughout most of the Front Range zone (fig. 3).

About two-thirds of the annual precipitation occurs in the April-to-September growing season, and thus accounts for the abundance of grass over much of the area. Most of the summer precipitation comes in thunderstorms of varying intensities. A study of 25 significant summer storms on the Missouri Gulch watershed from 1940 to 1949 showed the highest rainfall intensity for a 10-minute period to be 4.5 inches per hour (USDA FS 1949). The storms came from all directions and during all months of the summer season:

Months	Number of storms
May	1
June	2
July	15
August	6
September	1

The high-intensity storms are most common along the more exposed and steep slopes in the Front Range pine zone. The placement of the highest rainfall-frequency values will depend on the degree of exposure to moisture-bearing wind, steepness of the slope, and other orographic factors. The possibility of high-intensity storms should therefore be considered in all land treatment programs.

The potential water balance, computed by the procedures outlined by Thornthwaite and Mather (1957), is shown in figure 4 for the Missouri Gulch watershed. The values indicate that annual precipitation is in excess of potential evapotranspiration (ET) only during a portion of the year. The moisture regime is characterized by a moisture deficit when ET depletes soil-moisture storage. As a result, the streams originating in this climate are usually intermittent, and flow only during the late fall, winter, and spring. Depending on the frequency of summer thunderstorms, streamflow may be prolonged during some years.

Floods

The Montane Zone has had a long history of intensive rainfall and infrequent but major floods (Follansbee and Jones 1922, Follansbee and Sawyer 1948, Vaudrey 1960, Matthai 1969, Hansen 1973). Flooding can result from high-intensity summer rainfall, chiefly below 7,000 ft and extending eastward from the foothills for a distance of about 50 miles. Such storms are confined to a very small area and last for a short time. The most devastating floods usually occur in May or June from upslope storms in which precipitation can vary from approximately 2 to an extreme 20 inches over a period of 3 to 5 days. Although the rate of precipitation is typically not heavy by meteorological criteria, the large quantities of long-duration, steady, widespread rainfall make such storms a persistent threat to development and land use along the Front Range.

Above 7,000 ft most of the precipitation from spring storms falls as snow, which can attain depths of 4 ft or more. The snowfall retards runoff, but as Hansen (1973) points out, the potential for landsliding is increased. Thus rainfall and flooding in the Front Range produce significant geologic as well as hydrologic effects. Although small scale in terms of the overall geologic setting, these effects may be uncontrollable once they are set in motion.

Hansen (1973) found that geologic processes triggered by the May 5-6, 1973, storm in the greater Denver area "were intensified in places where the natural regimen has been altered by man." As the Front Range becomes increasingly urbanized, the incompatibilities between natural processes and people will continue to cause problems. Accordingly, careful land use planning is essential if needless risk to lives and

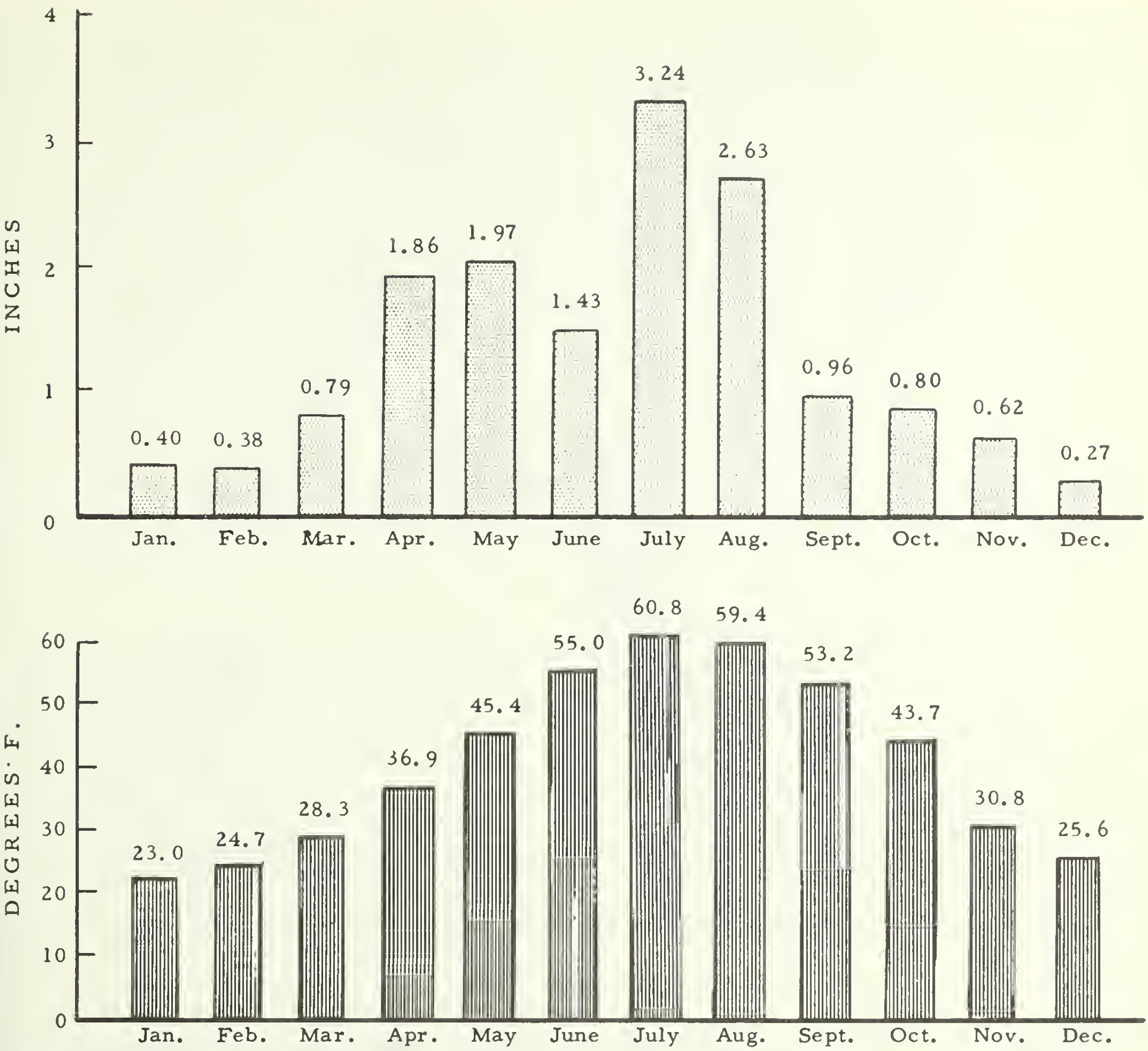

Figure 3.—Monthly mean precipitation (1937-58) and temperature (1942-58) for the Manitou Experimental Forest Headquarters (Berndt 1960).

roperty and damage to the environment are to e minimized.

Precipitation-Vegetation Interactions

An important factor affecting the disposi-on of precipitation is the relatively thin soil antle over most of the Front Range pine zone. he land management problem, therefore, is to ek ways to maintain and improve the hy-ologic functioning of the soil mantle. A part the general problem and the only factor easily altered is the vegetation cover. The specific problem appears to be, "What are the best combinations of soil type and amount of either tree, shrub, or grass cover (and perhaps mechanical structures) to control overland flow, soil erosion, and maintain high quality water yield?" Another aspect of the problem is how to increase water yields or alter the timing of streamflow. Some of the earlier studies of precipitation-vegetation interactions that influence soil protection and water yield are discussed under the headings of Interception, Litter, and Site Requirements.

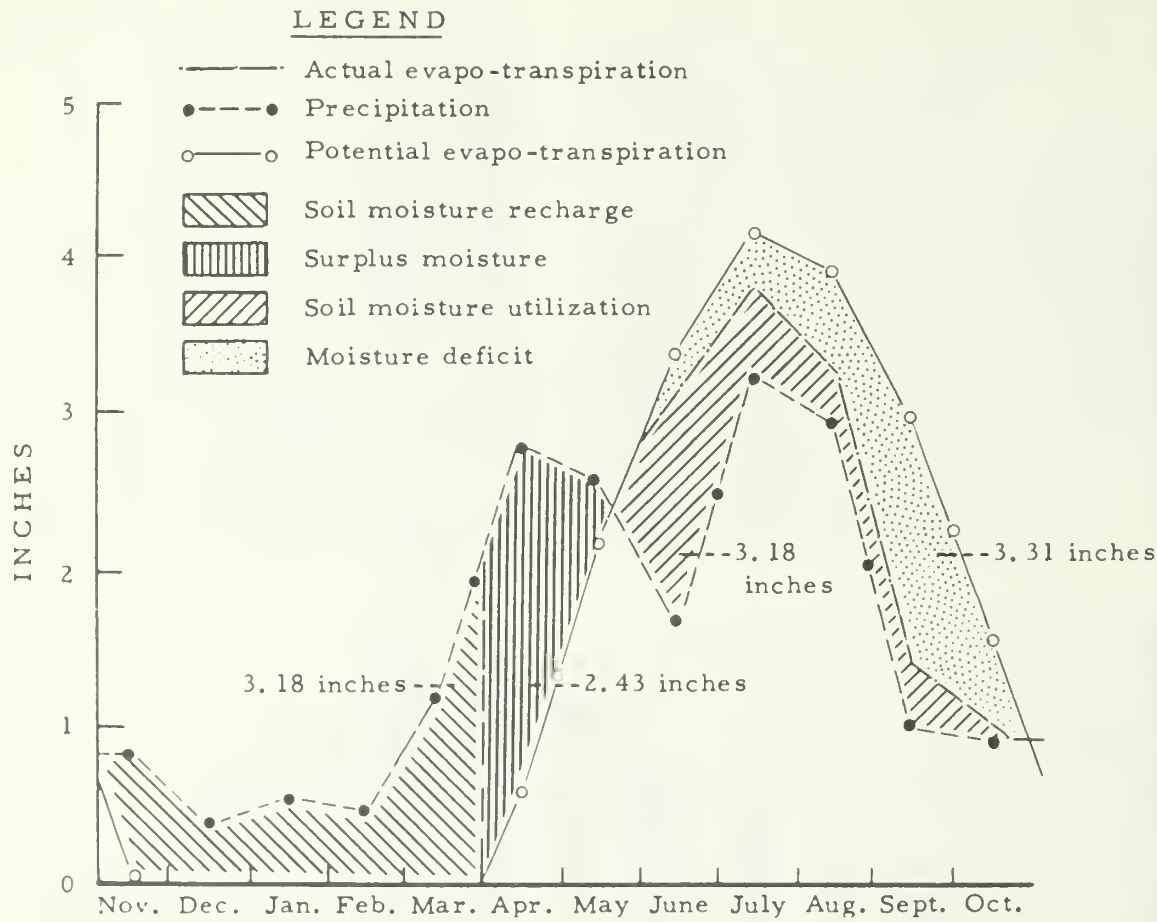

Figure 4.—Potential water balance for the Missouri Gulch watershed (Berndt 1960).

Interception

Part of the precipitation on watersheds is intercepted by the canopies of trees and grasses. Some of the intercepted precipitation eventually reaches the ground, and some is lost by evaporation from the canopies. In an early study of interception in the ponderosa pine in Colorado, Johnson (1942) concluded that an average of 81.4 percent of the total precipitation reached the ground under tree crowns. For heavier precipitation and larger trees in California, Rowe and Hendrick (1951) reported losses of 9.6 percent for snow and 13.6 percent for rainstorms. A loss of about 15 percent of the interception storage has been reported for dense grassy vegetation (Burgy and Pomeroy 1958). In the Colorado study, about 0.03 to 0.05 inch of precipitation was required to saturate the forest canopy in each storm; practically all of the subsequent rainfall reached the ground. Johnson (1942) concluded that interception of snow by tree crowns was quite similar in magnitude to the interception of rain, at least for the Front Range pine zone.

To gain additional knowledge of interception losses, Berndt (1961) studied how logging treatments and the resulting canopy reduction might influence snow accumulation in ponderosa pine-Douglas-fir stands on the Front Range. His 2-year study was in a National Forest timber sale about 35 miles northwest of Colorado Springs, Colorado, at an elevation of about 8,500 ft. Analysis of maximum snowpacks disclosed that snow accumulation after timber cutting increased significantly only on the commercially clearcut plots. Both intensities of cutting increased spring melt rates, but snow disappeared from all plots at nearly the same time. Similar results were observed by Wilm and Dunford (1948) in the subalpine zone of central Colorado.

Hoover and Leaf (1967) found no evidence :hat increased snow in openings was caused primarily by decreased interception loss; total snow on their study watershed (Fool Creek, Fraser Experimental Forest) was similar before and after strip-cutting treatments. They stated that "while total snow catch remained the same, t is distributed differently over the watershed." This study and others in subalpine forest have conclusively shown that the aerodynamic effect on snow distribution, rather than reduced interception loss, is the major cause of increased snow in openings. This work s reviewed in depth by Leaf (1975).

For precipitation in the form of rain, Croft (1961), and other workers, point out that it must not be assumed that removal of vegetation would result in decreased interception and increased water savings; the soil mantle may be wet only a few inches and the additional water lost by evaporation.

Litter

Retention of a portion of the rain and snow n the litter on the forest floor also affects the moisture supply to the soil and thus subsequent water yield. Litter accumulation is highly variable in the Colorado Front Range. Depending on ree and grass density, litter amounts may range from zero to perhaps 20 tons per acre. Under pole-sized ponderosa pine stands in Arizona, Aldon (1968) observed that moisture retention by litter (about 20 tons per acre) ranged from 7 to 27 percent of the gross precipitation. He found that total moisture retention was directly related to storm size.

In one study, the protective covering of litter was removed from six 1/100-acre plots under small pole stands of ponderosa pine on the Manitou Experimental Forest (fig. 5) to simulate what might happen in a ground fire (Dunford 1954). All plots faced north on 18-percent slopes at an elevation of 7,600 ft. Runoff was measured for 15 years. During a 3-year calibration period prior to litter removal, the runoff ratio of treated/untreated plots averaged 0.73, and for 10 years after litter removal the average ratio was 2.30 (table 1). The ratio ranged from 6.9 the first year after litter removal to a low of 0.7 after 9 years of recovery.

Most watershed management activities will disturb the litter and ground cover to some degree. A study on ponderosa pine lands in Oregon and Washington showed that tractor logging denuded herbaceous and shrubby vegetation an average of 21 percent (Garrison and Rummell 1951). Logging with a cable from a jammer denuded the ground cover 15 percent, and horse logging 12 percent.

Site Requirements

Specific knowledge of precipitation-vegetation interactions necessary for the establishment and maintenance of individual plants of the various timber types are generally lacking for the Front Range pine zone, although much information has been obtained for reseeding deteriorated rangelands (Hull and Johnson 1955). How to recover the productive capacity of the pine lands in terms of wood remains a major job for the land manager. Bates (1923) did some early work on the physiological requirements of the major forest types in the Front Range pine zone. Tarrant (1953) summarized Bates' work on the seedling stage of development for ponderosa pine:

> On dry, hot sites where moisture fluctuates rapidly, ponderosa pine is pre-eminently adapted—by reason of large seeds which produce large sturdy seedlings and by its prompt deep-rooting characteristic. Considering its xerophytic tendencies, ponderosa pine is an extravagant user of water. Probably this comparative extravagance helps protect the seedlings from excessive heat. Survival is dependent on the roots reaching a layer of soil which does not dry out dangerously through insolation. Ponderosa pine cannot grow in competition with trees, grasses, and herbs that draw heavily on moisture in the upper soil layers. The large moisture demands of ponderosa pine, which grows where precipitation normally is low, can be supplied only in open stands which permit first a deep penetration of the roots and later their extension into a large area of soil.

In contrast, the seedlings of Engelmann spruce, Douglas-fir, lodgepole pine, and limber pine (*Pinus flexilis*) have weak and slowly developing root systems, and require continuous high soil moisture during their first year of development.

Roeser (1940) also studied the relative water utilization and efficiency of water use of seedlings of several forest types in the Front Range pine zone. Seedlings were maintained in containers in sufficient number to simulate complete stocking, yet permit normal development and vigor. After 6 to 10 years, he summarized water use and efficiency. Based on the magnitude of water loss, the species ranked in decreased order as follows: Engelmann spruce, Douglas-fir, pinyon pine (*Pinus edulis*), ponderosa pine, and limber pine. In relative efficiency of water use in production of organic matter, the species ranked as follows: pinyon pine, limber pine, Douglas-fir, Engelmann spruce, and ponderosa pine.

Figure 5.—Ponderosa pine runoff plots before (A) and after (B) litter removal.

Infiltration, Runoff, and Erosion

Infiltration Capacities

The maximum rate at which water penetrates the soil surface is termed infiltration capacity. This capacity is affected by many factors, but is determined primarily by the noncapillary porosity of the soil surface after it has been thoroughly wetted but not saturated. The greater the diameter of the large pores, the higher the infiltration capacity. Most of the infiltration data for Front Range pine zone are based primarily on infiltrometer runs. Infiltrometers (fig. 6) measure the rate at which sprinkler-applied water soaks into the soil, the rate at which water runs off, and the amount of erosion that might be expected (Dortignac able 1.--Average annual surface runoff from ponderosa pine plots before treatment, after removal of litter in 1941, and after tree and litter removal in 1952 (Dunford 1954)

ear	Storms causing runoff	Average seasonal runoff		Ratio: Treated/ control
		Treated	Control	
	No.	*Inches*		
EFORE TREATMENT:				
938	13	0.10	0.17	0.6
939	13	.04	.05	.8
940	3	.05	.06	.8
FTER REMOVAL OF LITTER:				
941	14	1.17	.17	6.9
942	9	.43	.12	3.6
943	6	.20	.06	3.3
944	8	.65	.31	2.1
945	12	1.05	.59	1.8
946	6	.11	.10	1.1
947	13	.36	.23	1.6
948	6	.06	.07	.9
949	10	.07	.10	.7
950	3	.02	.02	1.0
951	1	(1)	(1)	--
FTER REMOVAL OF TREES AND LITTER:				
952	3	.49	.03	16.3

Trace.

1951). The studies were mainly undertaken to solate and evaluate how vegetation and soil in-luence infiltration on representative pon-lerosa pine-bunchgrass ranges.

The general influence of litter on the infil-ration capacity of forest soil has long been rec-ognized (Lowdermilk 1930), but specific data are lacking for most soils and in most forest types. In the Front Range ponderosa pine zone, for example, the quantitative influence of forest itter on infiltration was studied as a prelimi-nary step in a comprehensive watershed man-agement research program on the headwaters of the South Platte River (Johnson 1940). In the irst reported study undertaken in 1939, John-son (1940) removed litter and duff (3 inches leep) down to mineral soil from half of his study plots and applied water until a constant infiltra-ion rate for 15 minutes was attained. The time or more or less constant rate of infiltration varied from 45 to 90 minutes. Where litter was undisturbed, infiltration rate was 1.52±0.10 nch; on disturbed plots it was 0.92±0.10 inch.

In a later study near Woodland Park, Col-rado, Johnson and Niederhof (1941) directly

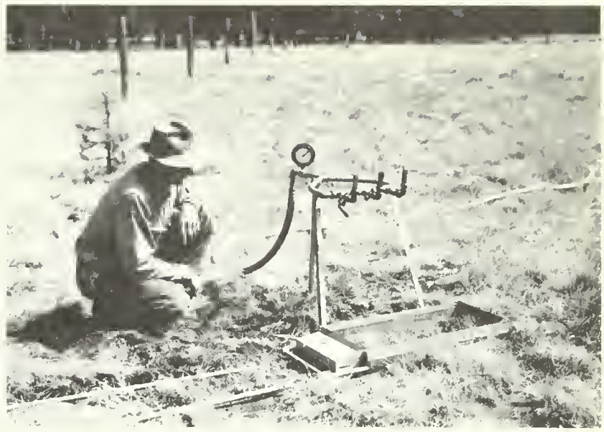

Figure 6.—Rocky Mountain infiltrometer showing rainfall applicator, rainfall trough, and runoff plot.

measured the influence of plant type and rain-fall intensity on the rate of surface runoff and erosion, and the effect of individual plant species on the infiltration capacity of the soil. They believed that plant cover such as blue grama (*Bouteloua gracilis*) sod, on soils with naturally high infiltration rates, tends to de-crease the rate at which water is able to enter the soil. Turner and Dortignac (1954) reported a similar decrease in absorption under Kentucky bluegrass (*Poa pratensis*) in southwestern Col-orado. In the former study, Johnson and Niederhof reported rates of 3 to 9 inches per hour under the mountain bunchgrass type. It was reasoned that the high absorption rates were not due to the effect of the plant cover, but principally to the greater porosity of the soil. Infiltration in bare soil was not measured in the mountain bunchgrass type. The results, though inconclusive in some respects, indicated that certain plant species and associations have more effect than others on infiltration, runoff, and erosion, and that the effectiveness of any species or type is greatly influenced by organic materials and physical soil properties. Litter and porosity of the surface soil were the two measured factors most highly and consistently associated with infiltration rates.

In a later study on the Manitou Experimen-tal Forest and elsewhere in the Colorado Front Range, Dortignac and Love (1960) reported that, on grazed areas, infiltration varies with cover and soil type (fig. 7).

For the Elk Ridge and Lower Elk Ridge Cat-tle Allotments (mainly above 6,500 ft and below 9,000 ft) in the Roosevelt National Forest, Reid and Love (1951) found that infiltration rates in-creased with increasing amounts of vegetation

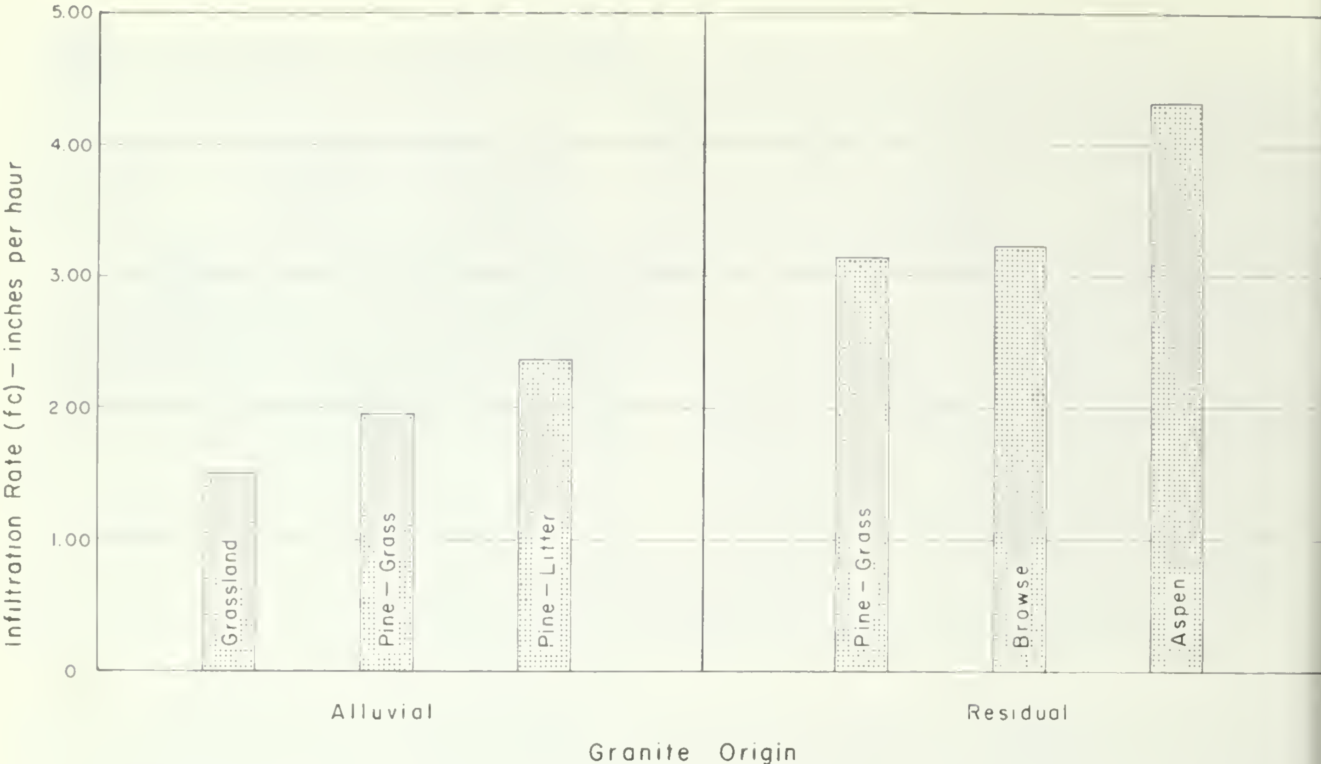

Figure 7.—Average infiltration rates on pastures grazed by cattle at Manitou Experimental Forest (Dortignac and Love 1960).

in the grassland types on soils derived from granite schist. In the timber-grass types on granite schist soils, the infiltration rate was related to total dry weight of litter, which takes the place of herbaceous vegetation in the grassland type as the dominant factor affecting infiltration. The average infiltration on the Elk Ridge Allotments and at Manitou Experimental Forest under similar cover and during the last 20 minutes of 50-minute infiltrometer runs was as follows:

	Elk Ridge	**Manitou**
	(Inches)	
Grassland	1.60	1.50
Pine-grass	2.04	1.94
Pine litter	3.68	2.37

Dortignac and Love (1961) observed that protection from grazing on the Manitou Experimental Forest also increased infiltration. The main effect of cattle grazing was to prevent an increase or recovery of infiltration rates. Litter accumulation in grassland and pine-grass areas grazed by cattle was less than where livestock were excluded.

The upper 2 inches of soil in grazed pastures had a smaller percentage of large noncapillary pores. The differences were reflected in the average infiltration rates obtained under grazing as compared with protection of grazing. The increase in infiltration rate after 14 years' protection from grazing was most pronounced in the grassland:

	1941	**1954**
	(Inches/hr)	
Grassland	1.95	3.26
Pine-grass	1.59	2.60

Surface Erosion

Removal of protective plant cover and soil disturbance caused by road construction, logging, and fire, can accelerate natural erosion processes (fig. 8).

Erosion rates obtained with the infiltrometer have provided the main index of soil erodibility over representative sites in the Front Range. The first erosion surveys in the pine and grassland types at the Manitou Experimental Forest were started in 1936 (Johnson and Niederhof 1941). To determine the influence of plant cover types on surface runoff and erosion, simulated natural rainfall was applied to 132 plots, 1/200

Figure 8.—Unprotected soil showing evidence of accelerated erosion.

acre in size. Collector troughs at the lower ends of the plots conducted surface runoff and eroded material to tanks. The plots were confined to natural parklike areas in an abandoned field, valley bunchgrass, and mountain bunchgrass. To minimize the effect of factors other than vegetation, the average degree of slope was selected within a given type. Slopes of 10 percent were studied in the abandoned field and valley bunchgrass types, and 40 percent in the mountain bunchgrass type. At rainfall intensities of 2 and 4 inches per hour, erosion per ft^3 of runoff was as follows:

Cover type and rainfall intensity	Soil texture (gravel/sand) *(Percent)*	Erosion *(g)*
Abandoned field	66	
2 inches/hr		233
4 inches/hr		173
Valley bunchgrass	76	
2 inches/hr		65
4 inches/hr		67
Mountain bunchgrass	83	
2 inches/hr		113
4 inches/hr		105

Erosion rate was highest on the abandoned fields and smallest on the valley bunchgrass. Variance analysis showed highly significant differences in erosion rates between types. The total volume of eroded material increased with increased intensity of rainfall, but amount of eroded material carried per ft^3 of runoff showed no significant change.

Dortignac and Love (1960) combined the grassland and pine-grass data—the two cover types with the lowest infiltration rates—and obtained the following erosion rates:

Exposed soil *(Percent)*	Elk Ridge Allotment (granite schist residual)	Manitou Experimental Forest (granite alluvium)
	(Lb/acre/inch of runoff)	
0- 9	170	96
10-29	440	194
30-69	1,200	289

From the above findings it was concluded that, when on-the-ground organic materials exceed 2 tons per acre, and where exposed soil is less than 30 percent and large noncapillary pores exceed 20 percent in the upper 2 inches of soil, erosion losses will usually be tolerable and less than 500 pounds per acre per inch of runoff. For some 750 infiltrometer tests conducted at the Manitou Experimental Forest, only two vegetation-soil conditions averaged more than 30 percent bare area. Accordingly, from the standpoint of ground cover and soil protection, watershed conditions sampled in the Manitou portion of the Front Range were generally satisfactory.

In Idaho, Packer (1953) also reported that 70 percent ground cover was required for satisfactory watershed conditions. The erosion rates reported by Dortignac and Love (1960) for the various cover types grazed by cattle (fig. 9) are of little consequence until infiltration capacities (previously shown in figure 7) are exceeded.

Dunford (1954) reported results of another study at the Manitou Experimental Forest where six 1/100-acre plots were used to determine how moderate and heavy grazing affect the amounts of surface water flow and the quantity of soil moved by erosion in the bunchgrass type (fig. 10). Grazing caused an increase in erosion, but not in direct proportion to intensity of use. Average annual erosion from summer storms (fig. 11) ranged from 111 to 163 pounds per acre. During the grazing treatments, 13 storms from 1941 to 1952 were of sufficient size to produce erosion. Average annual depositions were 134,145, and 316 pounds per acre for no grazing, moderate, and heavy grazing, respectively. Only heavy grazing significantly increased erosion, but erosion was measurable in only 8 of the 16 years of study on any plot. Months of greatest soil movement were July and August. It was also noted that erosion tended to occur during periods when large storms followed one another at short intervals. From larger grazing studies at Manitou, Johnson (1953) reported that moderate grazing was most efficient from the standpoint of economic returns in beef production. An additional watershed benefit is that surface runoff and erosion are controlled under moderate grazing.

On six plots of similar size and arrangement

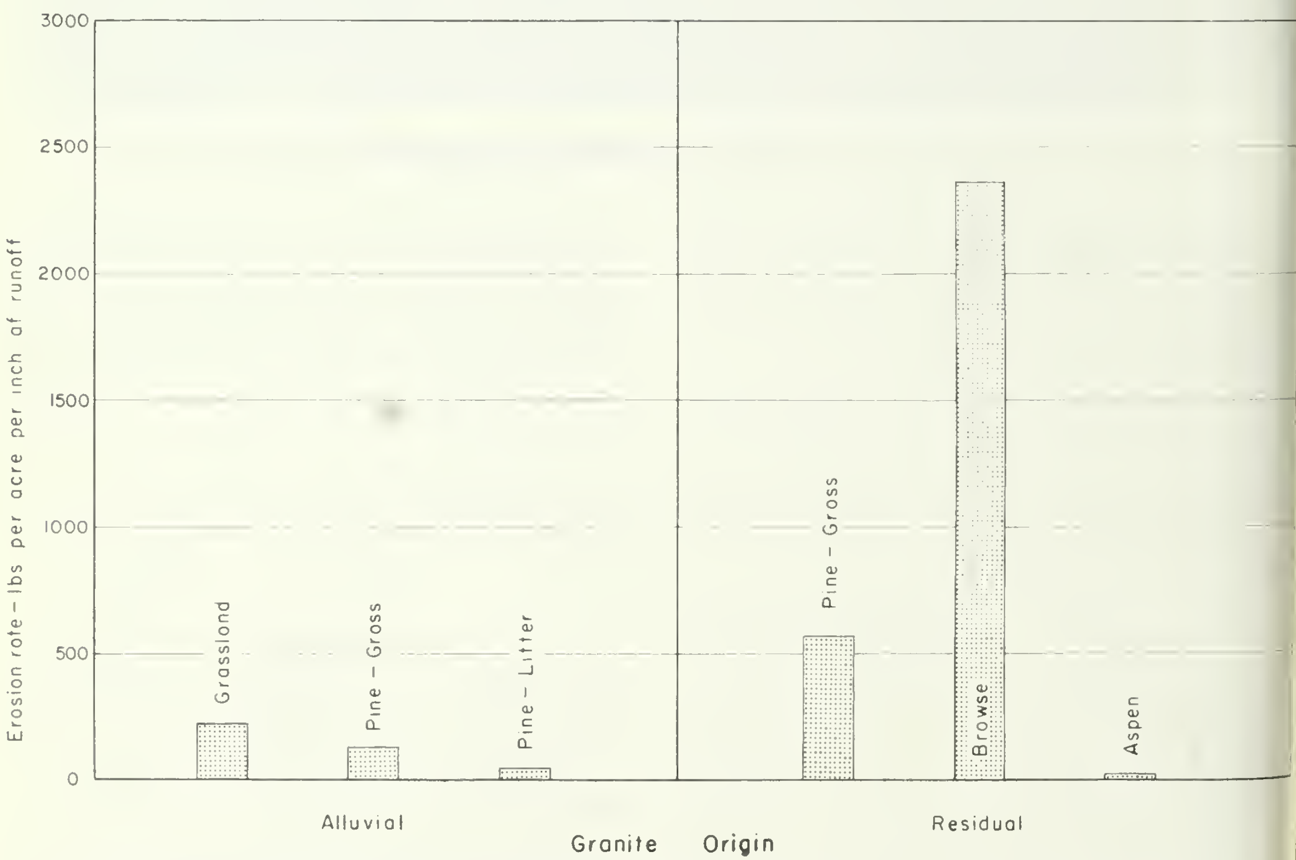

Figure 9.—Average erosion rates on pastures grazed by cattle at Manitou Experimental Forest (Dortignac and Love 1960).

A

B

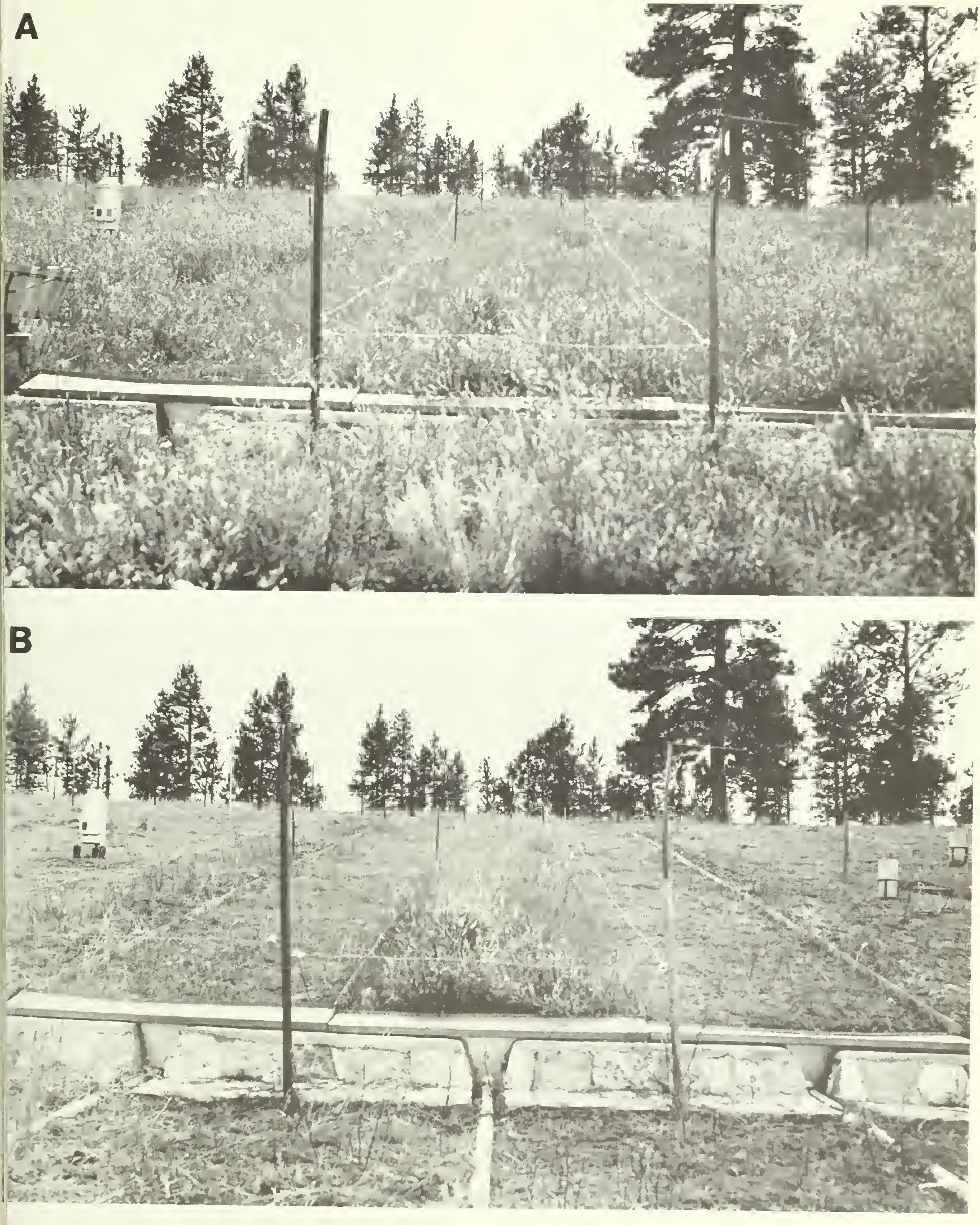

Figure 10.—Bunchgrass runoff plots: **A**, before grazing; **B**, after grazing by cattle (from left to right)—moderate, none, and heavy grazing.

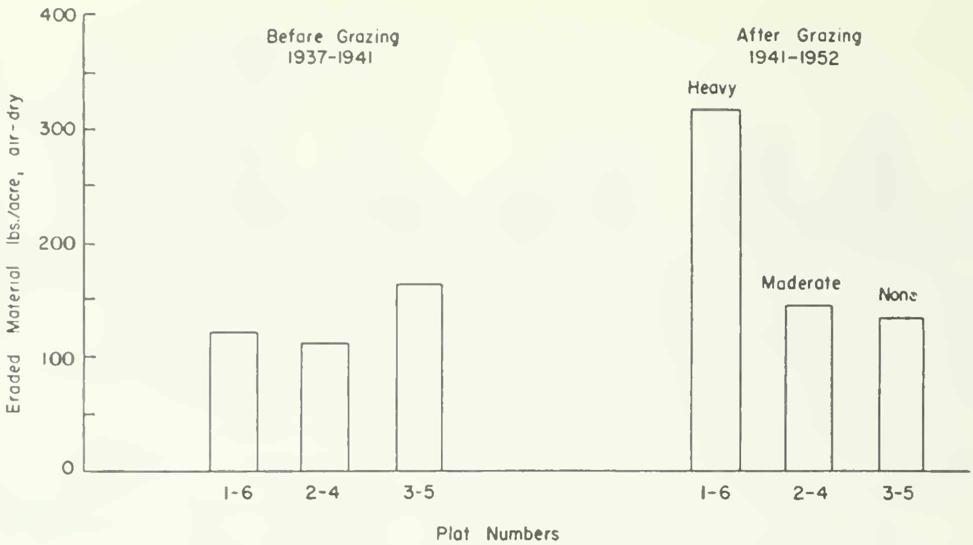

Figure 11.—Average erosion from summer rainfall, before and after grazing treatments (Dunford 1954).

in the ponderosa pine type, Dunford (1954) also found no erosion in the three summers of calibration, but did observe increases in erosion following litter removal in the first treatment, and after removal of trees as well as litter cover in the second treatment. In the first year after treatment, three plots in the treated block yielded an average of about 4 tons of air-dry eroded material per acre, while the untreated block yielded only a trace. After 5 years, the amount of air-dry eroded material derived from the treated plots (0.01 acre) decreased from 25.4 to 1.0 pounds per storm. No erosion occurred from 1946 through 1952, and it was concluded that the effect of litter removal in 1941 had been virtually eliminated by the gradual return of a ground cover. In the second treatment on the same plots, removal of trees and litter again resulted in seasonal average erosion in excess of 4 tons per acre, while the undisturbed plots produced none. These two treatments showed the protection afforded by forests in the Front Range watersheds, and suggested the use of forest management systems causing the least ground disturbance.

A forage condition survey by Reid and Love (1951) on the Elk Ridge Allotments showed that 96 percent of the usable range types were in depleted condition from the standpoint of the desired amount of forage. The grassland and meadow, brush, timber-grass, and aspen types were predominately in fair condition, but substantial portions of each were also in poor condition. From infiltration plot data, Reid and Love were able to develop a relation between erosion rate and live material plus litter on a schist-derived soil (fig. 12). Erosion rate was directly related to the amount of vegetation and litter. Where vegetation and litter are sparse, any increase in either or both would have a major effect in reducing erosion. The effect would be proportionately greater where amounts of vegetation and litter are relatively small. For the grassland and timber-grass types on granite-schist soils and on slopes less than 40 percent, Reid and Love (1951) considered that satisfactory watershed cover for protection against a 2.5-inch storm (30-year storm) would be: (1) on

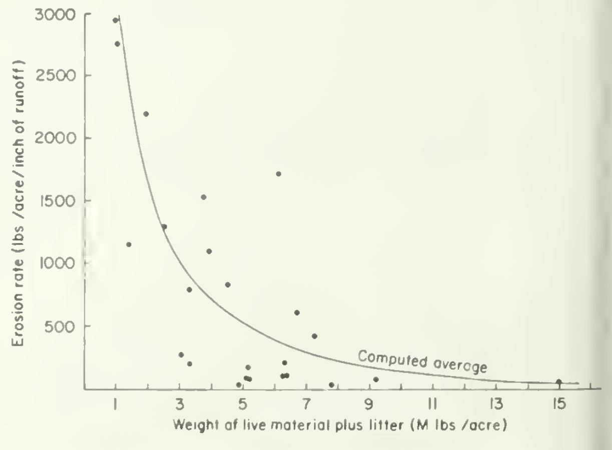

Figure 12.—Relations between erosion rate and live material plus litter on the grassland type on schist-derived soils (Reid and Love 1951).

grassland type, 1,100 to 1,300 pounds per acre of herbage; and (2) on timber-grass type, 17,000 to 21,000 pounds per acre of litter. From past storm records, infiltration, and erosion rates, they were able to estimate reductions in anticipated peak flows and erosion that would result from putting all grassland and meadow types and half the timber-grass types in good condition as a result of range management practices (table 2).

able 2.--Expected runoff and erosion reduction on four areas placed under good range condition class on Elk Ridge Allotments (Reid and Love 1951)

Area	1-inch storm	2-inch storm	2.5-inch storm
		Percent	
EDUCTION OF PEAK FLOWS:			
North Fork	75	26	13
Hell Canyon	35	11	6
North Fork, Little Thompson	50	11	5
Grassland (schist-derived soils)	0	0	0
EDUCTION IN EROSION:			
North Fork	69	32	31
Hell Canyon	40	19	21
North Fork, Little Thompson	53	24	27
Grassland (schist-derived soils)	0	60	60

In the same report, Reid and Love (1951) also found that general grassland and meadow types produced the least sheet erosion in proportion to the area of the types. Ninety-five percent of the areas with moderate sheet erosion were on the timber-grass and browse types.

Evaluation of Rainfall Infiltration and Erosion Studies

Much of the early concern for the protec-ion of pine-bunchgrass rangelands originated 'rom infiltrometer studies in which artificial 'ainfall was used to simulate short-duration ummer thunderstorms. Precipitation was ap-lied at a rate of 4 to 5 inches per hour for a 0-minute period (Dortignac 1951). These rates ar exceeded normally observed rainfall inten-ities in the area.[3]

[3]*According to Love (1958), maximum 10-minute intensities verage 3 to 3.5 inches/hr for summer cloudburst storms. Such orms produce a total precipitation of 2.5 to 3 inches, last pproximately an hr, and have a recurrence interval of 50 yr.*

While these studies have shown that good range management practices and revegetation of depleted land with trees, shrubs, and grass will improve watershed conditions, such measures cannot offer complete protection against damage from infrequent severe floods. It must be recognized that improved range and forest management practices are essential to avoid triggering and intensifying destructive geologic effects. However, no watershed management practice in itself can prevent normal geologic processes which are characteristic of the Front Range.

Channel Erosion

Throughout much of the Front Range pine zone, meadows and hillsides are typically lined with gullies (fig. 13). Accordingly, mechanical structures and treatments have long been used and are still needed in some areas to control runoff and soil erosion. Heede (1960) evaluated the gully-control structures installed some 30 to 35 years ago in the Pike and San Isabel National Forests, and made recommendations to guide future work in gully control.

Many gully-control structures have apparently failed because of poor engineering and because maintenance work is seldom performed. The main damage probably occurs during the infrequent storms that produce large floods.

Adequate field guides and engineering designs for gully control have long been available (Heede 1966).[4] In 1965, Heede designed a check

[4]*Rosa, J. Martin. 1954. Guides for program development: Flood prevention on small watersheds of the Rocky Mountain area. U.S. Dep. Agric., For. Serv., Ogden, Utah.*

Figure 13.—Erosion channel through a heavily grazed meadow.

dam system based on prefabricated concrete components to simplify construction of check dams in relatively remote areas (fig. 14). The best methods of plant establishment and kinds of plants to complement control structures are not fully known, however (Heede 1968).

Studies of channel morphology (Heede 1970) led to the development of computerized procedures for designing an engineered series of control structures for the entire length of a gully system (Heede and Mufich 1973, 1974).

In Heede's (1967) 7-year study of gully fusion on the Manitou Experimental Forest, only five summer storms produced gully flows. He also observed that gully flows were not recorded during spring snowmelt, and he believed that the usually limited snowpack and rate of melt were not sufficient to cause concentrated gully flow and the upstream progression of gully head cuts.

Heede's work and the flood events of recent years indicate that some gully activity is caused by short-duration summer cloudbursts; however, the most severe erosion takes place during large-scale moderate-intensity upslope storms. Such storms can be associated with snowmelt runoff from the higher elevations in May and June. Hansen (1973) reported that "in terms of geologic effects such as scour and especially mass wastage, the (May 5-6, 1973) storm was unusual—probably because of the thorough saturation of the ground that resulted from the moderate rate of sustained precipitation." In this particular storm, "nearly all perennial streams in the area, and countless intermittent ones,scoured segments of their banks and beds" (Hansen 1973). Several examples of severe scour by Front Range streams are cited by Hansen (1973). Of particular significance was West Creek between Deckers and Woodland Park, in which "two small reservoirs failed in sequence, the upstream one first, by overtopping, thereby swamping the lower dam and creating a 'wall' of water that destroyed much of the highway and several mountain homes."

Hansen (1973) also documented considera-

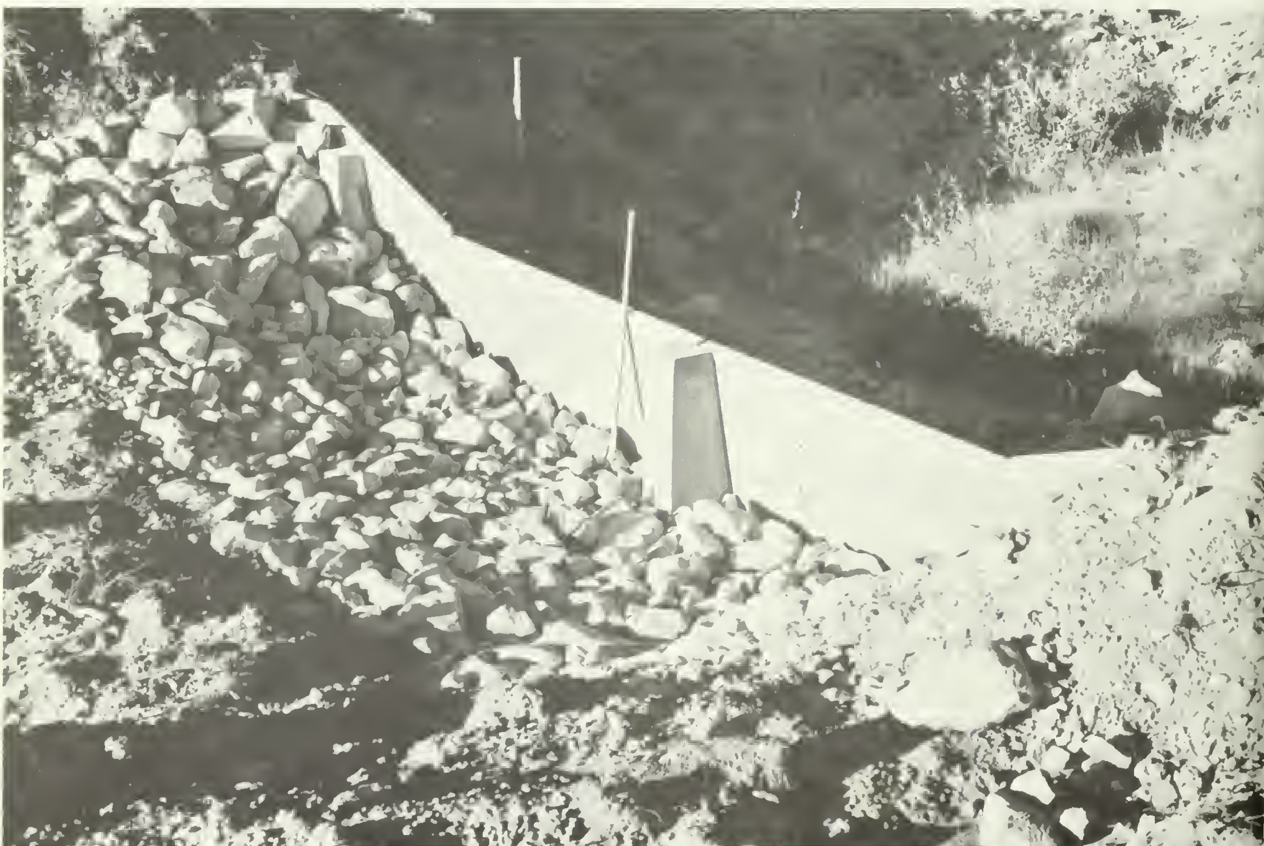

Figure 14.—Downstream face of completed prefabricated concrete check dam (Heede 1965).

ble mass wastage in saturated slide-prone areas. He noted that slumps and earthflows were most prevalent in foothill areas, underlain by sedimentary rocks; however, landslides and rockfalls also occurred higher in the mountains. Many of the slumps disintegrated into mud and earthflows that ran out onto roadways and into water courses.

Sediment Yield

Upstream channel erosion contributes sedimentation damage to downstream improvements. On the Manitou Experimental Forest it has been estimated that gully erosion accounts for 60 percent of the sediment in stream channels and reservoirs. Thus, reservoir sedimentation in the Front Range can be a significant problem. Within the Manitou Experimental Forest, there is a good example of the magnitude of sedimentation in a small reservoir (USDA FS 1949). The dam for Manitou Lake was completed in 1937. Original capacity of the reservoir was 93 acre-ft. By 1948, the capacity had been reduced by two-thirds, and approximately 60 acre-ft of sediment had accumulated below the spillway level. Total accumulation above and below the spillway level was about 200 acre-ft, with channel deposits as much as a mile upstream. Rate of sedimentation in this case is typical of many Front Range streams. The drainage basin above the reservoir is 69 mi^2. Based on estimates of total accumulation, the contribution from the drainage area is 18.2 acre-ft per year, or 0.26 acre-ft/mi^2 annually. Most of the sediment was probably deposited by infrequent flood events.

Watershed Protection Criteria

Forest and Range Management

A survey of about 30 timber sales and old cutover areas on the Roosevelt and Pike National Forests gave some indications of the need for watershed condition criteria (USDA FS 1944). It was found that even the most severe timber cutting in the spruce-fir and lodgepole pine types had few bad effects on watershed conditions. Some damage has been caused by repeated perennial use of skid roads and trails, and by poor planning of logging roads (fig. 15).

Figure 15.—A poorly planned skid trail established in the 1920's in the Front Range spruce-fir type. Elevation about 10,000 ft.

In general, however, cutover areas in these types are now in a stable condition, and most logged areas are well covered with vegetation.

In the same survey, it was observed that logging in the ponderosa pine and Douglas-fir types may be hazardous, compared to spruce-fir and lodgepole pine types. Watershed conditions and the effects of logging in these types vary greatly with environmental factors such as soil, topography, and exposure. In these types, practically no logging damage was observed on slopes under 10 percent. Logging in Douglas-fir areas had done little damage except through erosion from poorly planned logging roads. The selective logging in Douglas-fir areas has usually left an ample stand of trees and an understory of shrubs and herbs.

The most serious erosion problem in the ponderosa pine type was found on slopes steeper than 30 percent and on unstable soils such as those derived from Pikes Peak granite and volcanic rocks. Problems are greatest on warm and dry slopes, where erosion would result from timber cutting even without damage from skid roads or trails. Progressive deterioration of such sites after removal of trees is often aggravated by grazing damage, and may culminate in complete exposure of the soil with subsequent surface runoff.

Results from the survey above indicate that improved logging methods along with vegetation of denuded areas to either grass or trees will prevent depletion of the range and watershed values of the Front Range pine zone. Efficient means of recognizing and controlling active gullies, and sheet and streambank erosion are generally known, but the necessary controls have not been applied. Grading, mechanical structures, and the right combinations of vegetation should be applied to build up channel storage in many headwater streams. On less hazardous areas, such as the gently sloping valleys, controlled grazing can be allowed.

The extremely deteriorated areas need some direct improvement in addition to protection because natural return of vegetation is slow. Johnson (1945) believed the degree of grazing pressure in the Front Range was equally as important as erosion and runoff in its effect on plant succession and site restoration. Overgrazing may maintain an intermediate and undesirable stage of plant succession and poor ground cover indefinitely. Successful seeding of some depleted farm and grazing lands has resulted in herbage yields three to five times that of adjoining native range, and at the same time has provided adequate ground cover (Johnson 1959).

Onsite flood damage is usually at a minimum in the Front Range when native plants—grass, browse, trees—are produced at a maximum rate. Using infiltrometer tests, corroborated by plot runoff data, Dortignac and Love (1960) and Reid and Love (1951) have provided some basis for determining satisfactory watershed criteria. For soils derived from granite and schist on slopes up to 40 percent, organic materials should exceed 2 tons per acre, or 1,000 to 1,300 pounds of live herbage per acre (fig. 16). If any area on a 40 percent slope is capable of producing only 1,200 pounds of live herbage without being grazed, then it must be protected from grazing to meet satisfactory watershed criteria. Areas of lesser slope usually produce more than adequate herbage for watershed protection, and may be grazed to the extent that the herbage produced exceeds the guide figure; otherwise, increased surface

Figure 16.—Under good litter or grass cover, infiltration rates are usually sufficiently high to restrict surface runoff and erosion in the timber-grass types.

:unoff and erosion may be harmful to the con-
:inued productiveness of the site.

In the timber-grass types on soils derived from a mixture of granite and schist, trees occur in open stands and the understory is usually native bunchgrasses, which are often sparse. Quantity of litter appears to be a major hydrologic factor. On these areas, much of the litter is pine needles, cones, and small twigs. The grasses in the timber type contribute limited amounts of litter. It has been estimated that 19,000 to 21,000 pounds of litter per acre should be maintained on the timber-grass types (Reid and Love 1951). Tree removal should be avoided on areas with lesser amounts of litter and where shallow soils dominate. Areas with greater soil depth may be logged or grazed to the extent that the remaining soil protection does not fall below the guidelines.

Urbanization

Rapid urbanization of the Front Range is intensifying watershed protection problems. Of primary concern to planners are the hazards created by common land development practices with respect to road construction, drainage, steepness of natural slopes, building site location, and a host of related factors. Hansen (1973) has documented an excellent summary of many of these practices which tend to trigger geologic processes, thus compounding the intensity and damage from extreme flood events. Better land use planning is essential if future problems are to be minimized.

Present Water Yields

The classic Wagon Wheel Gap study provides some of the earliest detailed information and guidelines as to water yields that may be expected from the 9,300- to 11,300-ft elevational range along the east slope of the southern portion of the Colorado Rockies (Bates and Henry 1928). Water yield in that study averaged about 6 inches, and similar water yields may be expected under forest cover and in logged areas near the extreme upper limits of the ponderosa pine zone in other parts of the Front Range. The forest cover in their study area was mainly Douglas-fir and aspen, and precipitation averaged about 21 inches. On the average, about 29 percent of the precipitation was yielded as runoff. Runoff ranged from 42 percent of the precipitation during years of above-average snowfall to 17 percent during low snowfall years (fig. 17).

Annual water yields in the Front Range pine

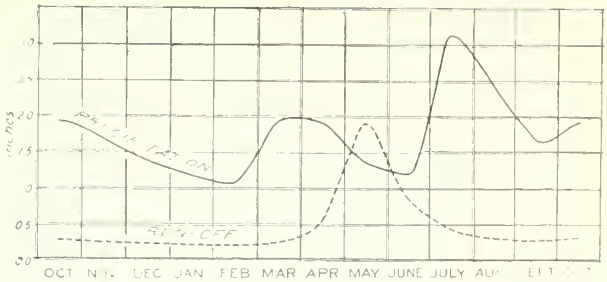

Figure 17.—Average monthly distribution of precipitation and runoff from a Wagon Wheel Gap, Colorado, watershed (Bates and Henry 1928).

type range between 3 and 5 inches, or about 10 to 15 percent of the annual precipitation. The greatest opportunity for runoff is probably from April through August (see fig. 3). Infrequent large storms of moderate intensity in May and June are the major source of damaging flood flows.

In the mid-elevations of the pine zone, plot studies have provided some runoff guides for land managers. In one such study, Dunford (1954) summarized the runoff from grass plots over a 16-year study period at Manitou, and found that individual summer storms produced measurable runoff four or five times per year from untreated plots; amount varied with vegetation cover. Average surface runoff was about 0.25 inch for 4 years before the grazing treatments. During 12 years of treatments, the heavily grazed plots yielded an average of 0.34 inch of runoff per season, moderately grazed 0.22 inch, and nongrazed 0.11 inch per season (fig. 18).

Reid and Love (1951) summarized streamflow and the timing of runoff for the North Fork of the Little Thompson watershed on the Elk Ridge Allotments and for the Missouri Gulch watershed at Manitou for the years 1949 and 1950. Inches of runoff for years of high and low water yield were as follows:

	1949	1950
	(Inches)	
North Fork,		
Little Thompson	3.78	0.69
Missouri Gulch	2.11	.58

In both years, streamflows on the North Fork watershed peaked in June. In 1949, about 80 percent of the total annual flow on North Fork occurred during the month of June as a result of prolonged rain-on-snow events. The period of greatest seasonal runoff was much the same for

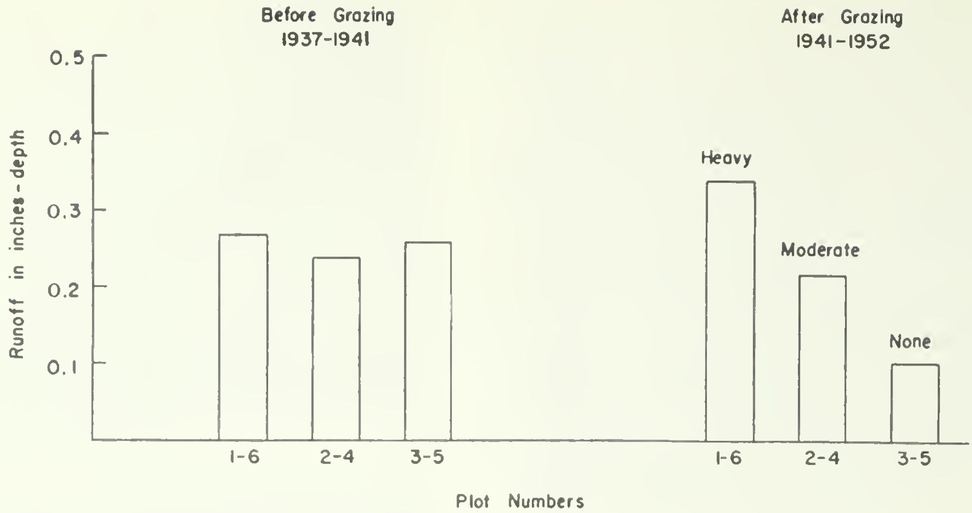

Figure 18.—Average seasonal runoff from summer storms before and after grazing treatment (Dunford 1954).

Missouri Gulch in 1949; more than half of the annual flow occurred during May, June, and July. In 1950, under low precipitation, more than 50 percent of the flow from both watersheds also occurred in May, June, and July.

Precipitation over the Missouri Gulch watershed is characteristic of that over much of the Front Range. Precipitation usually comes as snow from late September through May. Snow commonly melts on south exposures and valleys within a few days, and accumulates during the winter mainly on north exposures. Snowmelt from the lower end of the watershed (elevations below 8,300 ft) has the greatest influence on the spring peaks, which account for about 40 percent of the total annual yield. Yearly streamflow has varied from 8.14 inches in 1942 to 0.25 inch in 1956. Average annual streamflow for the 19 years of study was 2.22 inches. These runoff values are generally characteristic of Front Range drainages on granitic formations. Water yielded as streamflow from the Missouri Gulch watershed averages between 10 and 15 percent of the total annual precipitation. In contrast, the high-altitude watersheds of the Continental Divide yield about 50 percent of the precipitation (USDA FS 1948, Leaf 1975). Monthly mean precipitation and streamflow for the 19-year period on the Missouri Gulch watershed (fig. 19) are similar to those previously shown (fig. 17) for Wagon Wheel Gap.

On the Missouri Gulch watershed, Berndt (1960) reported that in 12 of 18 years, the maximum storm peak was recorded in May within 3 weeks after the instantaneous spring peak was reached. The May peak flows were the result of rain or very wet snow at a time when the watershed was still charged with snowmelt water. The occurrence of an instantaneous hydrograph peak some 30 minutes after the peak of the storm is characteristic (fig. 20). Summer thunderstorms of high intensity and relative short duration are responsible for the sudden rise and fall in streamflow. The peak intensities appear to be related to the size of the storm, and are responsible for surface runoff and erosion. At the Manitou Experimental Forest, it has been found that summer thunderstorms averaging greater than 0.96 inch will cause surface runoff and erosion (USDA FS 1949).

The frequency of thunderstorms and the antecedent storage in the soil mantle also affect the percentage of rainfall that will be yielded as streamflow. During the wet summer of 1945 at Manitou, a series of five large storms occurred in slightly over 5 weeks, with several smaller storms interspersed between (USDA FS 1949). The rainfall, runoff, and percent yield from the Missouri Gulch watershed were as follows:

	Precipitation	Storm runoff	Yield
	(Inches)		*(Percent)*
July 14	0.66	0.004	0.61
18	.56	.002	.36
31	.73	.013	1.78
Aug. 13	.65	.081	12.46
30	1.94	.540	27.84

The higher yields during August indicated high soil moisture and little opportunity for the storage of additional rainfall. The above conditions

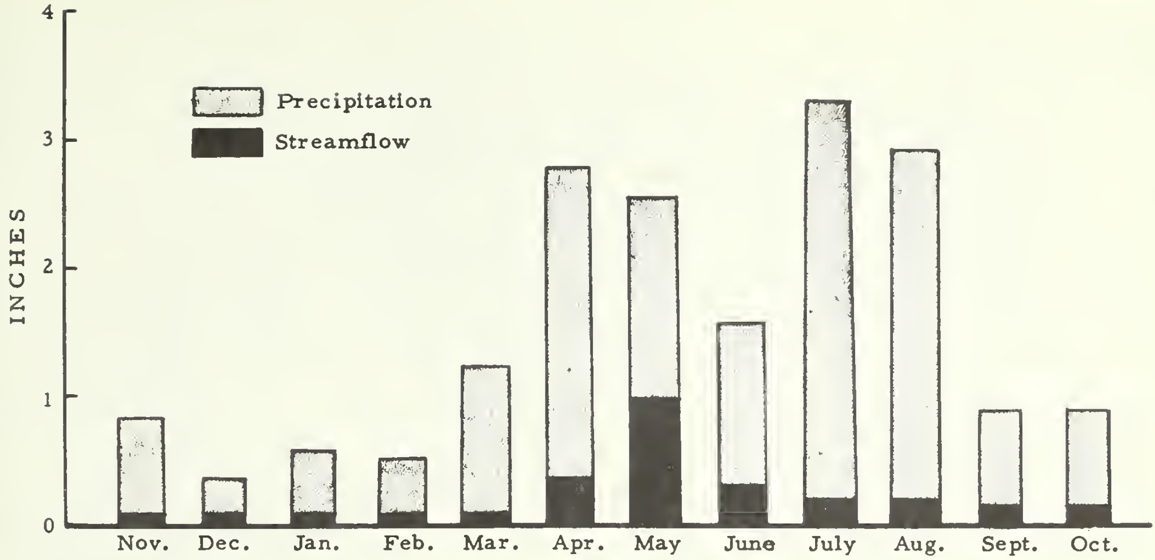

Figure 19.—Monthly mean precipitation and stream flow, Missouri Gulch watershed, Manitou Experimental Forest, 1940-58 (Berndt 1960).

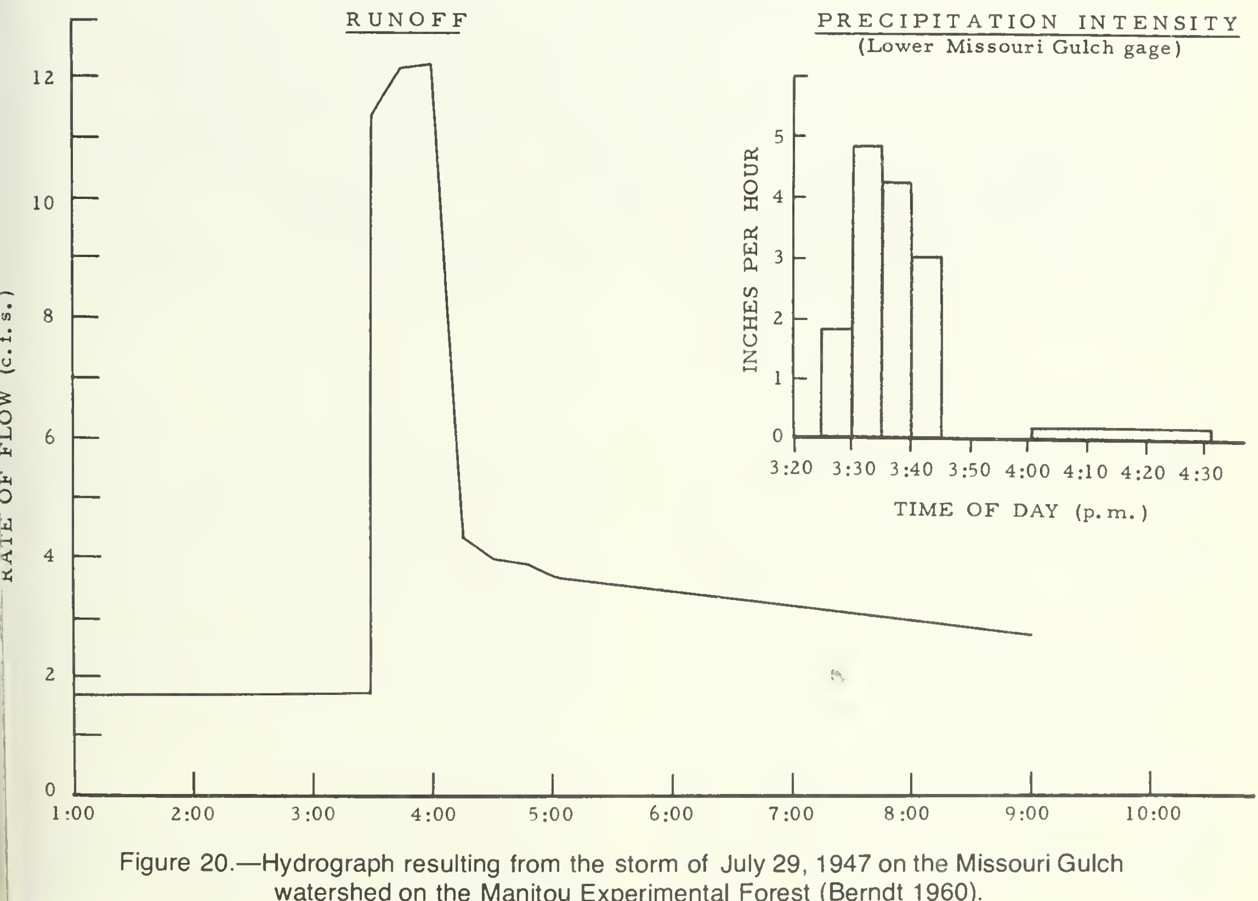

Figure 20.—Hydrograph resulting from the storm of July 29, 1947 on the Missouri Gulch watershed on the Manitou Experimental Forest (Berndt 1960).

are analogous to those in spring: low recharge requirements, a melting snowpack, and spring rains, which in some years can produce dangerous flooding. An analysis of 25 summer storms showed that volume of precipitation and antecedent flow accounted for 80 percent of the variability in storm runoff. Precipitation alone accounted for not more than 50 percent of the variability.

Improvement of Water Yields

There is adequate research evidence that water yields can be increased in the high-elevation subalpine forests in the Colorado Rockies after removing forest cover (Bates and Henry 1928, Goodell 1958, Leaf 1975).

Hoover (1959) believed that "much more is involved than simply cutting all of the trees or some percent of the stand. Too much attention has been given to the vegetation cut and too little attention paid to what vegetation should remain. The real need is to spell out what kind, size, age, and arrangement of plant cover is the most effective for specific situations." Similar views were held by Croft (1961). Some opportunities for increasing water yields in the Front Range are discussed in the following sections.

Snow Management

In the Colorado Front Range, the seasonal snowpacks develop mainly at elevations above 9,000 ft; few snow courses have thus been established to measure the shallow snowpacks in the pine zone below that elevation. Of some 30 snow courses on the South Platte River drainage, apparently only one is located in the ponderosa pine type, at an elevation of 7,900 ft. Three other snow courses are located between 8,600 and 8,800 ft, and the rest are at elevations above 9,000 ft (Washichek and McAndrew 1967).

Forest management in the ponderosa pine zone offers possibilities to change the pattern of snow accumulation and increase water yield. Love (1960) and Berndt (1961) pursued the possibility in a 2-year study of a National Forest timber sale near the Manitou Experimental Forest. In a mixed stand of ponderosa pine and Douglas-fir on a north exposure at 8,500 ft, the water equivalent of overwinter snow accumulation was measured under cut and uncut stands. Before harvest, the stand of merchantable timber (trees over 10 inches d.b.h.) had an average volume of 10,000 bd ft (fbm) per acre. Total basal area averaged about 120 ft^2 per acre. Two plots were left uncut, while 60 percent of the merchantable volume was selectively cut on two others. Basal area was reduced to 94 ft^2 per acre under selection cutting and to 43 ft^2 under commercial clearcutting.

Snowfall during the two winters studied was different, but the increase in water equivalent on the commercially clearcut plots ranged from 8 to 35 percent and was statistically significant when compared to the uncut plots. Snow cover over the selectively cut and uncut plots was similar. Snow disappeared from all plots at about the same time, indicating a speedup in snowmelt on the commercially clearcut plots. No provision was made to determine whether the increased water equivalent of the snowpack affected streamflow. Implications were that water yield might be increased from north exposures by commercially clearcutting mature stands of ponderosa pine and Douglas-fir.

Studies in the higher snowfall zones near the Continental Divide have indicated that increased runoff and higher spring freshets would be expected after patchcutting, which changes the usual snow distribution pattern by increasing snow accumulation in cleared areas and reduces evapotranspiration (Leaf 1975). The same principles apply to protected sites in the Front Range pine zone (fig. 21). Low evapotranspiration demands during the early spring period favor higher water yields from melting snows. The Wagon Wheel Gap study (Bates and Henry 1928) showed that about 50 percent of the annual precipitation came as snow, but water yield from the melting snows between March 30 and June 30 accounted for about 55 percent of the annual runoff. On the average, snowpack near Wagon Wheel Gap melted by March 25 on the south aspects and by May 15 on the north aspects. In the lower elevation Front Range ponderosa pine zone, the shallower snowpacks on similar slopes would probably melt prior to those dates.

For specific areas where water has extremely high value, it may be possible to increase the potential for water yield from the limited snow resource by applying evaporation suppressants, which slow or stop the movement of water vapor from the snow surface to the air. By applying monolayers of long-chain fatty alcohols such as hexadecanol to the snow surface in the central Sierra Nevada, Anderson and others (1963) found that evaporation reduction ranged from 35 percent under dense forest cover to 88 percent in large open meadows.

Forest Management

Reducing evapotranspiration and changing the patterns of snow accumulation by vegetal manipulation probably holds more potential for

Figure 21.—Late-lying snow in a small rectangular clearing on a north-facing slope on the Manitou Experimental Forest.

increasing streamflow than any other feasible means. Such increases in streamflow in the ponderosa pine zone will most likely come from drainages such as the Missouri Gulch watershed. This watershed, with its highly variable vegetation types and physiography, appears characteristic of much of the pine type. Average water yield is about 2.22 inches from an average annual precipitation of about 18.22 inches (Berndt 1960).

Management of selected riparian and other wet sites supporting trees or willows (*Salix* spp.) also offers considerable potential for increasing water supplies (Horton and Campbell 1974). It is worth noting that water rights resulting from such practices have already been adjudicated in the Front Range pine type and in the Arkansas River drainage basin near Swink, Colorado (Mountain Business Publishing, Inc. 1974). Type conversion from aspen-grass to only grasses and herbaceous plants in one Utah study resulted in an annual soil-moisture savings of about 3 inches (Croft 1950).

Clearcutting in about 80-year-old Front Range lodgepole pine, near Pingree Park, has shown a considerable savings of soil moisture. Dietrich and Meiman (1974) studied soil-moisture storage in the upper 6 ft of soil before cutting patches about 0.5 acre in size on slopes ranging from 20 to 30 percent at 9,000 ft elevation (table 3). From this and similar studies, it is presumed that less water will be required for

Table 3.--Summary of soil-moisture storage in the upper 6 ft of soil before and after small patchcuts in Front Range lodgepole pine, by aspect (Dietrich and Meiman 1974)

Aspect, treatment, and date	Treated area	Control area
	Inches of water	
South 86° East:		
Before patchcut, Sept. 1970	12.4	12.1
After patchcut, Sept. 1972	13.7	8.2
North 40° East:		
Before patchcut, Sept. 1970	12.7	12.1
After patchcut, Sept. 1972	14.3	7.8
North 33° West:		
Before patchcut, Sept. 1970	8.9	8.5
After patchcut, Sept. 1972	10.9	5.2

soil-moisture recharge, and any additional amounts of rain or snowmelt after recharge will be yielded as streamflow.

In Orr's (1968) study of a second-growth ponderosa pine stand in the Black Hills, thinning from 190 ft^2 of basal area and about 2,000 trees per acre to 80 ft^2 and 435 trees did not induce free water seepage to ground water in dry years. On his clearcut plot, free water seepage did occur even in dry years. The establishment of Kentucky bluegrass over the cleared plot subsequently reduced seepage yield potential, but the potential remained higher than in thinned and unthinned portions of the stand because of less capacity for moisture depletion from the entire soil mantle.

A root study of some native trees and understory plants on the Manitou Experimental Forest generally supports Orr's (1968) conclusions. Berndt and Gibbons (1958) observed that, in general, roots of ponderosa pine, Douglas-fir, lodgepole pine, and true mountainmahogany (*Cercocarpus montanus*) reached maximum depths between 4 and 5.6 ft, except where limited by bedrock. For mountain muhly (*Muhlenbergia montana*), Arizona fescue (*Festuca arizonica*), and kinnikinnick (*Arctostaphylos uva-ursi*), they noted that maximum rooting depths were between 2 and 3.4 ft.

Selective cuttings within forests have generally shown lesser soil-moisture savings and small or negligible increases in streamflow (Leaf 1975). In a 30-inch rainfall and 3-inch streamflow region in the ponderosa pine, Douglas-fir, white fir (*Abies concolor*) type (Workman Creek) in central Arizona, Rich (1965) found that a commercial timber harvest on an individual-tree selection basis, which removed 46 percent of the basal area of trees on the watershed, did not significantly increase streamflow. Water demands by the residual stand of trees evidently used most of the additional water made available by timber harvesting. In the same study, clearcutting 80 acres of moist-site forest vegetation increased streamflow about 46 percent. Rich concluded that clearcut openings and a change to even-aged timber management may be possible ways of maintaining the timber supply as well as increasing water yields.

The necessity of some form of clearcutting to increase water yields was again observed by Rich (1972) in eastern Arizona. He reported that clearcutting about one-sixth of the timber (mainly ponderosa pine) on the 900-acre West Fork Castle Creek watershed—roughly half of the proportion clearcut on the Workman Creek watershed—increased runoff 29 percent—slightly over half that computed for Workman Creek. Similar increases in runoff were observed from various patterns of clearcutting on Beaver Creek in central Arizona (Brown and others 1974).

In the subalpine zone of Colorado, where annual precipitation averages 30 inches, Leaf (1975) reported total water yield increases of more than 25 percent after strip cutting about 50 percent of the merchantable pine-spruce-fir timber on the Fool Creek watershed. After clearcutting the sparsely stocked stand of Engelmann spruce, Douglas-fir, and aspen on a watershed near Wagon Wheel Gap, Colorado, where precipitation averaged about 21 inches, Bates and Henry (1928) observed a 17 percent increase in streamflow.

Rangeland Management

Forage values have been damaged to some extent by excessive grazing or previous cultivation of productive rangeland in some areas of the ponderosa pine zone of Colorado (Hull and Johnson 1955). On such lands, it has long been recognized that runoff and erosion are closely related to the abundance of desirable bunchgrass, amount of litter on the soil surface, amount of bare soil, and infiltration capacity. Grazing use today is about half the estimated 300,000 head of cattle on the Front Range in 1950, but there remains a need to use improved methods of grazing management on native and reseeded pastures (Smith 1967, Currie and Smith 1970) to provide satisfactory watershed conditions (fig. 22). Other land use practices on the grazing lands, such as road building and urban development, must also be better planned to meet overall watershed objectives.

A

B

Figure 22.—Better grazing management on overgrazed rangelands (**A**), and revegetation on abandoned farmlands and completely deteriorated rangelands (**B**) will provide soil-protecting cover to minimize runoff and erosion.

Love (1958) pointed out that "forage production and water yield form a natural unit and reflect the interactions of soils, geology, climate, and vegetation by providing a common end product—runoff or streamflow—that can be measured and appraised." The rangelands in the Front Range pine zone are a mixture of forest, meadows, and abandoned croplands. On the Manitou Experimental Forest, for example, the pine ranges were divided into four classes: (1) grassland parks, untimbered; (2) open timber, ponderosa pine; (3) stands of dense timber with dense canopies; and (4) fields once cultivated, but now abandoned (Johnson 1953). Forage production is widely variable, and along with the diversity of the rangelands, complicates most rangeland watershed management programs.

From infiltration studies on the Front Range, it has been concluded that a good plant cover on coarse and porous soils minimizes surface runoff and erosion. In the grassland types, good plant cover generally indicates good range condition and potential for forage production. In a survey of range-watershed conditions on a Front Range grazing allotment, Reid and Love (1951) scored forage conditions on the basis of ecological development of the range vegetation. They then measured infiltration under four conditions of range forage growing on soils derived from a mixture of granite and schist (table 4). The infiltration rate of the plots in good forage condition was 118 percent greater than plots in very poor condition. The erosion rate on plots in good condition was about one-fourth that from the plots in very poor condition. Studies in different soil types showed similar results—the good condition class provided the best watershed condition.

Table 4.--Infiltration, erosion, and related factors of range condition on a Front Range grassland (Reid and Love 1951)

Factor	Forage condition class			
	Good	Fair	Poor	Very poor
Herbage production *(Pounds per acre)*	1,230	944	709	925
Infiltration rate *(Inches per hour)*	2.22	1.64	1.23	1.02
Runoff *(Inches per 50 minutes)*	2.45	2.72	3.05	3.58
Erosion *(Pounds per acre per inch of surface runoff)*	166	269	699	528
Bare area *(Percent)*	4.7	12.0	20.1	20.8

After studying the effects of livestock grazing on surface runoff and erosion, Dunford (1954) made recommendations as to the limits for intensity of grazing use of the bunchgrass type on Front Range watersheds. He believed heavy grazing (2.5 acres per cow-month) went beyond the limits allowable in good watershed management. Erosion under that intensity of grazing began to accelerate above a rate which he regarded as normal. He found that erosion did not appear substantially increased as a result of moderate grazing (4 acres per cow-month) in spite of some additions to surface flow. In practice, he believed that moderate grazing on relatively gentle slopes was permissible if the increased runoff from summer storms did not cause critical shortages of moisture for plant development. His observations were partially substantiated by a large-scale pasture study of three intensities of grazing —light, moderate, and heavy (Johnson 1953). Moderate grazing has proven to be the most efficient from the standpoint of economic returns in production. The moderately grazed pastures were also reported as maintaining good annual forage production, plant vigor, and density. In a later report on the same pastures Smith (1967) reached similar conclusions and recommended a grazing intensity that would utilize 30 to 40 percent of the dominant bunchgrass herbage by the end of the grazing season on ponderosa pine-bunchgrass ranges.

The infiltration studies, runoff plot studies grazing studies, watershed studies, and surveys on the Front Range have generally shown the advantages of careful use of the forage and forest resources.

The degree to which vegetation can lessen the impact of floods and hold the soil in place is important to wise use of the Front Range ponderosa pine zone. Love (1958) believed the water yield can be increased by managing vegetation on grazed lands, if two conditions are met. He believed the first conditions should be an adequate soil cover and highly permeable soil, so that maximum amounts of water will enter the soil. His second condition was that the cover be composed of shallow-rooted plants or other plants that do not make large demands upon soil moisture.

Love's second condition for water-yield improvement may be only partially compatible with the most desirable level of range management. A study of root depths and lateral spread for several native plants under three intensities of grazing use on a typical ponderosa pine-bunchgrass range revealed that heavy grazing reduced grass root mass and penetration (Schuster 1964). In general, the reductions in root mass were proportional to the amount of use on the individual grasses. Greater rooting depth under moderately grazed range appeared to indicate greater potential for soil-moisture withdrawal and less chance for increasing water yield than on heavily grazed range.

It is worth noting that a watershed experiment in Beaver Creek in central Arizona resulted in only an 8 percent increase in runoff due to 60 percent grazing use (Brown and others 1974). However, the authors point out that the increase "was not statistically significant at the 5 percent level and is not approaching practical importance." Negligible plant growth was observed, and soil compaction was apparently not sufficient to increase surface runoff.

The Role of Watershed Management in Land Use Planning

Watershed management technology has advanced to a level that warrants its consideration in comprehensive land use planning. Research has shown that carefully designed watershed management practices can provide practical solutions to many water problems resulting from development and urbanization along the Front Range (fig. 23). Although such solutions may be of a small scale, compared to the regional needs, they can be ecologically sound and feasible alternatives for maintaining water quality and augmenting municipal and domestic water supplies. In this connection, Storey (1960) observed that "even a small increase may mean an appreciable difference in total yield and would have great economic importance."

If watershed management has an important contribution to make, then land use planners will need to know how changes in the environment caused by timber harvesting will affect the water resource. The magnitude of any hydrologic change will depend on the pattern in which timber is harvested. Some logging methods can be detrimental to the water resource, whereas others can be beneficial. Therefore, the need for a planning tool which objectively evaluates the potential hydrologic

Figure 23.—Urbanization on private lands within the ponderosa pine belt along the Front Range. Inevitable development impacts on adjacent public lands are major challenges to land use planners.

effects of various timber harvesting strategies is obvious.

Progress has been made in the development of dynamic simulation models which predict the short-term effects of timber harvesting on snowmelt and water yield (Leaf 1975, Leaf and Alexander 1975). This work has been expanded to determine the long-term interactions between the water and timber resources with regard to partial cutting and regeneration practices in subalpine forests. The objective has been to design a model which: (1) is formulated in terms of the diverse form, structure, and arrangement of natural forest cover; and (2) at least qualitatively accounts for the response of these stands to management, based on the best information on hydrology and silviculture available.

These models are capable of simulating a broad array of timber harvesting alternatives; hydrologic changes can be determined for intervals of time which can vary from a few years to the rotation age of subalpine forests. The models have been calibrated for several representative drainage basins in the subalpine zone of Colorado and Wyoming.After additional calibration and testing to adapt them to the Front Range pine type, they should offer a relatively inexpensive means of providing improved information on potential hydrologic changes resulting from various forest and watershed management practices. Additional favorable aspects of these models are that they are no more complex than required to provide necessary information, and their application is not unduly restricted by data requirements. For the most part, data bases currently available in the Rocky Mountain region are adequate to begin operational testing of watershed management strategies in headwater streams.

Summary and Conclusions

The Colorado Front Range is generally regarded as the eastern foothills region of the central Rocky Mountain system. Land features consist of foothills, narrow mountain valleys, steep rocky canyons, large openings or parks, and mountain slopes and ridges. Most of the soils are derived from granites, are coarse textured, have relatively low productive capacity, and are potentially erosive once the protective covering is disturbed.

The area has a history of use going back more than 100 years, when the more accessible forests were cut over, and many ranges were heavily grazed by domestic livestock. The low-elevation (6,000 to 9,000 ft) forests and grasslands occur in various compositions. The major cover types include: (1) dense stands of pine with closed canopies and a ground cover of pine litter; (2) parks and other small openings consisting of herbaceous vegetation, mainly grass; (3) open pine stands with a ground cover of herbaceous vegetation; and (4) fields and valleys once cultivated. Stands of aspen are found scattered along valley bottoms, on benches, near the head of small drainages, and on old burns. Brush species grow at the lower elevations on south exposures and also on old burns. Mixed conifers (Douglas-fir, ponderosa pine, and Engelmann spruce) and lodgepole pine are common, but occur mostly on north exposures and on the more moist sites.

The climate in the Front Range pine type is highly variable. Most of the annual precipitation, which ranges from 15 to 20 inches, falls as rain during April through October. Precipitation amounts for selected stations range from about 10 inches to slightly more than 30 inches. Light afternoon showers are common from July through September. The average storm size required to cause runoff is about 0.96 inch. It is common for rainfall intensities to reach 3 inches per hour for 5-minute periods, but storms exceeding 4 inches per hour are rare. For the Front Range as a whole, three to five storms per year have sufficient intensity to produce surface runoff. Precipitation may be in the form of snow from late September through May, but snows commonly melt from the south exposures and valleys within a few days. The shallow snowpacks at the highest elevations and on the protected north exposures in the pine type generally disappear by the middle of May. Annual water yields in the Front Range pine type range from 3 to 5 inches, or about 10 to 15 percent of the annual precipitation.

The Front Range has had a long history of major flooding. Flooding can occur from high intensity rainfall on small areas in the foothills. However, major floods are caused by large upslope storms in May and June which deposit large quantities of rainfall below 7,000 ft, and deep snow above this elevation. Such floods trigger small-scale geologic processes which, in combination with high water, pose a persistent treat to uncontrolled urbanization along the Front Range.

Infiltrometer studies have provided guidelines for maintaining satisfactory watershed conditions in the Front Range ponderosa pine type. In the grassland type, on-the-ground organic materials should exceed 2 tons per acre, and live herbage should exceed 1,300 pounds per acre. In the pine type, about 20,000 pounds of litter per acre should be maintained. Tree removal should be avoided on areas with shallow soil and less than 20,000 pounds of litter

Figure 24.—A small clearcut patch in ponderosa pine after harvest by the seed-tree method. Small clearcut openings or drastically thinned forests are necessary to significantly increase water yields (Boldt and Van Deusen 1974).

reas with greater soil depth require somewhat sser amounts of litter to maintain satisfactory atershed conditions, and may be logged or razed to the extent where the remaining litter ccumulation does not fall below the guidelines.

In the Front Range pine type, as elsewhere, ydrologic studies have shown that clearcut penings are necessary to significantly in-eased water yields. Highest water yields ap-arently result when trees are harvested in nall patches (fig. 24). When forest openings e: (1) less than five tree heights in diameter;) protected from wind; and (3) interspersed so at they are five to eight tree heights apart, an timum pattern of snow accumulation results. ore snow is deposited in the openings, and less ow accumulates in the uncut forest so that total snow storage is not significantly increased. The snow in the forest openings melts earlier in the spring, at a time when evaporation is lower. Moreover, in the absence of trees, consumptive use is decreased; thus more water is available for streamflow. The pattern in which trees are harvested determines whether or not runoff will be increased. When the forest cover is removed in large clearcut blocks or by selective cutting of individual trees, water yields will be increased far less than if the same volume of timber were harvested in a system of small, dispersed forest openings. Under some conditions, streamflow may actually be decreased when timber is selectively harvested or clearcut in large blocks.

Minimal water-yield increases can also be expected on grazed lands under conditions of adequate soil cover and highly permeable soil, so that maximum amounts of water will enter the soil. Another requirement is that cover be composed of shallow-rooted plants that do not make large demands upon soil moisture. The second condition may not be compatible with desirable range management because high forage-producing plants on moderately grazed range have greater rooting depths and greater potential requirements for soil moisture.

Water yields are important in the Front Range pine zone. Although the 3- to 5-inch yields are comparatively small in contrast to yields of 12 to 25 inches of water from the high-altitude subalpine forests, watershed management practices can be expected to provide feasible solutions to many water-supply problems as competition for this limited resource increases. New problems, such as the chemical properties and bacteriological quality of water brought to the forefront by expanding foothills communities, all collectively show the need for careful land use planning and wise use of the forest and forage resources. The balance between the vegetation (timber and grass) that can be used and the amount sufficient for satisfactory watershed conditions is critical to management and preservation of the soil resource of the Front Range pine zone.

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The east flank of the Continental Divide consists largely of open timber stands and grasslands. Soils erode easily after abuse. Precipitation ranges from 15 to 20 inches, about two-thirds from high-intensity storms from April to September.

Guidelines are provided for maintaining satisfactory watershed conditions. The 3- to 5-inch water yields are comparatively small in contrast to yields of 12 to 25 inches from the high-altitude subalpine forests, but are important to development along the Front Range. Watershed management practices can be expected to provide practical alternatives for increasing water supplies.

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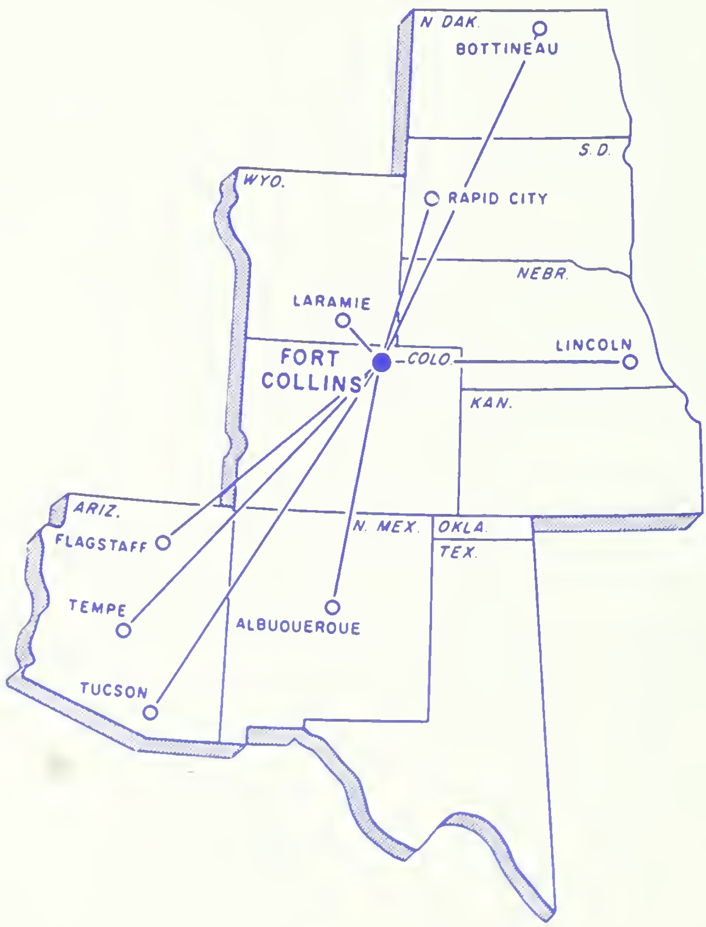
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MARCH 1975

Rocky Mountain Forest and
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HYDROLOGIC RELATIONS ON UNDISTURBED AND CONVERTED BIG SAGEBRUSH LANDS:

The Status of Our Knowledge

David L. Sturges

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Abstract

The status of our knowledge of watershed management for big sagebrush range lands is discussed. Climate, soils, vegetation, snow accumulation, and water yields are described, followed by a review and discussion of how management practices alter vegetative composition and the hydrologic regime. Potential hydrologic benefits from managing blowing snow in the big sagebrush type are outlined and research needs are highlighted.
Keywords: Multiple use, range hydrology, vegetation effects, watershed management, blowing snow management, *Artemisia tridentata*.

PREFACE

Information about the hydrology of big sagebrush rangelands is scattered through the literature and is often contradictory. This Paper reviews published research, outlines important hydrologic features of big sagebrush lands, and describes how management practices alter the hydrologic regime. It represents the author's personal assessment of available research results and as such, is not intended to be a complete literature review. Full responsibility is assumed by the author for the input and for any shortcomings that subsequently become evident with increased hydrologic understanding.

The purpose of the Paper is to guide professional hydrologists and land managers by providing information on (1) what is known about the hydrology of big sagebrush lands, and (2) how this knowledge can be effectively used in reaching management decisions. This purpose will be well served should it stimulate critical thinking and additional hydrologic research.

USDA Forest Service
Research Paper RM-140

March 1975

HYDROLOGIC RELATIONS ON UNDISTURBED AND CONVERTED BIG SAGEBRUSH LANDS:
The Status of Our Knowledge

David L. Sturges, Associate Plant Ecologist

Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University; research reported here was conducted at the Station's Research Work Unit at Laramie, in cooperation with the University of Wyoming. Portions of the research were supported by the Bureau of Land Management, U.S. Department of the Interior.*

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HYDROLOGIC RELATIONS ON UNDISTURBED AND CONVERTED BIG SAGEBRUSH LANDS:
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THE BIG SAGEBRUSH TYPE

The Physical Setting

Shrub members of the genus *Artemisia* L. occupy lands extending from southern Canada to northern Mexico, and from the edge of the Great Plains west to the Pacific Ocean in southern California. Their range in the 11 western States encompasses about 270 million acres. One *Artemisia*, big sagebrush *(A. tridentata)*, accounts for 196 million acres of the total acreage. The big sagebrush type embraces a wide range of environmental characteristics, extending as it does over much of western North America. However, certain hydrologic features are common throughout the type which permit a meaningful hydrologic discussion (fig. 1).

Figure 1.—Three subspecies comprise the big sagebrush complex:

A, Basin big sagebrush is an erect shrub 1-2 meters tall and usually grows below 5,000 ft;

B, Mountain big sagebrush is a flat-topped shrub up to 1 meter tall and commonly grows above 7,000 ft;

C, Wyoming big sagebrush is a dwarf shrub, often suggestive of black sagebrush (*A. nova*), and grows on shallow soils between 5,000 and 7,000 ft.

B

Although this Paper is restricted to a hydrologic discussion of big sagebrush, the explored relationships have broader applicability since many of the *Artemisias* are closely related to big sagebrush in growth form and habitat requirements.

Big sagebrush lands are semiarid, receiving about 8 to 20 inches of precipitation annually. One-half to two-thirds of yearly precipitation falls during winter, mostly as snow. The relocation of snow by winter winds and attendant water loss by sublimation during transport are important hydrologic features. Snow accumulates through the winter but melts rapidly as temperatures warm in the spring. The water then becomes available for onsite use, for export from the melt site as overland flow, or, in the higher precipitation zones, may enter a groundwater system and support perennial streamflow.

Vegetative growth depends on melt water stored in the soil. Summers are typically warm, the evaporation rate is high, and summer rainfall is ineffectual in replenishing soil moisture. Some sagebrush lands are subject to convectional summer storms that may produce high runoff rates and erosion.

The Individual Plant

Big sagebrush (fig. 1) is a species with enormous genetic plasticity. Three subspecies—basin *(A. tridentata tridentata)*, Wyoming *(A. t. wyomingensis)*, and mountain *(A. t. vaseyana)*—are recognized by Beetle (1960) and Beetle and Young (1967). Positive identification of species and subspecies, where appropriate, is important because plants are often indicative of important environmental differences. Mountain big sagebrush, for example, typically grows above 7,000 feet on lands receiving a large proportion of yearly precipitation as snow that is subsequently drifted by wind. Consequently, areas supporting this subspecies present a greater opportunity for water management than does Wyoming big sagebrush, which grows below 5,000 feet on sites with less soil development and lower precipitation.

The advent of thin-layer chromatography offers a means to identify sagebrush species and to separate subspecies independent of traditional taxonomic keys. Such identification in the past would have prevented many of the contradictions that presently abound in big sagebrush literature. Brunner (1972) describes how the technique can be used on a practical basis to identify sagebrush species as well as subspecies within the big sagebrush complex. Paper and thin-layer chromatography of big sagebrush seeds also provide the means of separating basin big sagebrush seeds from those of Wyoming or mountain big sagebrush (Hanks and Jorgensen 1973). The technique also provides a quantitative means of identifying individual big sagebrush plants palatable to livestock and big game (Hanks and others 1971).

Big sagebrush is particularly adapted to an environment with a warm and dry growing season, where vegetation exists primarily on moisture stored in the soil at the time of snowmelt. Diettert (1938) believes the presence of trichomes or hairs, which produce the silvery gray appearance of foliage, may be one of sagebrush's primary adaptations in limiting moisture loss from leaves. The numerous trichomes, present on both sides of a leaf, form a dense, hairy covering about 200 micrometers thick. The closing of leaf stomates also helps to maintain a favorable internal water balance as soil moisture becomes limiting.

Sagebrush responds to dry conditions by reducing the size of leaves. Plants growing on sites with less favorable moisture relations have smaller leaves than plants where moisture is sufficient. Leaves produced late in summer are considerably smaller than those produced earlier in the season when moisture was readily available. Big sagebrush has a pronounced leaf drop in midsummer, although some leaves are shed throughout the year (Diettert 1938). The rate of photosynthesis declines sharply at the time of midsummer leaf drop which De Puit and Caldwell (1973) attribute primarily to the closing of stomates caused by high internal water stress. However, phenological factors within the plant may also play a role in limiting photosynthesis and water loss as the growing season advances.

The root system of big sagebrush enables it to compete efficiently for moisture and nutrients. The majority of roots are located in the upper 2 feet of soil; a particularly dense network of interwoven roots develop beneath the crown in the surface 6 inches of soil. Plants either have a taproot or several dominant lateral roots commonly extending 5 to 6 feet deep. Much deeper roots have been observed on alluvial soils. The dense network of shallow roots competes directly with associated herbaceous species for moisture, usually the factor most limiting growth in the sagebrush environment. The deeper roots permit sagebrush to tap moisture reserves unavailable to herbaceous species and to remain physiologically active through the summer drought period. Deep roots also provide a definite competitive advantage in surviving prolonged climatic droughts.

Management of Big Sagebrush Lands

Grazing by domestic livestock (fig. 2) has been and will remain the dominant usage by man on most sagebrush lands, despite a burgeoning population and expanding recreational pressure. Although wildlife habitat, recreation, and mining are also important uses of the type, only livestock use is discussed here since past management practices on sagebrush lands affecting their hydrologic performance were done in a livestock context.

Big sagebrush is the most productive element of its ecosystem, but herbage has a low value for livestock forage except to sheep on winter range. Overgrazing the herbaceous species which comprise the forage resource in the type can reduce their competitiveness to such an extent that sagebrush completely dominates the site. The dense stands of brush persist for decades, since individual big sagebrush plants commonly live 50 to 75 years. Sagebrush conversion is one of the chief tools utilized by range managers to restore grazing productivity. After the brush is removed, sites are either reseeded, or allowed to return to native herbaceous vegetation if density of desirable plants is sufficient to quickly occupy the site.

Because economic returns from livestock grazing are low, sagebrush removal methods must be inexpensive. Burning, an early means of conversion, still remains a viable technique. Mechanical procedures came into widespread use with development of large crawler tractors, but they are limited to slightly rocky sites of moderate slope. Discovery of 2,4-D, one of the phenoxy herbicides, revolutionized management of big sagebrush lands. Spraying was adopted as the preferred method of sagebrush control[2] in the late 1950's. The practice was readily accepted by managers of both privately and publicly owned lands. Figures for sagebrush control acreages in Wyoming illustrate trends throughout the West. In the 10-year period from 1952-62, about 16,000 acres of sagebrush land were mechanically controlled but 319,000 acres were sprayed. Between 1963 and 1970, however, sprayed acreage in Wyoming increased to 1.3 to 1.4 million acres.[3]

[2] 2, 4-D is currently registered for control of big sagebrush. Since pesticide registrations are under constant review, use of any pesticide should be checked with appropriate State or Federal agencies.

[3] Unpublished material from W. G. Kearl, Agricultural Economist, University of Wyoming, Laramie.

Figure 2.—Big sagebrush rangelands are an important grazing resource for both cattle and sheep. Historically, these lands linked the vast desert ranges and the mountain summer ranges.

HYDROLOGIC FEATURES OF MOUNTAIN BIG SAGEBRUSH

Many phases of the hydrologic cycle for big sagebrush are poorly understood. The type has received little attention because watershed management research efforts have been concentrated in regions of greater precipitation. However, big sagebrush lands, particularly those vegetated by mountain sagebrush, include areas of heavy snow accumulation that support perennial streamflow. The features discussed here are not all inclusive, but were selected as especially important characteristics that shape the hydrology of mountain sagebrush lands.

Specific data contained in the text and figures of this report, unless otherwise noted, come from two Wyoming sites where big sagebrush hydrologic studies have been conducted by the Rocky Mountain Forest and Range Experiment Station. Wayne's Creek, located in the northwest part of the State at an altitude of 9,500 feet, is representative of conditions on high-elevation, mountain big sagebrush lands. The Stratton Sagebrush Hydrology Study Area, situated in south-central Wyoming at 7,800 feet, was established in cooperation with the Bureau of Land Management. Dense stands of mountain big sagebrush are present on mesic sites at Stratton, and Wyoming big sagebrush and black sage *(A. nova)* are found on the drier upland slopes and the ridges. Mountain sagebrush stands at both study locations are thrifty and underlain by productive soils. Such areas are typical of those where sagebrush has been controlled as a range improvement practice. This type of land is also the source of perennial streamflow.

Precipitation

Stands of big sagebrush indicate a climate with a relatively warm and dry growing season, where the bulk of yearly precipitation is received during the cold months. Mountain big sagebrush receives 15 to 20 inches of precipitation per year, about 60 percent of the total as snow (fig. 3). Temperatures are sufficiently low to prevent melting throughout the winter in the higher parts of the mountain sagebrush zone, but some melting does occur at lower elevations. The transition to a summer precipitation regime begins in April or May when precipitation may fall as snow, rain, or a rain-snow mixture. By September, reversion to winter conditions has begun. Precipitation received after October falls as snow, and by November temperatures are sufficiently cold to hold the snow until melt begins in April or May. Snow that falls in the spring and early fall usually melts within a few days.

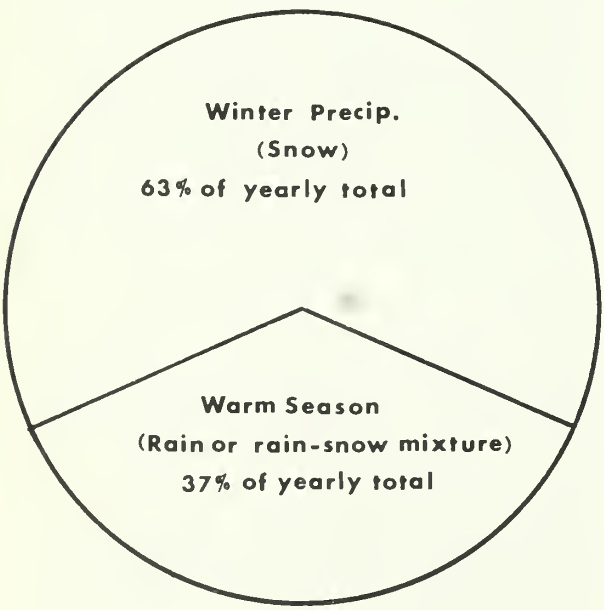

Figure 3.—The majority of yearly precipitation in the mountain sagebrush zone falls during the winter as snow.

Summer precipitation is concentrated in the months of June and September, when more than 60 percent of the warm-season total is received (fig. 4). June rainfall is important for plant growth, but that received during July, August, and September is of little consequence. September rainfall does replenish soil moisture, thus reducing the quantity of snowmelt water required for soil recharge in the spring. The distribution of summer rainfall by 0.10-inch precipitation classes (fig. 5) emphasizes the small size of most events. For example, 0.10 inch or less fell on about two-thirds of the days with precipitation. Precipitation exceeded 0.50 inch on just 6 percent of the days that rain fell.

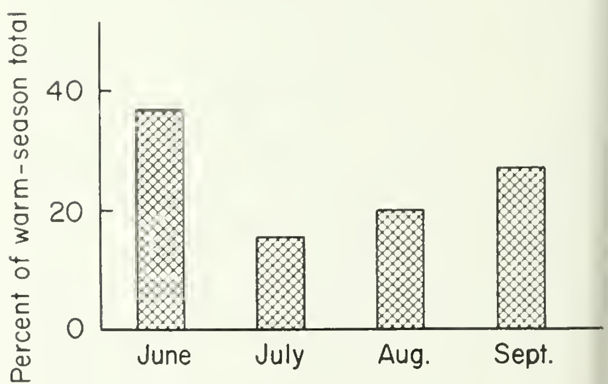

Figure 4.—About 60 percent of the warm-season precipitation is received in June and September in the mountain sagebrush zone.

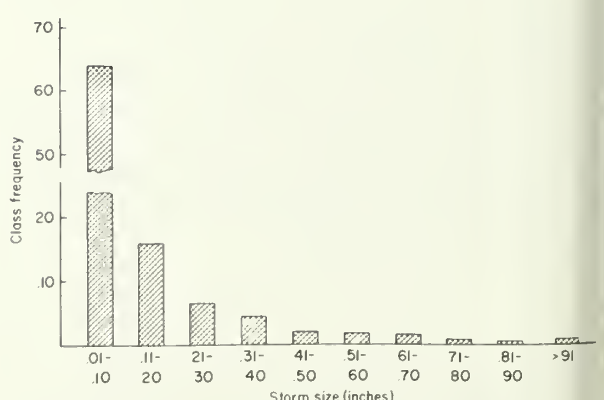

Figure 5.—The majority of summer precipitation events are small in the mountain sagebrush zone; daily precipitation is less than 0.21 inch on about 80 percent of days with precipitation.

Rainfall intensities greater than 1 inch per hour generally last less than 10 minutes. Average intensity for entire storm periods is usually below 1 inch per hour, considerably less intense than the period of maximum rainfall within a storm (table 1).

Table 1.--Precipitation characteristics for summer storms with rainfall bursts that exceeded 1.00 inch per hour (in/h) intensity at two hydrologic study sites in Wyoming

Characteristics	Stratton	Wayne's Creek
Years of record (number)	5	8
Minimum storm size (inch)	>0.25	>0.50
Events (number)	7	4
Total storm--		
Intensity of		
<1 in/h	6	3
>1 in/h	1	1
Duration of		
<30 min	4	1
30-60 min	0	0
>60 min	3	3
Maximum rainfall burst--		
Intensity of		
1-2 in/h	4	3
2-3 in/h	2	0
>3 in/h	1	1
Duration of		
<10 min	7	3
>10 min	0	1

Wind and Drifting Snow

Wind is an extremely important part of the physical environment on mountain sagebrush lands because of its role in snow transport. Speeds reach a maximum during the winter months, thus accentuating the blowing snow phenomenon, one of the distinctive features of sagebrush hydrology (figs. 6 and 7). Much of

Figure 6.—Blowing snow is a distinctive hydrologic feature of mountain sagebrush lands; a substantial portion of winter precipitation can return to the atmosphere during drifting.

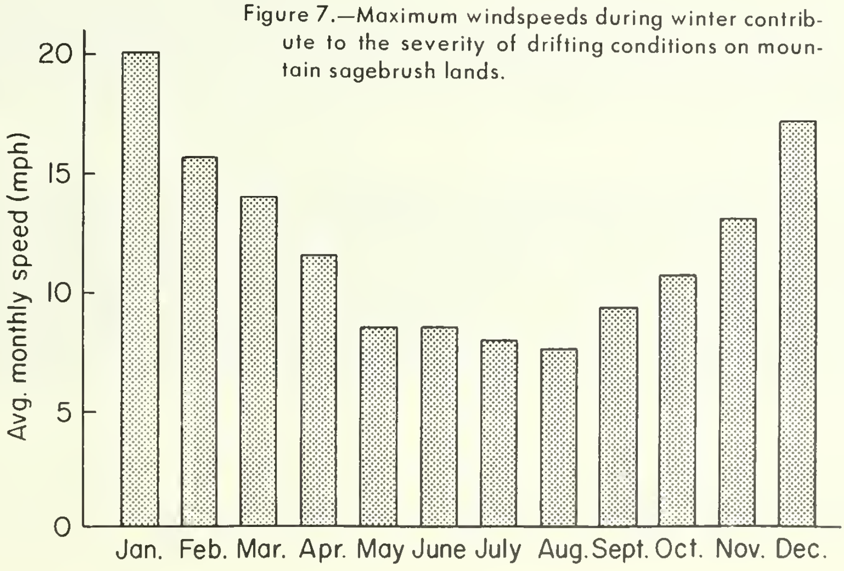

Figure 7.—Maximum windspeeds during winter contribute to the severity of drifting conditions on mountain sagebrush lands.

the snow that falls on higher elevation lands is blown from windward slopes and ridge areas to topographically controlled depositional sites such as the lee side of ridges or incised drainages. Newly fallen snow begins to drift when winds reach about 12 miles per hour; greater speeds are required for transport of metamorphosed snow.

An unknown proportion of winter precipitation is returned to the atmosphere during drifting. Schmidt (1972) formulated a mathematical model that describes the sublimation process in terms of relative effects of various environmental parameters on the sublimation rate. Calculations suggest that large quantities of water return to the atmosphere during a drifting event. Field measurements by Tabler (1972) in southeast Wyoming also indicate that a substantial portion of winter precipitation does return to the atmosphere. The average distance required for a drifting snow particle to sublimate (transport distance) was about two-thirds of a mile. Based on this figure, (Tabler (1973) subsequently showed that, when major natural traps which accumulate drifting snow are spaced at distances of 0.5, 1,0, and 2.0, and 3.0 times the average transport distance, 25, 50, and 75, and 83 percent, respectively, of the drifting snow returns to the atmosphere.

Snow commonly accumulates in drifts 10 to 20 feet deep where drifting conditions are severe. The larger drifts contain more water than required to satisfy the soil-moisture deficit, and the excess may be yielded to ground water. The concentration of snow by wind and subsequent ground-water recharge is probably responsible for the presence of springs and perennial streamflow from sagebrush lands. The large drifts persist into June, long after the general snowpack has melted (fig. 8). By this time, daytime temperatures reach 60° to 70°F and incoming solar radiation is near the yearly maximum. The magnitude of evaporation from the snow and moistened soil is unknown, but it could account for a substantial part of drift-water volume. This aspect of sagebrush hydrology needs investigation. Evaporation losses from isolated drifts behind 4-foot-high snowfences equaled about half of the water content of the drift (Saulmon 1973), but it is not known if losses of this magnitude are representative for large drifts.

Infiltration and Sediment Transport

The factors governing infiltration and sediment movement are complex, and their interrelationships poorly understood. Investigators have relied on multiple regression analysis to identify soil, cover, and topographic parameters that relate to infiltration and erosion. These studies were conducted on small plots with

Figure 8.—Deep snowdrifts thot persist long ofter general watershed snow cover hos melted recharge ground woter:
A, Snow conditions on June 3, neor the time of peak snowmelt runoff;
B, Snow conditions on June 16, obout 1 week ofter the hydrograph peok.

artificially applied rainfall. To date, it has not been possible to develop specific relationships that are generally applicable over widespread areas.

There is agreement that watershed cover, variously defined but often including litter and rock besides basal and canopy coverage of live vegetation, is an important factor influencing infiltration and erosion caused by overland flow. Soil protection must increase as slope angle increases since the erosive power of water is closely related to flow velocity. The size of particles that water can transport increases approximately as the fifth power of velocity, while the quantity of sediment water can transport varies from the 3.2 to 4.0 power of velocity (Twenhofel 1950).

The ability to predict infiltration is further compounded by the changing importance of factors that govern infiltration with time. An empirical relationship may be valid at one time of the year but in appreciable error 3 months later (Gifford 1972). Infiltration rates are characteristically higher in the spring because of increased soil porosity caused by freezing and thawing overwinter, but then decrease as the season advances. Grazing, by removing plant material and compacting the soil, reduces infiltration rates within a season (Gifford and Busby 1974). Soil texture and organic matter content are other important soil factors that influence infiltration and sedimentation. The relationship between organic matter content of soil and soil erodibility indicates the complexity of infiltration and erosion processes. Organic matter decreases erosion of clay soils but increases erosion of sandy soils (Meeuwig 1971).

Infiltration measurements at many locations n the sagebrush type indicate that steady-tate infiltration usually exceeds 1 inch per iour, and often exceeds 2 inches per hour luring the first 10 minutes of rain. The land nanager influences the amount of bare soil, tter, and vegetation through management deisions. Practices that increase the amount of vatershed cover at the expense of bare soil romote soil stability.

Soil has no single infiltration capacity; rath-r, the infiltration rate is related to moisture ontent. The rate decreases markedly as dry oil is moistened during the first 15 minutes f rain, but then decreases at a much slower ite as additional time passes, or it may be-ome constant (Gifford 1968). The initial infil-ation rate of premoistened soil is lower than iat of dry soil. These relationships have im-ortant implications for field situations. Over-nd flow will be produced from rain falling at lwer intensities when soil is moistened than if it were dry. Rain falling at a constant intensity on dry soil may be absorbed for a period of time, but then as the infiltration rate falls below rainfall intensity, overland flow can start.

Water Yield Characteristics

Sagebrush and Timbered Lands Contrasted

Streamflow characteristics of sagebrush lands can be appreciated by comparing flow regimes with those of a timbered subalpine watershed. Figure 9 compares yearly hydrograph of Loco Creek on the Stratton Experimental Area with Fool Creek on the Fraser Experimental Forest near Fraser, Colorado. The hydrograph of Fool Creek is a composite developed from 15 years of record prior to timber harvest (Leaf 1975). Selected flow characteristics for the two watersheds are summarized in table 2.

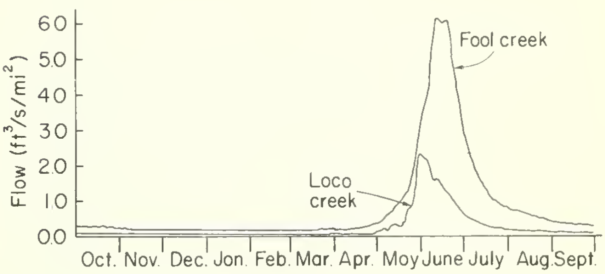

Figure 9.—Base flow, peak flow during snowmelt, and volume of snowmelt runoff are greater on forested subalpine watersheds (Fool Creek) than on sagebrush watersheds (Loco Creek).

Gross differences between the hydrographs are readily apparent. Base flow on the timbered watershed is more than twice as great as from Loco Creek, and peak flow rates during snowmelt are almost three times as great. Fool Creek yields 42 percent of annual precipitation as runoff, while the yield on Loco Creek is 22 percent. Snowmelt runoff persists longer on the forest watershed. The timing of snowmelt, and snowmelt discharge rates, probably vary more in the sagebrush type than on timbered land. Snowmelt is responsive to warm temperatures in the late winter and early spring because sagebrush lands are at a lower elevation, the snowpack is shallower, and snow is directly exposed to solar radiation. Advected energy is

Table 2.--Selected flow characteristics for a timbered subalpine watershed (Fool Creek, Fraser Experimental Forest, Colorado) and a sagebrush watershed (Loco Creek, Stratton Experimental Area, Wyoming)

Parameter	Fool Creek (1940-55)	Loco Creek (1968)
Area (acres)	714	1,639
Average annual precipitation (inches)	26.1	15.2
Runoff (area-inches)	11.1	3.3
Yield efficiency (percent)	42	22
Peak daily discharge ($ft^3/s/mi^2$)	6.1	2.3
Duration snowmelt runoff (days)	134	118
Days to accumulate:		
First 25% of snowmelt runoff	50	33
Second 25% " " " "	9	9
Third 25% " " " "	11	11
Fourth 25% " " " "	64	65

probably an important energy source driving melt on sagebrush lands, but is of lesser importance in the forest environment.

The form of the snowmelt hydrograph is similar for Loco Creek and Fool Creek even though runoff volume, flow rate, and runoff duration were greater for the timbered watershed. For example, the time required to accumulate the first 25 percent of snowmelt runoff equaled 37 percent of the melt season on Fool Creek and 28 percent of the season on Loco Creek. The next 50 percent of runoff volume was produced during a brief interval that comprised just 15 percent of the runoff period for both the forested and sagebrush watersheds. This flow volume equaled about 35 percent of total annual flow on the two areas. The time required to accrue the last 25 percent of snowmelt runoff equaled 48 percent of the runoff interval for Fool Creek, and 55 percent of the runoff interval at Loco Creek.

Snowmelt Runoff in Mountain Big Sagebrush

Flow volumes during the snowmelt season are extremely sensitive to daily fluctuations in weather, as reflected by the erratic nature of daily discharge for Wayne's Creek (fig. 10). Maximum snowmelt discharge can vary from early to late in the melt season, depending on the availability of energy to drive the melt process and the quantity of snow remaining on the watershed. The depth of snow and watershed slope orientation are other important factors contributing to the variability of snowmelt runoff. The warmer south- and west-facing slopes promote faster melting than a north exposure where radiation influx is less. The volume of snowmelt runoff is also more responsive to short-term weather patterns on areas with a shallow snowpack than where snow is in deep drifts because of the energy difference required to warm snow to the melting point.

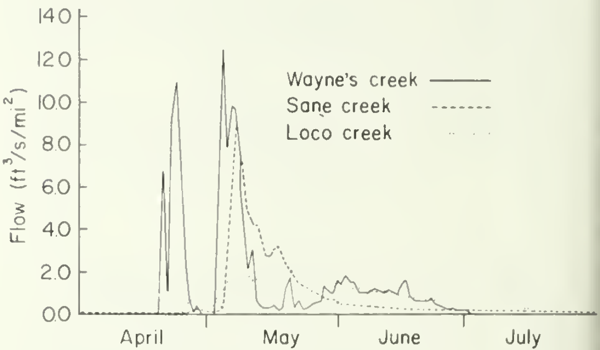

Figure 10.—Snowmelt runoff from sagebrush lands is sensitive to daily fluctuations in weather, as shown by flow on Wayne's Creek. Water flowing on top of the snow caused the high discharge rates on Sane Creek compared with those of Loco Creek, an adjacent watershed that did not develop over-the-snow flow.

Flow delivery on Sane Creek in 1970 (fig. 10) illustrates another hydrologic phenomenon, over-the-snow flow, that is probably best expressed in the sagebrush type. A well-developed drainage network on top of the snowpack in Sane Creek efficiently conveyed melt water from the watershed. The lower flow rate on Loco Creek is representative of the usual snowmelt runoff pattern. The channel eroded into the Sane Creek snowpack was about 6 feet deep and 3 feet wide (fig. 11). Discharge characteristics of Sane Creek were appreciably altered by the short-lived delivery system. Maximum instantaneous flow was more than three times as great as lfow in years without over-the-snow flow. Yield efficiency also exceeded that of Loco Creek for the only time on record because of the efficient drainage network provided by channels incised in the snowpack.

Over-the-snow flow develops when snowmelt on upland areas exceeds soil infiltration capacity. Water movement through the deep,

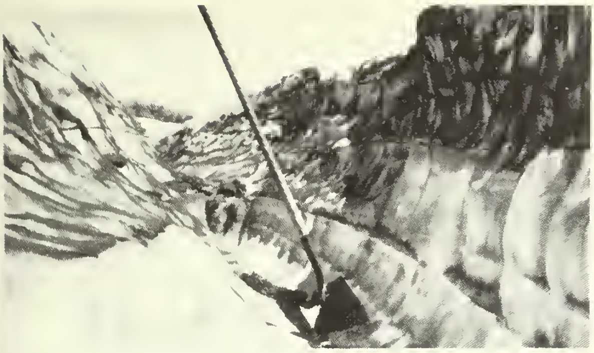

Figure 11.—Water flowing over the snow surface from melt on upland areas produced this channel in the dense snow filling a drainageway. Such channels quickly convey melt water from the watershed with negligible transport losses. Dark material on the sides and bottom of the channel is soil deposited by runoff water.

dense snow in channels is quite slow, and continued input causes the water to flow across the snow surface. The surface flow minimizes transport losses since little water infiltrates into the soil, but probably contributes to flooding that sometimes occurs from midwinter thaws on sagebrush land. Over-the-snow flow has been observed at the Wayne's Creek watersheds and at other locations in Wyoming as well. t is probably a common, but short-lived, phe-nomenon that develops to some degree every year wherever substantial quantities of snow ccumulate in the sagebrush environment.

ummer Runoff from Rainfall

Runoff from summer rainfall is a function f the infiltration capacity of the soil, the mount and duration of rainfall, and rainfall ntensity. Although instances of severe runoff nd erosion resulting from convectional storms re evident throughout the sagebrush zone, etailed information about precipitation and unoff characteristics is limited for small water-heds. Thirteen years of study at Wayne's Creek uggests that most runoff events, in the higher arts of the sagebrush zone at least, are in esponse to rain falling on soil that is already et, rather than in response to high-intensity torms. The majority of runoff events took lace in June soon after snowmelt was com-leted or when soil was wet from previous ains; the runoff-producing storms were not articularly large or of high intensity (table 3).

The highest runoff from rainfall equaled about 7 percent of precipitation. Instantaneous flow rates produced by rainfall were lower than those from snowmelt.

Table 3.--Characteristics of summer runoff events for a 13-year record period, 1959-71, in Wayne's Creek--a 60-acre high-elevation mountain sagebrush watershed in Wyoming

Date of events	Precipitation: Amount	Precipitation: Intensity, Maximum	Precipitation: Intensity, Average	Runoff: Percent of precipitation	Runoff: Maximum instantaneous flow
	Inches	*Inch/hr*			*ft³/s/mi²*
1962:					
June 22	0.26	3.60	0.08	0.5	0.3
1963:					
June 21	.12	.48	.07	1.5	.3
July 9	.50	--	--	.1	.5
1964:					
June 17	.39	1.80	.13	6.8	4.9
June 21	.20	.26	.06	.6	.4
1965:					
July 4	.10	1.50	.22	5.8	2.0
July 19	.35	2.70	.19	.1	.1
July 24	.72	1.88	.39	2.2	9.9
July 25	.16	.18	.04	.1	.4
July 25	.13	.60	.56	3.7	1.8
July 30	.44	.48	.17	.5	1.6
Aug. 19	.80	.36	.09	<.1	.2
Aug. 19	.41	.98	.18	1.3	3.1
Aug. 21	.31	.75	.14	.4	.7

HYDROLOGIC RESPONSE OF SAGEBRUSH LANDS TO MANAGEMENT PRACTICES

Vegetative Response to Sagebrush Conversion

An understanding of the hydrologic consequences of land management practices in the big sagebrush type requires a thorough knowledge of vegetative changes that accompany sagebrush removal. Past management practices have largely been oriented toward increasing the quantity of forage available to domestic livestock by killing sagebrush, thereby diverting site resources to herbaceous species.

Big Sagebrush

Removing sagebrush converts a shrub-dominated vegetation to one dominated by herbaceous species. As a practical matter, not all sagebrush plants are killed by any method of conversion. Popular mechanical measures, except harrowing and railing, kill at least 90 percent of sagebrush plants when properly implemented (Pechanec and others 1965). Mechanical methods must be suited to the site and to the condition of the sagebrush stand. Kills approaching 100 percent are achieved by disking or plowing on rock-free sites where equipment can function properly. Carefully executed burns also kill most of the sagebrush plants. Spraying with 2,4-D in the spring when sagebrush is susceptible kills at least 90 percent of the plants. About 2 months is required for plants to completely defoliate.

Reseeding must be planned in conjunction with removal methods such as plowing and disking that destroy all vegetation. Failure to reseed permits sagebrush seedlings to establish, thus negating the control objectives. Planting is also necessary, whatever the control method, if there are inadequate numbers of valuable herbaceous plants to quickly occupy the site. Reseeding is recommended by Pechanec and others (1965) where desirable plants comprise less than 20 percent of total plant cover prior to treatment.

Crested wheatgrass *(Agropyron cristatum)* or Siberian wheatgrass *(A. sibericum)* have been the principal grasses planted on sagebrush lands. Rumsey (1971) found that production by introduced species exceeds that of undisturbed big sagebrush vegetation prior to conversion. Production by crested and Siberian wheatgrasses seeded in the 8- to 12-inch precipitation zone and a grass-alfalfa *(Medicago sativa)* mixture planted in the 12- to 16-inch precipitation zone was 46 percent and 124 percent greater, respectively, than herbaceous production by the climax big sagebrush stand.

Grass Production

Grass production commonly doubles after sagebrush removal. Burning, and methods other than plowing and disking, do not greatly alter herbaceous composition. Spraying strongly favors grasses over forbs, however. Early reports of chemical sagebrush control documented the increase in grass growth following treatment (Hull and others 1952, Hyder and Sneva 1956). Native grass production often doubles the year after sagebrush spraying and may further increase to triple that of unsprayed areas within 3 years. However, the increase to be expected over the long-term has not been adequately established. Certainly, subsequent grazing management is an important factor governing the length and magnitude of the response of grasses to sagebrush control. A typical response is shown in figure 12. Average production in the 6 years after treatment was 677 pounds per

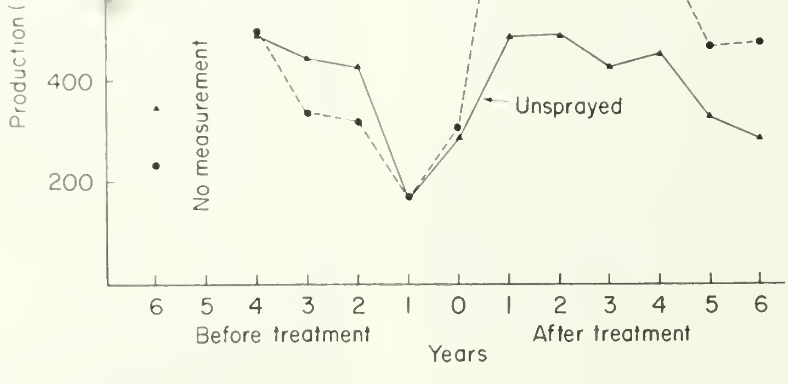

Figure 12.—Grass production (air-dry) for a sprayed and adjacent unsprayed high-elevation watershed.

acre (air-dry), about double the 312 pounds-per-acre average for 5 years preceding treatment. The watersheds were grazed moderately by cattle before spraying, but animals were excluded from both after treatment.

Forb Production

In climax big sagebrush stands, forbs can contribute from less than 20 to more than 50 percent of the herbaceous vegetation (Hyder and Sneva 1956, Tabler 1968, Smith 1969, Rumsey 1971). Of the sagebrush control methods that leave herbaceous vegetation relatively undisturbed, spraying is the only technique that drastically affects forb abundance. Phenoxy herbicides are not selective for sagebrush alone, but act against all broad-leaved plants. Spraying not only kills sagebrush, but severely curtails forb growth as well. The effect on a particular forb species depends on the growth stage of that species when spray is applied, whether it has food stored in roots, as well as its basic vulnerability to 2,4-D. The spray moderately or severely affected 13 of the 38 forbs evaluated by Blaisdell and Mueggler (1956).

Spraying a mountain big sagebrush watershed decreased forb production an average of 50 percent in the 6 years after treatment (fig. 13). Forbs recovered slowly. They contributed 37 to 45 percent of total herbaceous production in 5 years preceding treatment, but only about 15 percent the first 4 years after spraying. By the 6th year, forbs contributed 24 percent of total herbaceous production. Recovery can be faster than that indicated in figure 13. Thilenius and Brown (1974) found that grass dominance began to decline 2 years after spraying, and after 3 or 4 years the percentage composition of forbs had substantially recovered.

Forb damage is a little appreciated byproduct of spraying. The value of forbs as a forage resource for sheep and big-game is well known, but the dependency of other organisms on forbs is not fully appreciated. Forbs, for example, are an essential ingredient in the diet of young

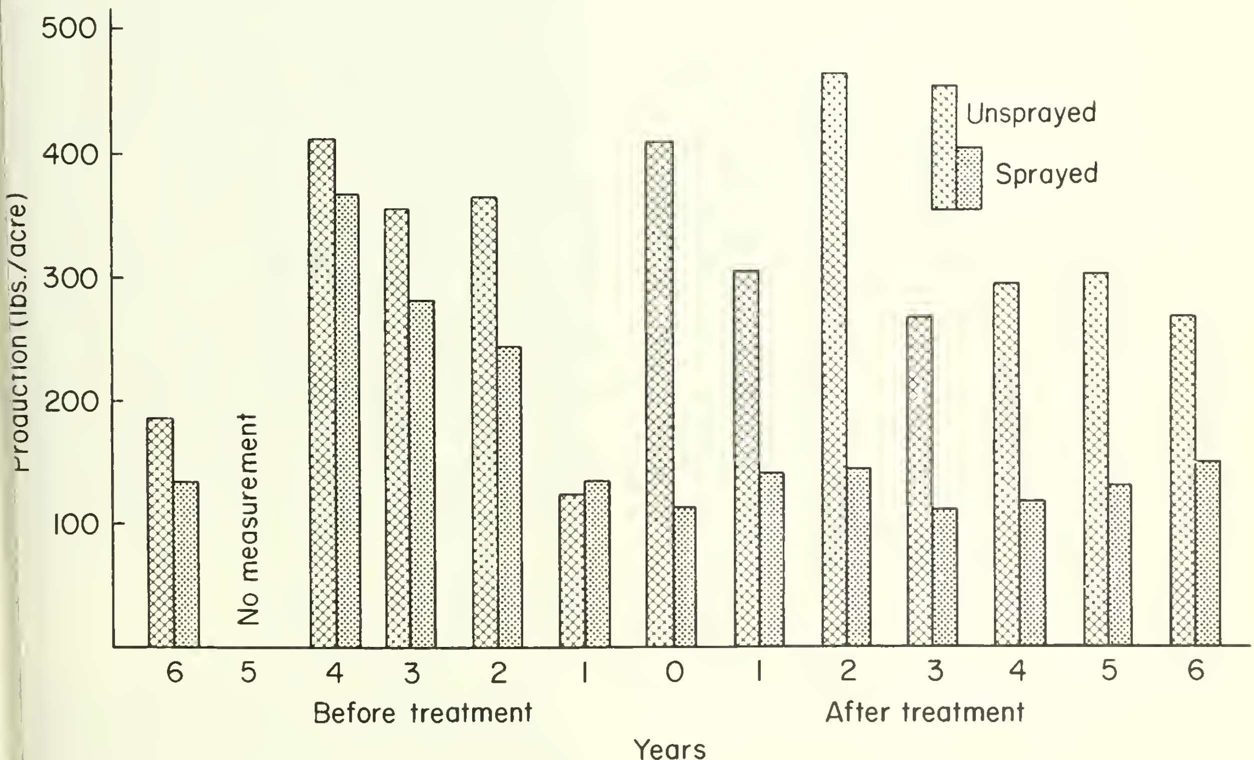

Figure 13.—Chemical herbicides used to kill sagebrush strongly reduce forb production as well. Forb production (air-dry) before and after spraying is shown on the same high-elevation watersheds as in figure 12.

sage grouse. Chicks consume forbs and insects about equally the first week of life, but for the next 9 weeks at least 70 percent of the diet is composed of forbs (Klebenow and Gray 1968). Cattle are thought of as grass consumers, but they seek out forbs as well, as shown by a study on sprayed range in the Bighorn Mountains. The contribution of forbs in the diet of yearling steers fell only from 42 to 33 percent, even though spraying reduced forbs from 80 to 10 percent of vegetation.[4]

Spray projects contemplated for sites with a productive forb component should be thoughtfully evaluated. Treatment shifts the forb-grass ratio to a strong grass dominance, but total herbaceous production does not respond proportionally to the increase in grass production. Sagebrush should not be sprayed where forbs are desirable from the standpoint of other land uses, and are still a productive part of the vegetative complex.

Combined Grass and Forb Production

The net effect of spraying depends upon the proportion of grasses and forbs in untreated vegetation. Where forbs comprise a substantial part of pretreatment vegetation, much of the increase in grass growth is offset by decreased forb production. For example, Tabler (1968) worked in an area where forbs contributed about 40 percent of the production total. After spraying, the loss of forbs was so great that combined grass-forb production did not equal that of unsprayed vegetation until the second year after treatment, when grass production had doubled. In contrast, if forbs contribute only a small part of the grass-forb total, the net effect of spraying more closely parallels the production response from grasses. Spraying had no effect on combined grass-forb production the year of treatment in a location where forbs contributed only about 15 percent of the production total before treatment (Sturges 1973). Combined grass-forb production was 1.8 and 2.1 times as great as for unsprayed vegetation the first and second years after treatment in this location.

A land manager can tailor plant composition to the projected resource use by reseeding after sagebrush removal. Palatable forbs and shrubs can be included in the seed mixture as well as grasses. These mixtures enhance seeded ranges from a wildlife point of view, and also provide valuable forage for domestic livestock.

[4]Unpublished material from John F. Thilenius, Plant Ecologist, Rocky Mountain Forest and Range Experiment Station, Laramie, Wyoming.

Above-Ground Biomass Production

Sagebrush production is seldom, if ever, considered when evaluating the effect of sagebrush removal, since its herbage is considered of negligible value from a livestock standpoint except for sheep on winter range. Rumsey (1971) believes big sagebrush and three-tip sagebrush *(A. tripartita)* contribute no more than 35 percent of vegetative matter produced by climax big sagebrush vegetation in Idaho. However, sagebrush's contribution to total annual production is much higher than this on sites where sagebrush is to be removed as a range improvement practice. Big sagebrush contributed about 66 percent of total above-ground vegetation in south-central Wyoming (Sturges 1973), while Pechanec and others (1954) report sagebrush production in Idaho comprised 54 percent of the yearly total.

The production of above-ground biomass is reduced by sagebrush control practices, even though combined grass-forb productivity may substantially increase. Sturges (1973) attributed a 63 percent decrease in production of herbaceous biomass on a sprayed site the year of treatment solely to loss of sagebrush growth. Combined grass-forb production increased 79 percent the year after treatment, but the above-ground herbaceous biomass produced by sprayed vegetation was still about 30 percent less than that of unsprayed vegetation. Similarly, total production was 910 pounds per acre (air-dry) 4 years after burning in Idaho, but adjacent unburned range produced 1,080 pounds per acre (Pechanec and others 1954). The response of native vegetation to sagebrush conversion supports the ecological adage that a diverse mixture of species or classes of plants more fully utilizes site resources than does a single species or plant class.

Effective Life of Sagebrush Conversion

None of the methods used to kill big sagebrush permanently eradicates the brush. Not all plants are killed by treatment, and the remnants provide a seed source in addition to that already present in litter and soil, or carried onto a site by animals, birds, wind, and water. The rapidity of sagebrush invasion is a function of many things, but the degree of initial brushkill and subsequent grazing management are probably the most important. The importance of regulated grazing cannot be overemphasized.

Uncontrolled grazing of a burned Idaho range resulted in rapid brush invasion. The production by sagebrush reached pretreatment levels within 9 years under an unregulated seasonlong grazing regimen, but was less than 50 pounds per acre with proper grazing management (Pechanec and others 1954). Johnson (1969) also found unmanaged grazing accelerated invasion of sagebrush. On the other hand, the full benefits of sagebrush conversion are realized for a substantial number of years where conservative grazing practices are followed. Blaisdell (1953) found big sagebrush production was still at a low level 12 years after burning, but sometime in the next 18 years sagebrush attained preburn levels with a concomitant decline in production by grasses and forbs (Harniss and Murray 1973). Thilenius and Brown (1974) also noted sagebrush canopy cover was still substantially below pretreatment levels 12 years after spraying. In an Oregon study, the full benefit of spraying was present 17 years after treatment under a moderate grazing regime in which grazing was delayed until forage had matured (Sneva 1972).

Smith (1969) found moderate grazing the year of spraying did not increase sagebrush seedling establishment in comparison to grazing deferral for one, two, or three growing seasons after treatment.

Evidence now accumulating points toward an effective projected life between 15 and 30 years. Many crested wheatgrass plantings 20 to 30 years old are still productive in southern Idaho with little sagebrush invasion (Hull and Klomp 1966). Some stands, though, have required treatment to suppress the brush even where initial sagebrush kill was satisfactory and sound grazing management practices were observed. The 15- to 30-year projected lifespan is not well documented, particularly for spraying, since the majority of sprayed land was treated less than 15 years ago.

Ground-Cover Response

Factual descriptions of how ground cover esponds to sagebrush removal are limited. The erial canopy coverage provided by sagebrush s almost totally lost with treatment. Spraying high-elevation, mountain sagebrush watershed ncreased litter cover slightly at the expense f rock and bare soil. However, the level of soil protection was high even before treatment due to a dense vegetative cover. Hyder and Sneva (1956) report the basal area of grasses increased about one-third after big sagebrush was controlled either by spraying or grubbing in an Oregon study. Most of the response was observed the year following treatment and was attributable to an increase in the number of grass plants as well as an increase in basal area of existing plants. Thus, the loss of sagebrush canopy is offset by increased basal area of herbaceous species. The resulting vegetative cover is more evenly dispersed than before treatment.

Soil-Moisture Response

Most information describing the soil-moisture regime under native and treated big sagebrush is derived from studies conducted in sprayed and unsprayed vegetation. These relationships still hold, however, for situations where a high level of sagebrush kill is achieved by other techniques.

The conversion of a mountain sagebrush stand to herbaceous vegetation reduced seasonal moisture withdrawal about 15 percent, and this difference develops while vegetation is actively growing (fig. 14). Moisture depletion is rapid when vegetation is actively growing, but sharply declines in midsummer. After midsummer the rate of moisture use is similar for both treated and untreated vegetation. The sharp decline in withdrawal coincides with the time herbaceous vegetation matures and the sagebrush drops many leaves.

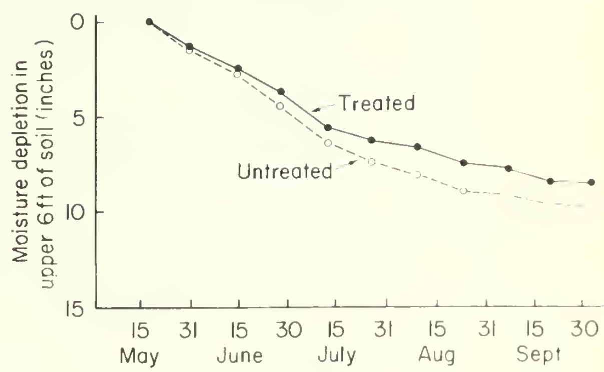

Figure 14.—Sagebrush conversion reduces summer moisture use about 15 percent. The reduction accrues during active vegetative growth, not uniformly through the summer season.

Most soil moisture is saved below the major rooting zone of residual vegetation (fig. 15). Native sagebrush utilizes moisture primarily from the upper 3 feet of soil until midsummer, then use shifts to the 3- to 6-foot depth. Most of the available water in the upper part of the soil has been utilized when deeper roots of sagebrush begin to actively extract water. About 80 percent of the reduction in withdrawal after sagebrush control, accrues in soil 3 to 6 feet deep. Moisture to support herbaceous species on treated land comes primarily from the upper part of the soil profile, and withdrawal there is about the same or exceeds that of undisturbed sagebrush (Hyder and Sneva 1956, Cook and Lewis 1963, Tabler 1968, Sturges 1973).

Some soil moisture is used by both sagebrush and replacement vegetation until late in the fall. However, once snow begins to accumulate, soil-moisture content remains static through the winter. This is not surprising in country where sagebrush is covered with snow and air temperatures seldom rise above freezing during the winter. In regions with a less rigorous winter climate, big sagebrush may continue to transpire in winter (Rickard 1967).

The reduction in soil-moisture depletion probably stabilizes at approximately 15 percent when replacement vegetation fully occupies the site (Tabler 1968), but can be substantially higher before vegetation fully responds to release from sagebrush competition (Shown and others 1972, Sturges 1973). To realize the savings, two conditions must be satisfied. First, soils have to be sufficiently deep that roots of replacement vegetation lie above soil occupied by sagebrush's deeper roots. Secondly, there must be sufficient precipitation to wet the soil throughout the profile. The method of killing sagebrush will not affect the magnitude of reduction as long as the rooting zone of herbaceous replacement vegetation is confined to the upper part of the soil and vegetation fully occupies the site.

Snow Accumulation

Snow relocation by winter winds is one of the more distinctive features of big sagebrush lands. Sagebrush leaves and twigs reduce wind velocity so that drifting snow is deposited and held in place. Live sagebrush plants and the

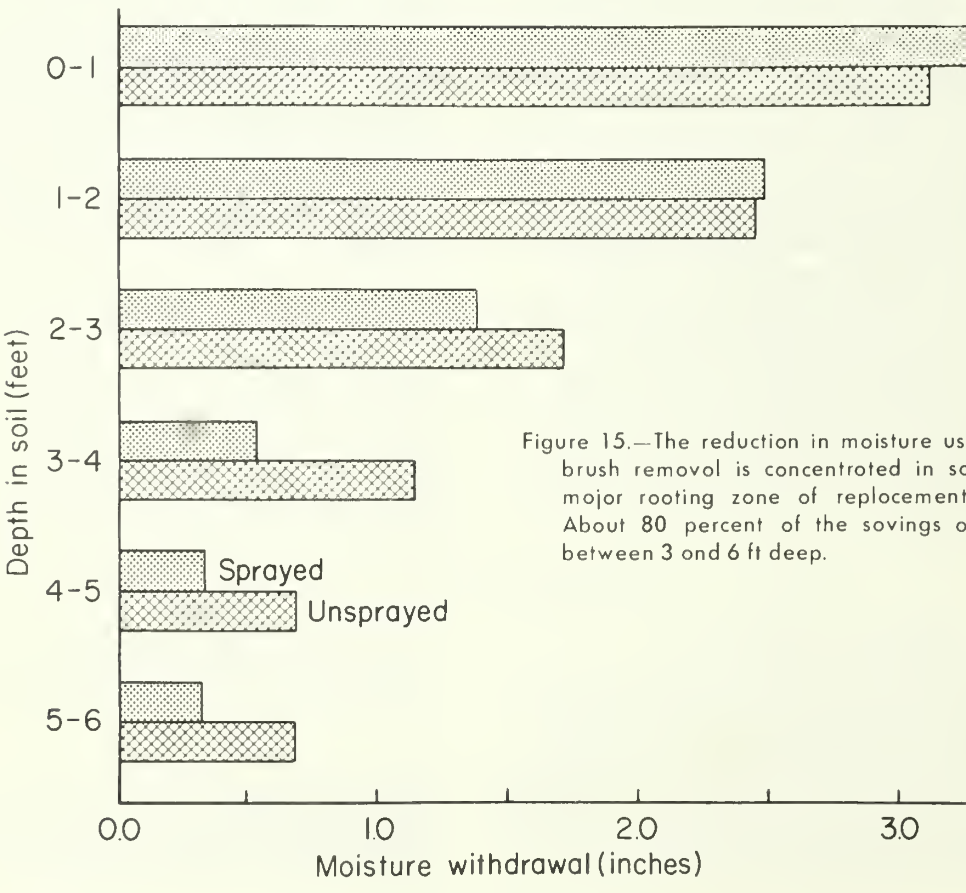

Figure 15.—The reduction in moisture use after sagebrush removal is concentrated in soil below the major rooting zone of replacement vegetation. About 80 percent of the savings accrue in soil between 3 and 6 ft deep.

skeletal remains of sprayed plants are more effective than herbaceous vegetation in retaining snow (Hyder and Sneva 1956). Snow accumulates faster in sagebrush cover than in grasslands as long as the brush remains above the snow surface. A stand of mountain sagebrush about 20 inches high contained an additional inch of water by the time the brush was covered compared with adjacent grassland (Hutchison (1965). The rate of snow buildup for the two cover types was the same after sagebrush plants were submerged within the pack, but the disparity in snow-water equivalent persisted through the accumulation period. Both vegetative types had a similar snowmelt rate, about 0.4 inch per day, during the period of rapid melt.

The relationship between sagebrush cover, aspect, prevailing wind direction, and snow accumulation is complex. Sagebrush conversion reduces snow accumulation most strongly on windward slopes, since the loss of sagebrush foliage opens the site to the scouring action of wind. Snowmelt and soil-moisture recharge may start earlier as a result of reduced snow accumulation (Tabler 1965). On leeward slopes, the effect of sagebrush removal is less pronounced. Here, removal may reduce the rate of accumulation early in the winter growing season while vegetation is uncovered, but have no effect on final depth if topography becomes the factor controlling snow deposition (fig. 16). Once vegetation is covered, further deposition becomes primarily a function of prevailing wind direction in combination with topographic location.

The above discussion treats snow accumulation at a particular point, not over an extensive area. Snow measurements on a sprayed and adjacent untreated watershed at Wayne's Creek

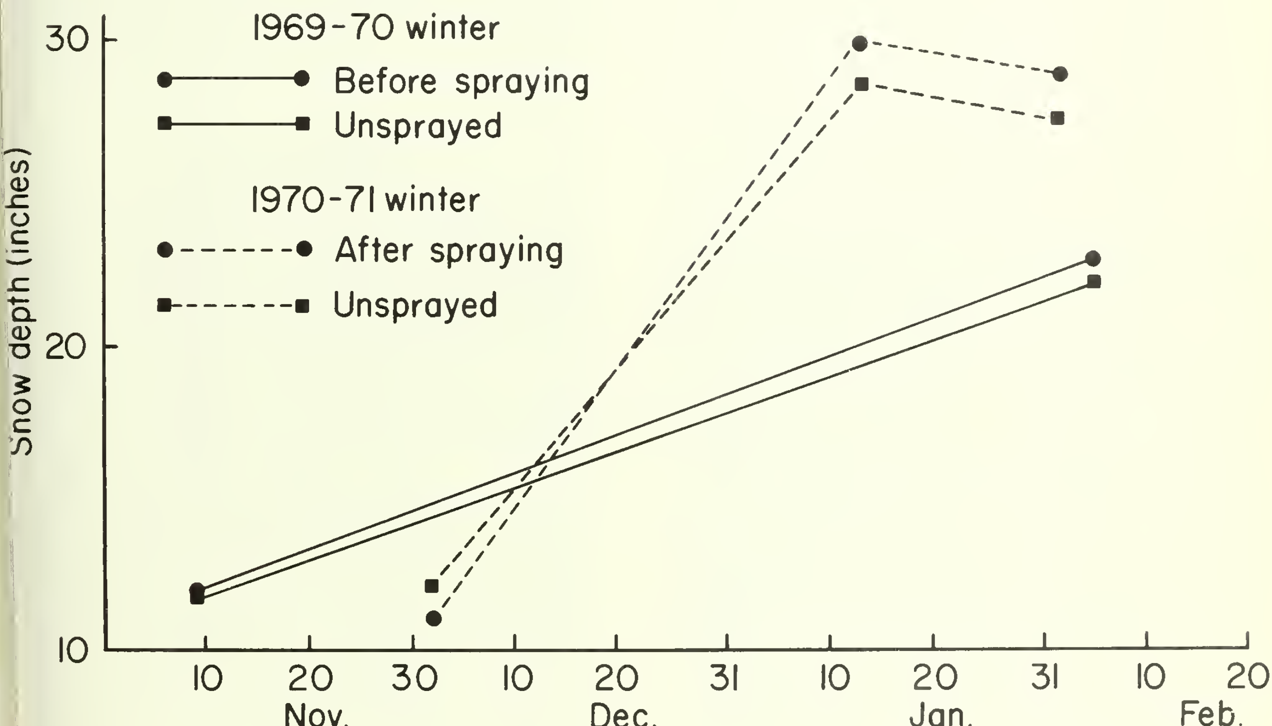

Figure 16.—Live sagebrush vegetation accumulates snow faster than herbaceous vegetation as long as sagebrush plants remain above the snow surface. In topographically controlled depositional areas, sagebrush removal may reduce accumulation early in the season but have no effect on maximum accumulation.

indicate sagebrush control did not affect snow storage. Watershed snow storage was dictated for the most part by topography, and ample snow-holding capacity existed in natural traps. Similar measurements to define the effects of sagebrush removal on snow accumulation over an extensive area at other locations have not been made.

Sediment Transport

Sedimentation rates from big sagebrush lands are not well known. Measurements of bedload and suspended sediment movement are being obtained on the Stratton Sagebrush Hydrology Study Area. Both types of sediment transport are low, and water flowing from watersheds is excellent in quality. The annual movement of bedload sediment at Loco and Sane Creek was recorded as follows:

Year	Loco Creek	Sane Creek
	(ft^3/mi^2)	
1970	355	179
1971	204	23
1972	168	8
1973	234	95
1974	121	14

The relationship between flow volume and suspended sediment concentration for Sane Creek (fig. 17) also indicates low suspended sediment movement. After snowmelt runoff, suspended sediment levels are usually less than 20 p/m (parts per million) on both Sane and Loco Creeks.

The high suspended sediment concentration associated with the May 20, 1973 runoff peak at Sane Creek (fig. 17) occurred during an over-the-snow flow event (see fig. 11). The flow rate at Sane Creek during 1974 was much lower than in 1973 and runoff water never did contain appreciable sediment. The deposition of bedload material at Sane Creek in 1970 and 1973 reflects an increase in sediment movement associated with an over-the-snow runoff event. Sane Creek's May 1973 peak streamflow rate and suspended sediment content emphasizes the importance of extreme events. Increased sediment movement can be expected in years with high snowmelt rates or with intense summer storms that produce overland flow, no matter how well the watershed is vegetated.

Sagebrush conversion techniques which minimize soil disturbance best maintain watershed protection values immediately after treatment. Gifford (1968) evaluated infiltration and erosion under simulated rainfall where sagebrush was killed by plowing, spraying, or ripping. He concluded that spraying was the best watershed rehabilitative treatment, and suggested plowing be used only where the likelihood of establishing a seeded stand quickly is high.

The only measurements relating sediment movement from an entire basin to sagebrush removal were conducted as part of the Wayne's Creek Study. Suspended sediment samples were collected at random intervals for 6 years preceding treatment and for 2 years afterward. Coarse sediment moving from watersheds was trapped in stilling ponds, and yearly deposition was measured in the fall. Suspended sediment

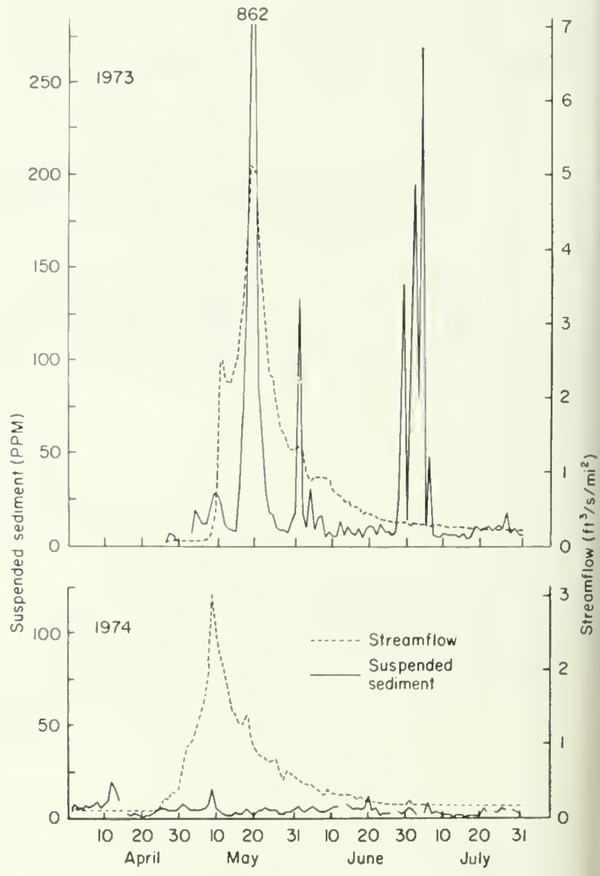

Figure 17.—Suspended sediment levels and flow volumes for Sane Creek during 1973 and 1974.

concentrations were consistently low, and averaged less than 30 p/m. The maximum concentration ever detected was 746 p/m and the minimum level was 1 p/m. No change in sediment load was observed after the brush was killed.

Coarse sediment transport was also small, as might be inferred from the small amount of suspended sediment present in stream water. Sediment deposition averaged between 4 and 5 pounds per acre per year. The greatest movement occurred in response to unusually high runoff. Coarse sediment movement was about three times the average yearly rate when winter precipitation was 53 percent above normal, again affirming the link between extreme events and accelerated rates of sediment transport. Suspended and coarse sediment measurements emphasize the importance of a vigorous vegetative cover in maintaining soil stability. The water coming from the watersheds was of excellent quality even during the height of runoff in most years. Sagebrush conversion further increased herbaceous production, which was reflected by an increase in litter cover and a decrease in bare soil and rock.

Streamflow Regime

Watershed streamflow measurements provide a means of assessing the net hydrologic effect of sagebrush control, since streamflow is the result of all hydrologic processes operating in a watershed. The relationship between sagebrush control and water yield has been studied at Wayne's Creek. Total annual flow was increased 13 percent by converting the shrub-dominated vegetation to a herbaceous type by spraying.

The increase in water yield closely approximates the difference in soil-moisture withdrawal between treated and untreated vegetation. Snow measurements indicated that water available for streamflow from snow was not altered by treatment. The increase in flow volume gradually accumulated through the snowmelt period because less melt water was required for moisture recharge. Treatment had no effect on the yearly maximum discharge rate, mean daily maximum discharge rates, or summer discharge during the low flow period.

Progress has been made in adapting a hydrologic simulation model developed by Leaf and Brink (1973) to model hydrologic processes operative in the big sagebrush type. Once this model is adapted, it will provide a useful tool for reliably predicting changes in water yield that will result when different range or watershed management practices are imposed on big sagebrush lands.

The 13 percent increase in streamflow is probably about the maximum that can be expected from sagebrush conversion at any location. Hill and Rice (1963) identified three essential conditions before conversion of chaparral shrub vegetation could influence water yields: (1) the rooting depth of shrubs must be deeper than 3 feet, (2) grass replacement vegetation must be kept free of deep-rooted species, and (3) precipitation must exceed the loss of soil water by evapotranspiration. These conditions were maximized at the Wayne's Creek site. The effect of sagebrush control on water yield at other sites will depend upon how well the three conditions are satisfied.

WATER-YIELD IMPROVEMENT IN THE SAGEBRUSH TYPE

Converting big sagebrush to a herbaceous vegetative type can probably increase water yield about 15 percent under the most favorable of circumstances. Because of low precipitation and shallow soils, conversion will not increase water yield on much of the land occupied by big sagebrush. Changes in the flow regime can be expected where precipitation is in excess of that required to replenish soil moisture, and where replacement vegetation utilizes less moisture than does native big sagebrush vegetation. The mountain big sagebrush type probably best fits these restrictions.

Recent research casts an entirely new light on water-management possibilities for big sagebrush lands, even on sites with relatively low precipitation and shallow soils. Wind is one of the paramount factors controlling snow accumulation. Not only is snow redistributed by wind, but vast quantities of water return directly to the atmosphere during drifting (Tabler 1973). Sublimated water is a total loss to the plant-land phase of the hydrologic cycle. Tabler (1971) has synthesized a means of estimating snow transport at a particular location, and based on this value, snowfence systems can be designed to capture drifting snow (Tabler 1972, 1973). Snowfences can be placed to provide water where there is none, much as trick-tanks do for rain, or they can be used to augment already existing sources. Thus, blowing snow ordinarily lost through sublimation during a drifting event can be trapped and the water diverted to meet a management objective.

The quantity of snow-water equivalent transported by wind is estimated by (Tabler 1971):

$$Q = \frac{1}{2} \Theta \bar{P} \bar{D}$$

where

Q = Annual volume of water-equivalent tha moves across a line 1 ft wide as drifting snow, in ft^3

Θ = Mean annual snow transfer coefficient, the ratio between the quantity of snow relocated by wind to that which falls during the winter drift period,

$\bar{P}$ = Mean winter precipitation received during the time snow is subject to drifting, in ft,

$\bar{D}$ = Average distance a snow particle travels before sublimating during the winter drift period, in ft.

This formula assumes that no barriers, other than natural vegetation, cause snow deposition in the area upwind of the measurement point, and that sublimation is proportional to the distance a snow particle travels.

Representative values of Θ and $\bar{D}$ were determined by Tabler (1972) from field measurements conducted in south-central Wyoming. The average winter snow transfer coefficient (Θ), was 0.7 for mountain big sagebrush stands 8 to 16 inches high. This coefficient indicates that 70 percent of the precipitation received during the time snow is subject to drifting returns directly to the atmosphere when no barriers cause deposition. The other 30 percent is stored in sagebrush crowns which protect the snowpack against the wind. Average annual values for $\bar{D}$ ranged from about 3,300 feet at a 7,500-foot elevation to 5,000 feet at an 8,500-foot elevation. The drift period extended from November 1 to March 30 at the Wyoming site, but can be adjusted to fit the climatic regime of any location.

The water equivalent of winter snow transport has been calculated for differing regimes of precipitation and maximum transport distances (table 4). Calculated values are astonishing, and suggest tremendously exciting management possibilities. These quantities are really "new" water completely outside the traditional resource base. Furthermore, the drifting-snow resource can be utilized with minimal impact on other land uses.

Snowfences properly located provide an efficient means to capture and retain windborne snow (fig. 18). A single fence traps about 80 percent of incoming snow between the time drifting starts and the fence is saturated.

Table 4.--Calculated quantity of water moving as drifting snow (per foot of width perpendicular to wind) for selected precipitation inputs and maximum transport distances, assuming a snow transfer coefficient of 0.7

Precipitation (Inches)	Water movement at maximum transport distances ($\bar{D}$) of -- 2,000 ft	3,000 ft	4,000 ft	5,000 ft
	- - - - - - - - ft^3	- - - - - - - -		
4	233	350	467	583
6	350	525	700	875
8	466	700	934	1,166
10	583	875	1,167	1,458
12	700	1,050	1,400	1,750

Preliminary measurements show that, at saturation on level terrain, standard snowfences used by the Wyoming Highway Department 6, 8, 10 and 12 feet high hold about 300, 500, 700, and 1,000 cubic feet of water per lineal foot of fence, respectively.

The following examples indicate the size of the drifting-snow resource. In an area where winter precipitation is 4 inches with a maximum transport distance of 3,000 feet, a snowfence would capture 280 of the 350 cubic feet of water transported across a line 1 foot wide. To accumulate 1 acre-foot of water requires a fence 6 feet tall and 156 feet long. The size of the drifting snow resource increases proportionally with greater precipitation and longer transport distances. If winter precipitation is 10 inches and the maximum transport distance 5,000 feet, two fences 38 feet long placed in tandem, one 10 feet high and the other 8 feet high, are necessary to hold the volume of drifted snow containing 1 acre-foot of water.

SUMMARY

Hydrologic Features of Mountain Big Sagebrush

Precipitation

Big sagebrush grows in an environment where the growing season is relatively warm and dry, and the bulk of yearly precipitation is received during the cold months. About 60 percent of annual precipitation falls as snow in

Figure 18.—Water that otherwise returns to the atmosphere during drifting can be trapped and stored behind snowfences, then used to meet a management objective. Blowing snow represents an extensive untapped water resource wherever snow is transported by wind

the mountain sagebrush zone. Summer precipitation is concentrated in June and September. Rain falling during July, August, and September contributes little toward vegetative growth. The amount of precipitation received in the summer is less than 0.21 inch on about 80 percent of days with precipitation, and in excess of 0.50 inch 6 percent of the time. Rainfall intensities in excess of 1 inch per hour generally last less than 10 minutes.

Wind and Drifting Snow

Wind is an important factor in the big sagebrush environment because of its role in redistributing snow. Windspeeds are highest during winter. A substantial part of winter precipitation returns directly to the atmosphere on lands where drifting is common. Snow is blown from windward slopes and ridges, and accumulates in topographically controlled depositional sites. Drifts, which may reach 10 to 20 feet deep, recharge ground water. Evaporation loss from late-lying snowfields and surrounding moistened soil is not known, but is probably an important constituent in the water balance of large drifts.

Water-Yield Characteristics

Streams originating in the mountain sagebrush zone yield a smaller percentage of precipitation as streamflow, and have a lower base flow and lower snowmelt discharge rate than forested subalpine watersheds. However, the form of the snowmelt hydrograph is similar for sagebrush and subalpine watersheds. The time required to accumulate a specified proportion of snowmelt runoff is similar when expressed as a percent of the runoff season. The timing of snowmelt, and discharge rates, are probably more variable in the sagebrush type than on forested land. Sagebrush lies at a lower elevation than timbered lands for the most part, snow depth is less, and snow is exposed directly to solar radiation.

Daily snowmelt flows in sagebrush country are extremely responsive to day-to-day fluctuations in weather partly because much of the snowpack is relatively shallow. Watersheds with a preponderance of south- and west-facing slopes are also subject to higher melt rates than watersheds where slope orientation minimizes solar energy input. Advected energy is probably an important source of energy for melting snow on sagebrush lands, because of persistent winds and the relatively large portion of the watershed that becomes bare soon after melt begins. It is a particularly important component of the energy budget of late-lying snowdrifts. The proportion of energy contributed by advection to melt has not been measured, however, either on a watershed basis or for isolated snowdrifts.

Over-the-snow flow, one of the more unique hydrologic features of sagebrush lands, occurs when the melt rate on upland areas exceeds soil infiltration capacity and melt water accumulates in drainages. Runoff water can erode well-defined channels in the snow surface to form an efficient surface-drainage network that quickly transports melt water off the watershed. Over-the-snow flow is probably a common but short-lived phenomenon wherever sagebrush lands accumulate substantial quantities of snow. Sediment movement is accelerated during over-the-snow flow events.

Runoff from summer rainstorms on high-elevation, mountain sagebrush watersheds is generally the result of rain falling on premoistened soil; storm intensity need not be high. Most surface runoff events occur soon after snowmelt or are associated with rainy periods. Wet soil has a lower initial infiltration capacity than dry, and a constant infiltration rate is reached sooner. Summer runoff rates are generally substantially lower than maximum discharge rates during snowmelt.

Hydrologic Response of Big Sagebrush Lands to Management Practices

Vegetative Response to Sagebrush Conversion

Big Sagebrush.—More than 90 percent of big sagebrush plants are killed by burning, mechanical removal techniques, or chemical herbicides, when control measures are properly implemented. The use of 2,4-D revolutionized range management practices on sagebrush lands. Reseeding must accompany sagebrush conversion on sites where all vegetation is destroyed, or the population of desirable species is low. Reseeding presents an opportunity to establish the kinds of plants suited to a particular management objective.

Grass production.—Burning, and mechanical methods that do not destroy herbaceous vegetation, do not greatly alter herbaceous composition. Spraying, however, strongly favors grasses over forbs. Grass production commonly doubles after spraying. Subsequent grazing management is an important factor governing how long the production response by grasses persists after treatment.

Forb production.—Spraying is the only sagebrush control method that drastically affects forb abundance. Phenoxy herbicides act against all broad-leaved plants, not just sagebrush. The effect on individual forb species depends on the time of spray application in relation to growth stage, and the amount of root reserves. Spraying reduces forb production approximately 45 to 65 percent. Forb damage should be carefully considered when assessing the suitability of a particular site for spraying, since forbs are essential to some land uses.

Above-ground biomass production.—The production of above-ground herbaceous biomass (including production by sagebrush) is reduced by sagebrush removal. Native grasses and forbs do not increase sufficiently to replace herbage produced by sagebrush. Combined grass-forb production can increase approximately 50 to 200 percent after sagebrush control. The increase in grass production alone is not a valid measure of treatment effect when sagebrush is sprayed. Forbs as well as sagebrush are killed, so that part of the grass response simply compensates for decreased forb growth. There is some indication that production by introduced forage species may exceed that of climax big sagebrush vegetation.

Effective life of sagebrush conversion.—No control method eradicates big sagebrush; periodic recontrol is necessary to hold it in a subordinate position. The degree of initial sagebrush kill and grazing management are the most important factors controlling the rapidity of brush invasion. The effective projected life is probably 15 to 30 years, but this timespan has not been conclusively established.

Ground-Cover Response

Quantitative data describing the response of ground cover to sagebrush removal are limited. Litter cover increased slightly, while rock and bare soil decreased after spraying on a high-elevation watershed. More than 80 percent of the watershed surface was protected by vegetation or litter before treatment. The basal ground cover of bunchgrasses increased by a third following sagebrush control in a study located within the drier part of the sagebrush zone. Individual grass plants respond to release from sagebrush competition with an increase in overall vigor, including an expanded basal area.

Soil-Moisture Response

Summer soil-moisture withdrawal decreases about 15 percent after sagebrush removal if (1) the roots of residual vegetation are above soil previously occupied by the deeper roots of sagebrush, and (2) precipitation is sufficient to wet the entire soil mantle. The reduction accrues in soil below 2 feet while vegetation is actively growing. Moisture depletion in the top 2 feet of soil is the same or slightly greater since the zone of major root activity is shifted to the upper part of the soil profile.

Snow Accumulation

Snow relocation is an important hydrologic feature of big sagebrush lands. Vegetation, and wind in combination with topography, are the dominant factors controlling snow deposition. Live sagebrush plants collect snow more efficiently than herbaceous vegetation or dead sagebrush skeletons. Sagebrush removal can reduce snow accumulation or windward slopes. However, overall snow storage was not affected by sagebrush removal in a small basin with ample snow storage capacity where topography and wind were the primary factors controlling accumulation.

Sediment Transport

Techniques that minimize soil disturbance are best for converting big sagebrush vegetation to a herbaceous vegetative type. Plowing should be restricted to lands with little erosion potential where a seeded stand can be established quickly. Sediment transport from a high-elevation watershed with a small amount of bare soil before treatment was unaffected by sagebrush conversion. How sagebrush removal affects soil stability at sites with lower initial soil protection has not been determined.

Streamflow Regime

Changes in streamflow regime provide a measure of the net hydrologic effect of sagebrush control. Total annual flow increased 13 percent after mountain big sagebrush was sprayed on a high-elevation watershed. Treatment did not affect maximum discharge rates during snowmelt or flow volume after the snowmelt period. The maximum potential increase in streamflow from sagebrush control at any location is probably about 15 percent.

Water-Yield Improvement in the Sagebrush Type

The maximum increase in water yield that can be realized by conversion of big sagebrush to a herbaceous type is probably about 15 percent. Brush removal will not affect water yield where soils are shallow and precipitation is insufficient to rewet the soil.

Snow currently lost to sublimation represents an untapped water resource on sagebrush lands wherever snow is drifted by wind. Vast quantities of water return directly to the atmosphere during drifting; sublimation from wind-transported snow equaled 70 percent of winter precipitation at a site in south-central Wyoming. Snowfences provide an efficient means of capturing drifting snow, and have little impact on other land uses. When saturated, fences 6, 8, 10, and 12 feet tall located on level terrain hold about 300, 500, 700, and 1,000 cubic feet of water per lineal foot of fence, respectively. Fences can be effective in lower precipitation regions of the sagebrush type as well as regions of higher precipitation, as long as winds are sufficient to induce drifting. Direct sublimation of snow and evaporation of melt water may also account for a substantial portion of water stored in isolated drifts behind snowfences, however.

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Although this report discusses research involving pesticides, such research does not imply that the pesticide has been registered or recommended for the use studied. Registration is necessary before any pesticide can be recommended. If not handled or applied properly, pesticides can be injurious to humans, domestic animals, desirable plants, fish, and wildlife. Always read and follow the directions on the pesticide container.

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Sturges, David L.
1975. Hydrologic relations on undisturbed and converted big sagebrush lands: The status of our knowledge. USDA For. Serv. Res. Pap. RM-140, 23 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521

The status of our knowledge of watershed management for big sagebrush range lands is discussed. Climate, soils, vegetation, snow accumulation, and water yields are described, followed by a review and discussion of how management practices alter vegetative composition and the hydrologic regime. Potential hydrologic benefits from managing blowing snow in the big sagebrush type are outlined and research needs are highlighted.

Keywords: Multiple use, range hydrology, vegetation effects, watershed management, blowing snow management, *Artemisia tridentata*.

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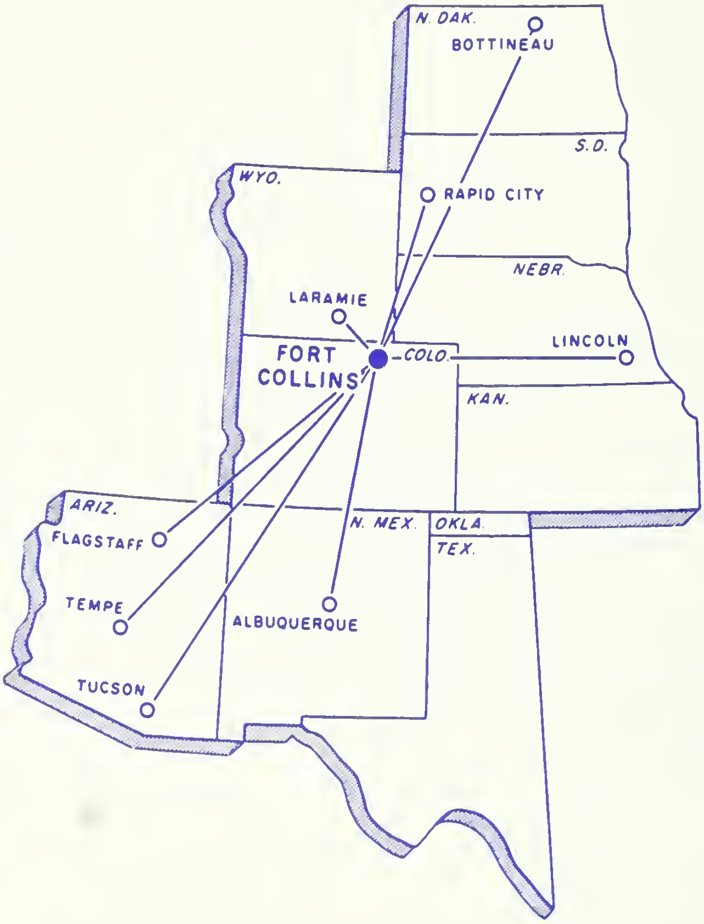
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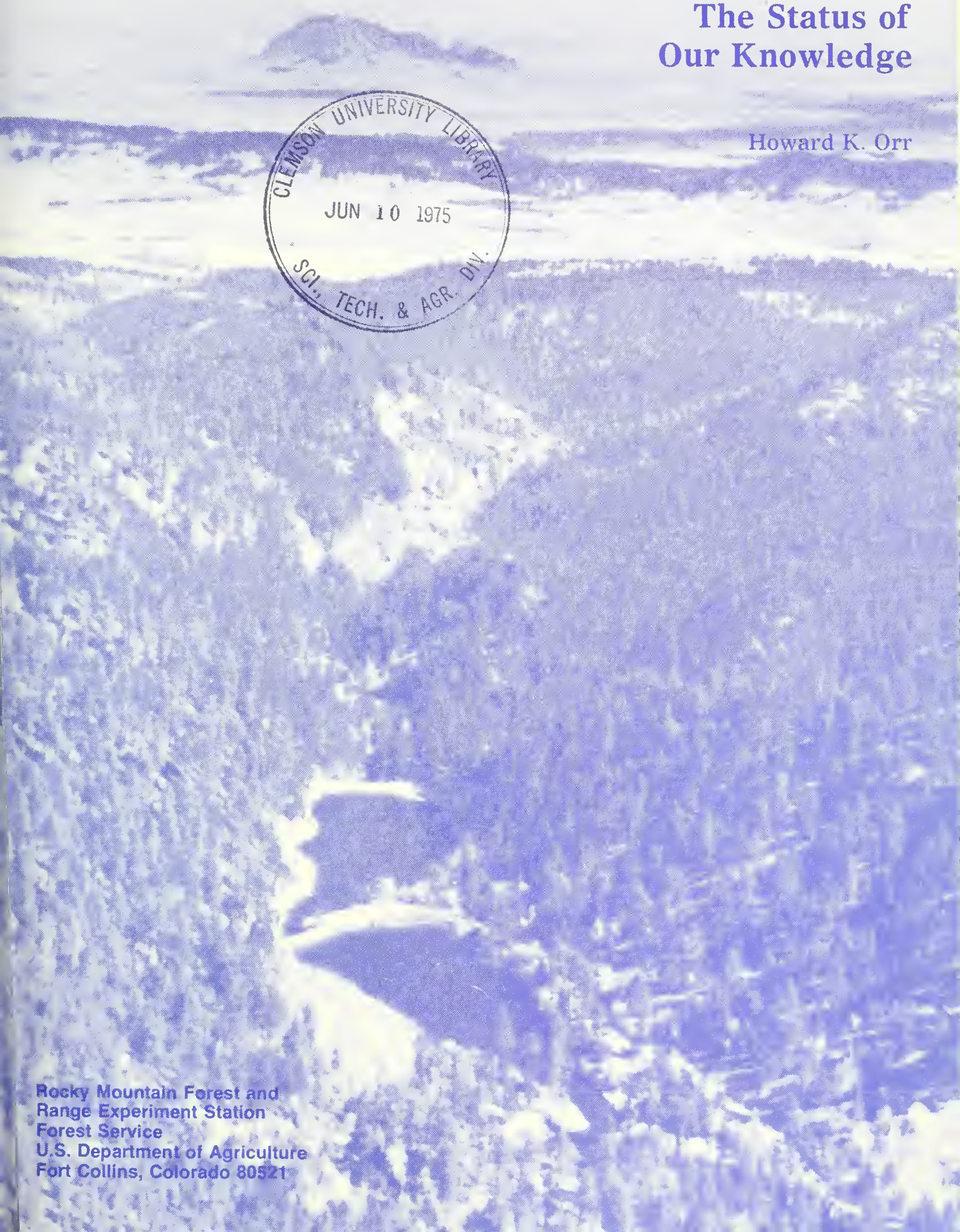
March 1975

WATERSHED MANAGEMENT IN THE BLACK HILLS:

The Status of Our Knowledge

Howard K. Orr



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Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture
Fort Collins, Colorado 80521

Abstract

Climate, geology, soils, vegetation, and water yields are briefly described, followed by a review and discussion of watershed management research and problems unique to the Black Hills. Research needs with respect to water quality, data collection, and model development are highlighted.
Keywords: Multiple use, coniferous forest, forest management, vegetation effects, land use planning.

ABOUT THE COVER:

Forest, Water, City, The Plains. The forest land yields the water that is stored in the reservoirs and is in turn fed into the water supply system of the city. This forest/water system is in stark contrast with the surrounding semiarid Plains, and plays a dominant role in the strong esthetic appearance of the area.

USDA Forest Service
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WATERSHED MANAGEMENT IN THE BLACK HILLS:
The Status of Our Knowledge

Howard K. Orr, Hydrologist

Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University; research reported here was conducted at the Station's Research Work Unit at Rapid City, in cooperation with the South Dakota School of Mines and Technology.*

Contents

WATERSHED MANAGEMENT IN THE BLACK HILLS:

The Status of Our Knowledge

Howard K. Orr

The Black Hills Region

Location and Extent

The Black Hills are a forested island in the vast expanse of the Northern High Plains, covering about 5,150 square miles in southwest South Dakota and northeast Wyoming. Because of the pine forest (fig. 1), more water, and a more temperate climate, the Hills are especially attractive to the tourist and traveler as well as the resident population.

Figure 1.—A typical Black Hills scene showing the dominant ponderosa pine, scattered deciduous species, and streambottom meadow. The granite heart of the Hills is visible in the far background.

Climate

General climate in the Black Hills area is of the Continental type (Johnson 1949), which is typically cold in winter and relatively hot in summer. The Hills receive more precipitation and average temperatures are lower than in the surrounding Plains, but both precipitation and temperature extremes are less. Orographic effect is pronounced—the area has been cited as one of the best examples in the interior United States (Foster 1948). Winter effect is especially pronounced.

Temperature.—Temperatures are higher at comparable elevations in the southern than in the northern Hills. For example, average annual air temperature at Hot Springs in the southern Hills is 48.8°F, 2° higher than at Spearfish in the northern Hills. The difference is greatest in the growing season, which extends from about mid-May to mid-October at these lower elevations.

Precipitation.—Greatest average annual precipitation, nearly 30 inches, occurs in the northern high Hills and in the Bear Lodge Mountains. Amounts decrease rapidly toward the Plains (14 to 16 inches) and from north to south along the uplift. Average annual precipitation is about 2 inches more at comparable elevations in the northern than in the southern Hills. These and other precipitation factors have been reviewed and summarized by Orr (1959).

Seasonal distribution of precipitation is similar to that of the surrounding Plains; greatest amounts fall in the form of rain in the spring and early summer months. May and June are the maximum months, May in the southern Hills and June in the northern Hills. Minimum amounts fall in the winter. Though snow is a relatively minor component of annual precipitation, heavy wet snows are not uncommon in March, April, and even May. These are produced from weather systems moving southwest to northeast across Nevada, Utah, and Colorado. Circulation about lows moving in this direction draws warm moist air from the south.

Year-to-year variation is great. For example, annual precipitation at Rapid City has ranged from a maximum 28.89 inches in 1962 to minimum of 7.51 inches in 1936—a ratio of nearly 4 to 1. In the drier years there is little excess water (over evapotranspiration) for streamflow. In the average to maximum years, water available for streamflow increases with precipitation. The Black Hills are subject to infrequent extreme flood events. Flash floods after the most recent storm, in June 1972, caused unprecedented damage and loss of life (Orr 1973).

Growing season.—Average growing season ranges from a maximum of about 154 days at Rapid City to a minimum of just under 100 days in the higher northern Hills. The general area of shortest growing season also receives maximum precipitation, and is in the zone of highest water-yield potential.

Winds.—Prevailing winds are westerly. During CY 1970 (the best one year of several years' record) 67 percent of recorded wind movement was from 225° to 315° at the Black Hills Experimental Forest. Averages were 115 miles per day and 4.8 miles per hour at 10 meters above ground level in the center of a 5-acre forest opening. The maximum month was April, with an average velocity of 6.6 miles per hour. During this 1 month, 76 percent of total recorded miles were in the west quadrant (225° to 315°).

Sunshine.—Total incident solar radiation (wavelength 0.36 to 2 micrometers) on a horizontal surface at the Black Hills Experimental Forest averaged 398 langleys per day over a period of 3 years (1968-70). Day averages ranged from a maximum of 593 langleys in July to a minimum of 184 in December.

Physiography and Geology

Primary structure.—The Black Hills and Bear Lodge Mountains are erosion remnants of ancient domal structures formed by granites pushing up beneath overlying sedimentary formations. Processes and resultant general geology are best described by Darton and Paige (1925). More than one cycle of raising and lowering occurred. The upthrusting granite and later igneous intrusions resulted in metamorphism of overlying sedimentaries. More sediments were later deposited. Sedimentary formations have since eroded away, exposing the granites (fig. 2) and metasediments which are collectively called the central crystalline area. The truncated edges of the eroded sedimentary formations now are exposed as a series of ridges encircling the central crystalline area (figs. 3 and 4).

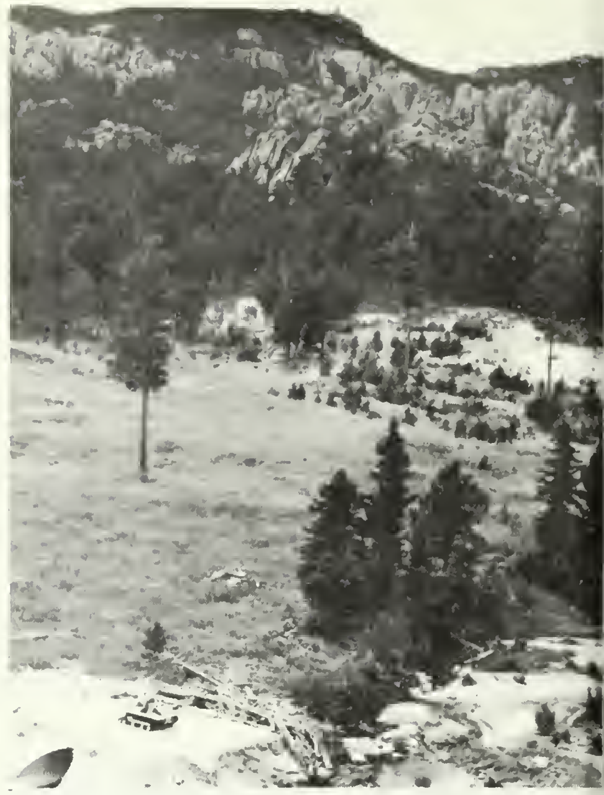

Figure 2.—Typical terrain in the granite "core" of the Black Hills. High point in center background is Harney Peak, the highest in the Black Hills (7,242 feet). Soil lacks cohesion and is highly erosive.

The sedimentaries include 12 or more separate formations. Rock types vary greatly, in some cases within individual formations, and range from limestones and sandstones to shales and conglomerates. The central crystalline area, which includes the Precambrian granites and metamorphics, occupies about 20 percent of the Black Hills area and is relatively impervious to water. This is of particular management significance because the most dependable and constantly flowing streams in the Hills originate in or flow across the crystalline area. But the flow of these streams diminishes or disappears during at least a part of each year where they cut the encircling sedimentary formations. This has been a major water problem from the start of settlement (Brown 1944). Pahasapa limestone (fig. 5), in particular, is cavernous and evidently takes in, stores, and transmits large volumes of water.

There are a number of Tertiary intrusive areas across the northern Hills. These areas are a relatively small proportion of the total Black Hills area, but research and observation have

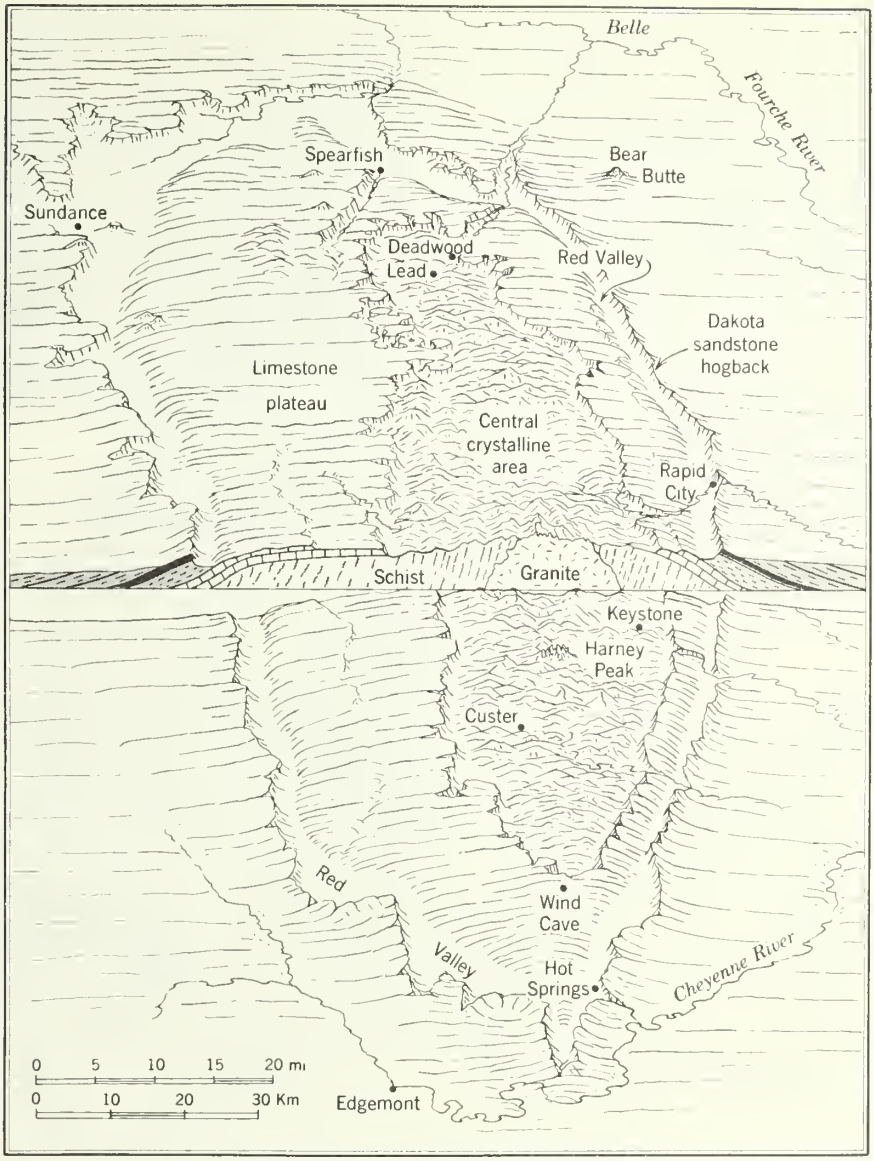

Figure 3.—Main topographic regions of the Black Hills of South Dakota and Wyoming (from Strahler's Physical Geography, 3d ed., copyrighted 1969. Reprinted by permission of John Wiley & Sons, Inc., N.Y.)

ndicated that, from a surface water standpoint, hey are of much greater importance than indi- ated by their percentage of total area (see ig. 2). These intrusive bodies and adjacent reas are relatively impermeable, and thus are ependable sources of surface water yield. 'hese areas very likely have the greatest man- gement potential for water-yield increase of ny in the entire region.

Relief.—Elevation ranges from about 3,200 eet (m.s.l.) at Rapid City to a maximum of 7,242 feet at Harney Peak in the granite area. Elevation is nearly as high along a segment of sedimentary formations in the west central Hills referred to as the Limestone Plateau (see fig. 2). Through the approximate 4,000-foot range in elevation in the Hills, there are wide variations in climate, geology, topography, soils, and vegetation.

Drainage pattern.—The present drainage, definitely related to physiographic and geologic history, is of a radial-dendritic pattern. Thus,

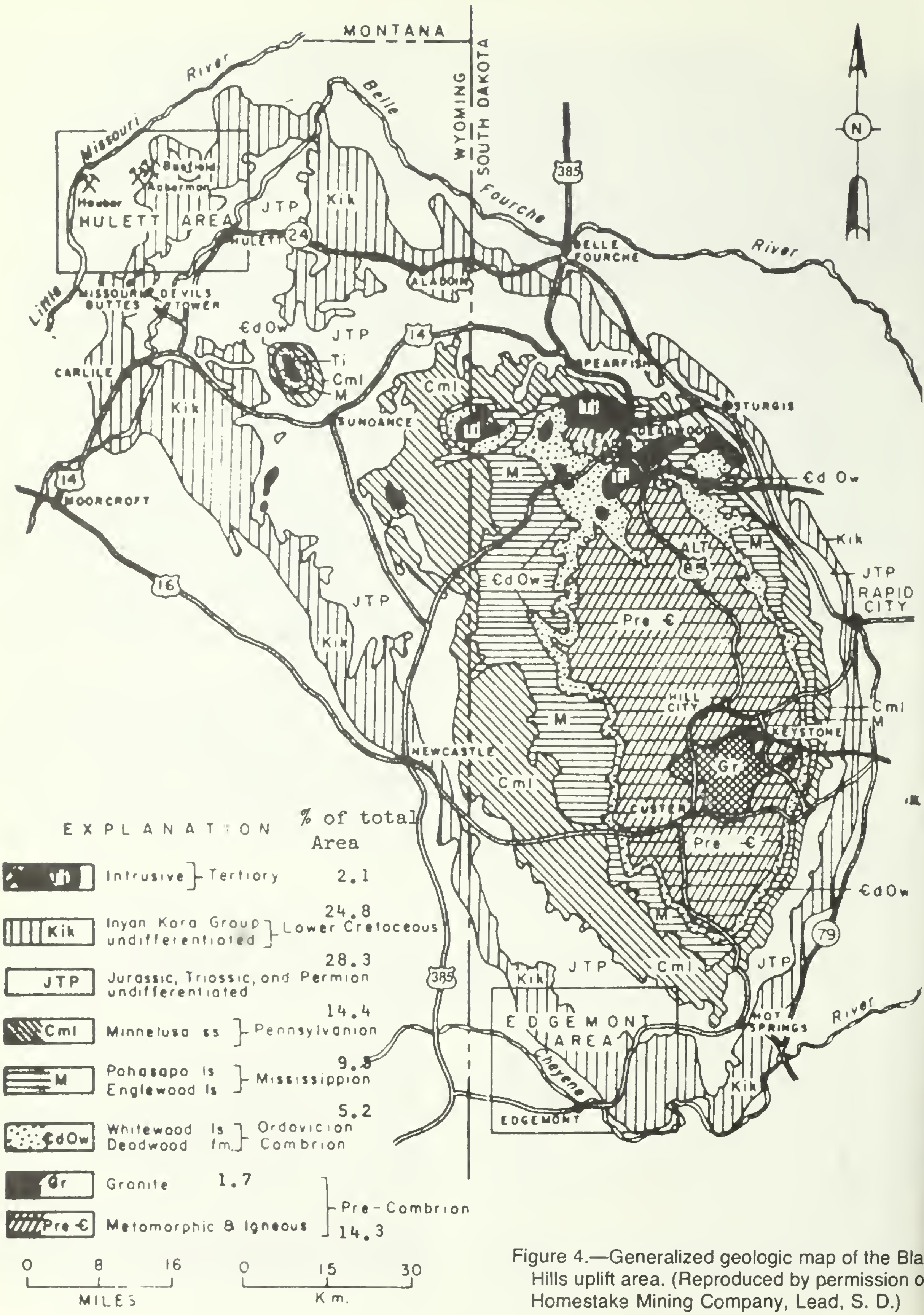

Figure 4.—Generalized geologic map of the Black Hills uplift area. (Reproduced by permission of Homestake Mining Company, Lead, S. D.)

Figure 5.—Massive limestone (Pahasapa formation), a primary water loss zone in the Black Hills.

many of the streams cut through the peripheral sedimentaries at nearly right angles (fig. 6).

One feature of particular significance to watershed management is the diminution or complete disappearance of flow where streams cross sedimentary formations (Brown 1944). These channel segments are recharge zones to aquifers which are important ground-water sources and still have a large untapped potential. At the same time, the diminution or disappearance of flow means that surface water yields can be significantly increased only in areas upstream from the loss zones—except in the case of floods or other high flows that exceed the intake capacities of channels.

Surface water yields (upstream from loss zones) can be increased in the Black Hills only by management of relatively small amounts of water at many locations (a large number of relatively small streams).

Soils

Ridge and slope soils in areas of granite and metamorphic parent materials are relatively shallow, coarse textured, and porous. The more easily transported fines have been deposited on lower slopes and in the valley bottoms. Hence the valley soils are generally finer textured, deeper, and more fertile. Topographic stratifications of soils are similar in areas of sedimentary formations. However, the soils are, in general, finer textured. Clays and clay loams are not uncommon, particularly in limestone areas.

In broad terms, the soils of the Black Hills classify as "gray wooded" (Westin et al. 1959, Radeke and Westin 1963). This is a broad classification indicative of the relatively humid forest environment in which the soils have developed. In this subhumid to humid climate and under conditions of rapid drainage, the surface layers leach rapidly, leaving an A_2 horizon of distinctive ash-gray color and as much as 10 to 12 inches thick. Deposition in the B horizon has resulted in fairly well defined blocky structure, depending on parent material, and a definite brown color.

Azonal soils also are present, including regosols, lithosols, and alluvial soils. Zonal soils with characteristics of both true prairie and gray wooded series occur in the open grassland and "prairie" areas of the interior Hills (White et al. 1969). Zonation varies from weak to strong. The more pronounced similarity to gray wooded soils of forest origin suggests that soils in these areas developed under forest.

Vegetation

In the cooler, more humid climate of the Black Hills uplift, forest cover is dominant—a sharp contrast with the grass cover of the surrounding plains. The forest, in turn, is dominated by ponderosa pine[2] except on more moist sites in stream bottoms and on north-facing slopes where white spruce grows—often in nearly pure stands. In contrast to much of its natural range, ponderosa pine reproduces easily in the Black Hills. "Dog hair" stands are common.

Interspersed with these two conifer species are small amounts of quaking aspen and paper birch on the more moist sites. Willow, red-osier dogwood, and water birch are found along many of the streams.

Comprehensive reports on the state of our knowledge in timber management in the Black Hills are given by Alexander (1974) and Boldt and Van Deusen (1974).

Although "forest" characterizes the Black Hills in general, there are numerous open meadows, parks, and "prairies" (fig. 7) ranging up to hundreds of acres in size. Here are found representatives of the true prairie, the plains, and Rocky Mountain floras.

Many narrow stream bottoms (fig. 8) support herbaceous cover. Kentucky bluegrass is a dominant species. These stream bottoms are some of the most productive and most highly favored livestock range in the Hills area. Con-

[2]Common and botanical names of species mentioned are listed inside the back cover.

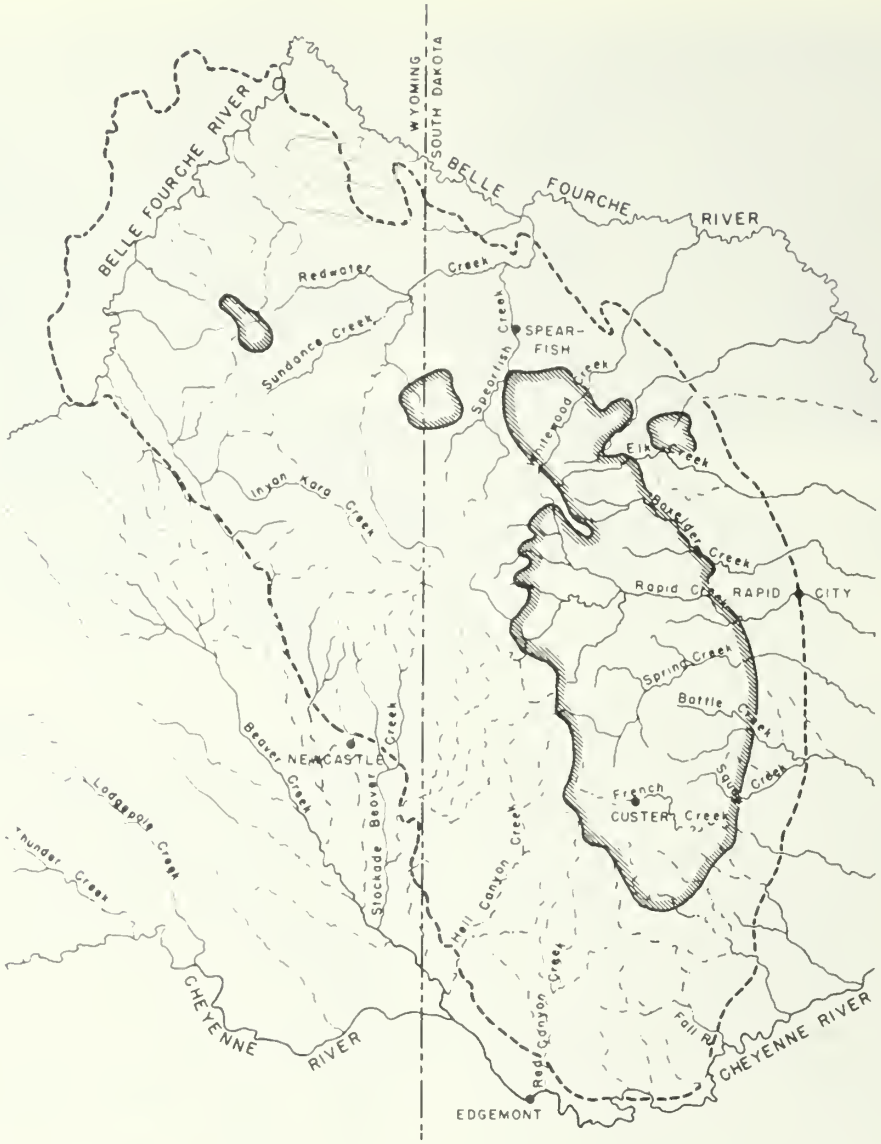

Figure 6.—Drainage map of the Black Hills and Bear Lodge Mountains. The heavy dashed line is along the sedimentary formation of the outer encircling ridge. The hatched lines encircle areas of metamorphic and igneous rock formations. Sedimentary formations are found in the remainder of the area (Orr 1959).

sequently many areas have been subjected to heavy use. Ranch and farm properties, many of them originally homesteads, are dispersed within the boundaries of the National Forest in and adjacent to stream bottoms.

These descriptions are of vegetation as we see it today. Actually the region has a unique intermixture of northern, southern, western, and eastern elements in the flora (Hayward 1928). For example, the dominant ponderosa pine is a western species. Typically eastern species include bur oak, American elm, boxelder, and hophornbeam (ironwood). Black Hills spruce and paper birch are typical northern species. Southern species are predominantly shrubs. True prairie species are found in the foothills and in some "prairie" areas within the Hills. Similar relationships have been described by McIntosh (1949). An up-to-date listing of the vascular plants of the region with their presently accepted scientific names was published by Thilenius in 1971.

Figure 7.—Gillette Prairie, one of the number of naturally treeless areas within the confines of the Black Hills. Representatives of true prairie flora are found in such areas.

igure 8.—A typical "bluegrass streambottom." These are highly favored cattle and sheep ranges. White spruce grows low on the north facing slope (left). Remnants of quaking aspen, white birch, and willows are also present. Beaver were once present but they have been trapped or have starved themselves out. Almost all dams are broken and eroded. Roads are present in virtually all such stream bottoms in the Black Hills.

The Water Situation

The trend in the Black Hills is toward more ıtensive management of smaller areas. Inforıation and means of satisfactorily modeling the hydrology of small areas are available for subalpine and Montane forests (Leaf 1975, Gary 1975). The technology developed for these areas and information presently available in the Black Hills will provide a sound basis for a higher level of watershed management in the future. There is still a need, however, to adapt the modeling approaches presently being developed for the Rocky Mountain region as tools in decisionmaking for the Black Hills. These models are essential to our understanding of natural water relations, how these relations have been and are influenced by man, projections of need and demand, and capacity of the area to meet demands without serious deterioration of the environment. Inventory of water quantity and quality is necessary, together with other elements of the environment that are known to significantly influence the production and utilization of water.

Water Yield

Flow is measured by the U.S. Geological Survey on most of the main streams, but usually downstream from zones of water loss into the sedimentary formations. Yields, including subsurface, are therefore greater than indicated by published figures. Surface yields from three gaged streams on the Sturgis Experimental Watersheds (fig. 9 and 10) averaged slightly in excess of 7 inches per year, almost exactly 25 percent of precipitation, from 1964 through 1969. Losses, closely approximating total evapotranspiration, were 21 inches per year (Orr and VanderHeide 1973). Except for the Sturgis watersheds, there are virtually no data for sizes of areas now considered in unit area management plans.

Watershed management is complicated by the large number and diversity of small drainage basins. Management objectives are thus more variable and the planning processes are more complex than in areas where only one or two streams are involved.

No areas have been or now are managed primarily for water-yield increase in the Black Hills. One reason is that much developmental work can be done to improve utilization of presently available water. A second is concern about our ability to increase water yield, and at the same time maintain site stability. Although these reasons are judgmental, they are nevertheless based on general knowledge of the Hills and well-established hydrologic principles.

Figure 9.—Area of the three Sturgis Experimental Watersheds, on the Vanocker Laccolith in the northeastern Black Hills. These watersheds are instrumented for basic hydrologic studies and evaluation of the effects of timber stand manipulation on quantity and quality of water yield.

Figure 10.—Spring runoff from one of the Sturgis Watersheds. Station is a tandem San Dimas flume for measurement of high flows and a 120° V-notch weir for measurement of low flows.

Water Quality

In land and forest management in the Black Hills, concern for water is focused primarily on quality. Some quality problems stem from inherent geochemistry of source areas and others from land and water use.

Chemical quality.—The surface waters of the Black Hills are of better chemical quality for domestic use than any other waters in the State (South Dakota Department of Health 1966). Content of dissolved solids varies with season, (lowest during high flow periods) but it is consistently less than for wells in general, though increasing numbers of wells are being drilled to obtain domestic water. Well waters vary from moderate to very hard. Total dissolved solids increase rapidly with increasing distance from the Hills, and generally with increasing well depth.

From a limnological standpoint, surface waters from areas of limestones and associated formations in the Hills contain largest amounts of essential nutrients and are the most productive. Waters from metasediment areas are less productive because the rock is less soluble. Water originating in granite areas is still less productive.

The iron problem.—One of the best known problems of water chemistry in the Black Hills involves "bog iron" in some areas of metasediments, particularly in upper Rapid Creek tributaries. The general problem of iron mining and aquatic resources in the Black Hills has been reviewed in detail by Lyons.[3]

Limited areas of bog iron have been mined, leaving channels in practically sterile condition despite diligent rehabilitation efforts. Although some areas have been regraded, top soil replaced, and lime applied, acidity along the channels remains too high for most plants to establish and grow. Channels are a distinctive rust red color. This color, plus the higher-than-average acidity and precipitation of phosphate in combination with iron, are detectable considerable distances downstream. This problem has also been discussed in considerable detail by Stewart and Thilenius (1964). Not many areas have been mined, but some rather extensive stream bottom areas remain where bog iron concentrations are known.

Roads and sedimentation.—"Quality" is rated the number one water problem in the Black Hills, sedimentation is most often cited as the number one quality problem, and roads are most often cited as the number one source of sediment. The Hills are interlaced with an extensive network of both old and new roads, a large proportion of which are in or near stream bottoms (see figs. 5 and 8). New roads are built with important elements of environment taken into account, but such was not the case with

[3] *John R. Lyons. Iron mining and aquatic resources in the Black Hills. 14 p. (Unpublished report presented at the meeting of the Board of Directors of the Black Hills Conservancy Subdistrict, March 29, 1966.)*

most old roads. A large part of the old road network served logging, mining, or other utilitarian land uses. The locations and grades were dictated by intended use, and limitations of equipment that would be traveling the roads. Seldom were special precautions taken to keep a road stable during use or to stabilize it later.

Although many old roads, more by chance than by design, were located and constructed in such a way that they stabilized and remained stable, there remain segments that need attention—a situation that is particularly evident after a flood (Orr 1973). Trouble areas most often encountered are steep pitches in grade and channel bottoms. Two types of areas are especially susceptible—soils that are highly permeable but with low cohesion and hence erodible (as in granite areas, see fig. 2), and soils that are medium to fine textured, easily compacted, and hence subject to larger volumes and more rapid runoff for given rainfall.

The significance of primitive roads has increased greatly with the advent of four-wheel-drive vehicles, motor bikes, snowmobiles, and all-terrain vehicles (ATV's). Many old roads now receive more use (or would if use were allowed) within a few years than they did in several prior decades. Thus the undesirable effects of poor locations of old roads are in some cases more evident now than they probably were in the early years following original construction.

Many old roads have been closed, and methods are available to stabilize "sore" spots once they are recognized and included in management planning.

Research Perspective of Knowledge Base

Hydrology

Enough is known about the hydrology of the Black Hills to define general characteristics of climate and streamflow. Pertinent relationships were reviewed by Orr (1959). A complication, however, is that although a considerable number of measuring stations (mostly standard gages) are scattered about the Hills, there are extensive areas in which few or no records are available. These have been interpolated into isohyetal maps, but uncertainty levels are high.

The scarcity of time distribution records of precipitation (from automatic recorders) was dramatically illustrated during the June 9, 1972, storm which produced record floods in Rapid Creek and other watersheds draining to the east out of the Black Hills. Certain areas are known to have produced unprecedented rates and amounts of runoff (Orr 1973), but without intensity records it is impossible to realistically estimate flow separation components or how much flood flow was due to overwhelming volumes of falling water. Recognition of waterflow and quality problems in relation to land use was practically impossible in this situation.

As we develop more explicit hydrologic models, pertinent climatic and atmospheric factors will need to be more precisely and more extensively measured. Experience has shown that the primary variables should include precipitation, temperature, and radiation (Leaf and Brink 1973). These variables will have to be measured at locations and in terms compatible with modeling concepts and goals.

Vegetation

National Forests have been under relatively intensive management for more than a half century. According to Alexander (1974), "Regeneration silviculture in the Black Hills has been learned by experience during nearly a century of harvesting that has included all silvicultural systems, and led to the replacement of the original old growth by well-stocked, manageable second-growth stands." There is, therefore, a large volume of forest inventory data and knowledge already in existence (Boldt and Van Deusen 1974). Data are being added continuously, but mainly through routine timber sales and inventories.

Vegetation complexes other than trees are highly variable in both composition and distribution. Such variability is due to type of land use, climate, forest cover, geology, exposure, soils, and probably other factors. Hence, species occurrence is predictable only within very broad geographical limits. Variations in distribution very likely affect moisture relations and water yields, but such relationships are known only in very general terms. Efforts to gain more exact information will depend on the need for more exact prediction of watershed behavior and response to changes in management.

Fortunately, from the standpoint of site stability, several introduced herbaceous species are adaptable over extensive areas in the Hills. One obvious reason is the concentration of precipitation in the early part of the growing season when moisture for plant establishment is most critical. On most sites, given a reasonable chance, vegetation reestablishes quite easily. This is one of the main reasons why there are no large sediment source areas in the Hills. Unstable sites are usually so obvious—for example, lack of soil, hyperacidity, or steepness of slope—that the manager would recognize the problem potential.

If there is a seed source close enough, forest cover will in time reestablish itself in most denuded forest areas. Areas which will not come back to forest cover are usually recognizable and plans can be made to seed or plant.

Soils

Lack of soils information is a serious hindrance to watershed management in the Black Hills. In general, soils characteristics relate to the parent materials but are less variable. In other words, broad soil classes occur across a broad range of geologic types that are known to have significantly different water yield characteristics and potentials. For example, gray wooded soils occur in areas where parent materials include a variety of sedimentary formations, metasediments, and also igneous rocks. Thus the classification is broad and needs improvement for modeling and more effective unit area management.

Information relating soil physical characteristics to land use is limited. Orr (1960) demonstrated that soil in grazed bluegrass meadow areas is more compact and has less pore volume than soils in exclosures protected from livestock trampling for 5 to 20 years. In a followup study it was found that improvement is relatively slow in terms of reduced bulk density and increased pore volume, especially in medium-textured soils, which are more susceptible to compaction than either coarser or finer textured soil. Thus 1 year of rest in a rotation grazing system is not likely to significantly improve soil conditions. Several years of protection may be necessary. The hydrologic impacts of grazing mountain ranges have been discussed by Gary (1975).

Geology and Physiography

Water-yield significance of these factors is known in broad terms. General relationships have been described by Darton and Paige (1925) and by many others. Published material usually lacks the detail needed for systematic refinement of geologic and physiographic elements in management analysis and design, however.

Detailed information is being obtained from the Sturgis Experimental Watersheds. Hydrologic implications of geomorphology have been carefully analyzed by a unique approach involving dimensional analysis (Yamamoto and Orr 1972). In this approach, we have attempted to refine the accounting of geological and morphological factors, which in the past have been dealt with almost exclusively on a broad regional basis.

Geophysical analysis of mantle depths, physical characteristics, and distribution are progressing. In each case, hydrologic implications are analyzed. This meshing of geologic and hydrologic (or hydraulic) elements will be necessary before geologic elements can be accounted for on smaller than a regional basis. As stated by Reene (1967), " . . . many researchers have found that the principal difficulties in applying research results from one watershed to another adjacent and seemingly identical watershed **lie below the surface.** Top watershed scientists have noted that soil and geologic properties, in particular, are poorly defined as they relate to moisture storage and transmission."

Timber/Water Relationships

Irregular patchcutting will produce maximum increases in water yields (Leaf 1975). Studies in the subalpine zone of central Colorado have indicated that patchcutting changes the usual snow distribution pattern by increasing snow accumulation in cleared areas where it melts more efficiently. Because recharge requirements in openings are less, more water is available for streamflow. The same principles apply to the Front Range pine zone in Colorado (Gary 1975) and to the Black Hills. Irregular patchcutting of some portion of first-order basins and interbasin areas would generate water-yield increases in a topographic position (bedrock channels in many places) where conveyance and other losses would be minimal.

Moisture disposition in dense second-growth pine was measured in a series of study plots—clearcut versus thinned (80 ft^2/acre basal area) versus unthinned (190 ft^2/acre basal area). The dense unthinned stand intercepted about 25 percent of precipitation, while the thinned intercepted only about half as much. Net interception (taking stemflow into account) can be estimated for different measured canopy densities (Orr 1972).

This same study also provided information about soil-moisture disposition. The thinning reduced soil-moisture demand, resulting in less soil-moisture deficit (Orr 1968) and greater potential for seepage to ground water. The study was carried out in a period of increasingly severe drought, and practically no seepage to ground water was observed except in the clearcut, which for a time was kept bare of vegetation. There the moisture surplus continued despite drought—until a luxuriant weed and grass stand was allowed to become established and quickly depleted the available soil moisture to 6 feet or deeper. Studies in other areas have shown that thinnings result in lesser soil moisture savings and small or negligible increases in streamflow, even during good years (Leaf 1975, Gary 1975, Rich 1965).

Further Research Needs

Several water-related questions remain in de-ign and application of watershed management.)ne has to do with the range of timber stand onditions—taking all relevant site factors into ccount—that will produce significant increases n water yield. Exploratory soil moisture meas-rements have been made to as deep as 24 feet in rge sapling stands, 20 level stocking.[4] At this tocking level there were definite soil-moisture radients across the space between trees, indicat-ng less than full site occupancy. At high stocking evels, 80 or higher, it is questionable whether any ncrease in yield could be achieved. Therefore, nere is a broad range of vegetal patterns within hich water yields can be significantly increased.

Geology and geomorphology are significant, nseparable parts of all systems related to water-ield improvement. These space variables need nore study in a variety of situations and locations the Black Hills to provide better guidelines for nd use planning.

Questions having to do with the range of appli-able land use options and treatments which will nprove water yields without deterioration of en-ironment are many. For example, how much mber can be removed without triggering accel-rated soil erosion? How much and in what pat-rns should timber be harvested to promote es-blishment of desirable vegetation? What are fe limits of other land uses? The manager ould know his options with respect to the best e of the land and water resources. Adaptations available hydrologic and land use models to the ack Hills would help him determine these op-ns.

Summary and Conclusions

The pine-forested Black Hills are an impor-nt water-yielding area, both for surface flow d ground-water recharge. Because the area is island of forest and flowing streams in the oad expanse of the northern High Plains, it is especially attractive to the traveling public. Therefore esthetics are especially important.

[4] *Basal area that will gradually increase to 20 ft² per acre en trees reach 10 inches d.b.h.*

Quality is an ever present water problem in the Hills; sedimentation is the primary quality problem, and roads are most often cited as the main source of sedimentation. Nowhere are there large problem areas, however. Instead, problems are small and relatively scattered. Corrective measures are especially complex and expensive under these conditions.

The extensive network of old roads in the Hills is especially troublesome. Many are located in stream bottoms or on steep grades. With the advent of the four-wheel-drive vehicles, motor bikes, snowmobiles, and ATV's, intensity of use may actually be greater in places now (or would be if allowed) than it was when roads were in intended use, mostly utilitarian, many years ago. Stability problems have grown accordingly.

A chemical quality problem exists in and downstream from stream bottom areas mined for bog iron. Fortunately, these areas are few in number. Despite intensive restoration efforts, some areas remain practically barren after many years. Further mining of bog iron should be discouraged unless methods are developed that will insure site stabilization within a short time.

Quantity of water yield cannot be ignored, though no part of the Hills is now or ever has been managed specifically to increase water yield. Some reasons for this are the current overriding importance of quality and uncertainty about land use. Because increase in demand for water is as inevitable as increase in population, the possibility of need to increase yield must be considered in land use planning.

One key to sound management planning is careful inventory of pertinent resource factors and relationships, which vary greatly within the relatively small area of the Black Hills. While this variability is a complicating factor in management, it is an ideal situation for research because a wide variety of conditions can be sampled and studied within a relatively small geographic region.

Watershed management in the Black Hills can be improved most easily by adapting technology developed here and elsewhere in the Rocky Mountain region. Irregular patchcutting, which produces maximum water-yield increases without causing adverse ecologic effects can be expected to produce similar results in the Black Hills.

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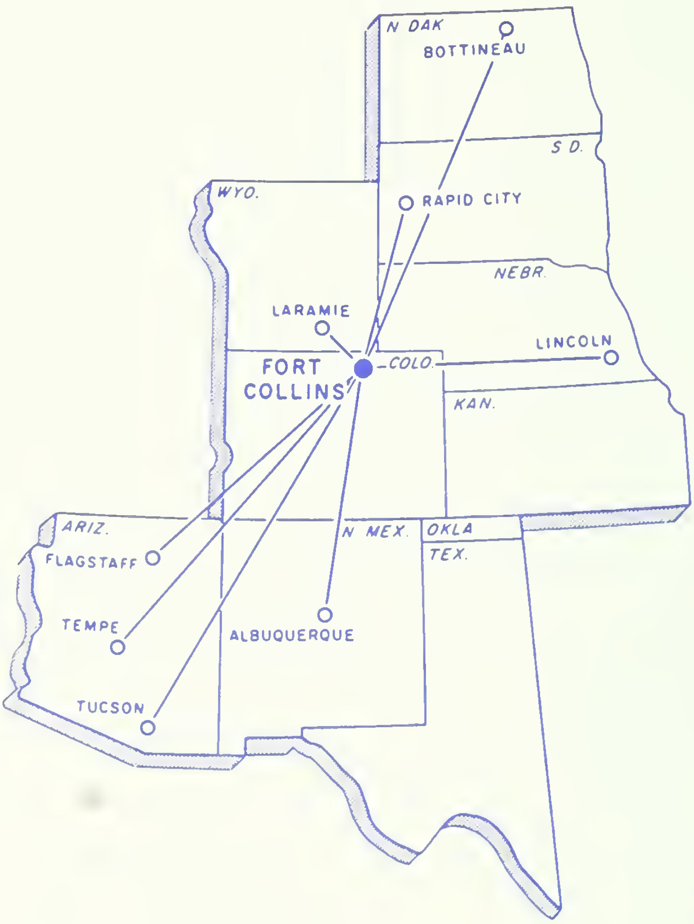
Common and Botanical Names of Species Mentioned

Aspen, quaking	*Populus tremuloides*
Birch, paper	*Betula papyrifera*
Birch, water	*Betula occidentalis*
Bluegrass, Kentucky	*Poa pratensis*
Boxelder	*Acer negundo*
Dogwood, red-osier	*Cornus stolonifera*
Elm, American	*Ulmus americana*
Hophornbeam (ironwood)	*Ostrya virginiana*
Oak, bur	*Quercus macrocarpa*
Pine, ponderosa	*Pinus ponderosa*
Spruce, Black Hills (white)	*Picea glauca* var. *densata*
Willows	*Salix* spp.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WATERSHED MANAGEMENT IN THE CENTRAL AND SOUTHERN ROCKY MOUNTAINS:

A Summary of the Status of Our Knowledge by Vegetation Types

Charles F. Leaf

U.S. Forest Service
Research Paper RM-14?

…h 1975

Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture
Fort Collins, Colorado 80521

Abstract

Summarizes a series of comprehensive reports on watershed management in five major vegetation zones: (1) the coniferous forest subalpine zone; (2) the Front Range ponderosa pine zone; (3) the Black Hills ponderosa pine zone; (4) the alpine zone; and (5) the big sagebrush zone. Includes what is known about the hydrology of these lands, what hydrologic principles are important for multiresource management, and what additional information is needed for each vegetation type.

Keywords: Watershed management, land use planning, alpine hydrology, range hydrology, snow hydrology, blowing snow management, water yield management.

PREFACE

Comprehensive reports on the status of our knowledge in watershed management, applicable to the important central and southern Rocky Mountain vegetation types, have been prepared as Research Papers by the Rocky Mountain Forest and Range Experiment Station. These include:

"Watershed Management in the Rocky Mountain Subalpine Zone: The Status of Our Knowledge," by Charles F. Leaf, (RM-137),
"Water-Yield Improvement From Alpine Areas: The Status of Our Knowledge," by M. Martinelli, Jr., (RM-138),
"Watershed Management Problems and Opportunities For the Colorado Front Range Ponderosa Pine Zone: The Status of Our Knowledge," by Howard L. Gary, (RM-139),
"The Hydrology of Big Sagebrush Lands: The Status of Our Knowledge," by David L. Sturges, (RM-140), and
"Watershed Management in the Black Hills: The Status of Our Knowledge," by Howard K. Orr, (RM-141).

These papers have been condensed in this report to provide a general summary of what is currently known about watershed management in all the major vegetation zones of the central and southern Rocky Mountains. Acknowledgments and literature citations are included in the full-length papers.

USDA Forest Service
Research Paper RM-142

March 1975

WATERSHED MANAGEMENT IN THE CENTRAL AND SOUTHERN ROCKY MOUNTAINS:

A Summary of the Status of Our Knowledge by Vegetation Types

Charles F. Leaf, Principal Hydrologist
Rocky Mountain Forest and Range Experiment Station[1]

[1] *Central headquarters is maintained at Fort Collins in cooperation with Colorado State University. Dr. Leaf is now privately employed in Fort Collins.*

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CONTENTS

WATERSHED MANAGEMENT IN THE CENTRAL AND SOUTHERN ROCKY MOUNTAINS:

A Summary of the Status of Our Knowledge by Vegetation Types

Charles F. Leaf

INTRODUCTION

Watershed management in the central and southern Rocky Mountains includes land use practices varying from manipulation of forest and range vegetation to building fences upwind of natural snow accumulation areas. The effectiveness or desirability of these practices depends on how well management goals consider the inherent hydrologic characteristics of a given area, vegetation type and condition, and environment. All these factors affect the quantity, quality, and timing of runoff. Because most undisturbed hydrologic systems are in dynamic equilibrium, the resource manager must be certain that natural processes are not altered by land use to the extent that undesirable hydrologic changes result.

Although not all limiting factors and optimum watershed management practices have been identified in the Rocky Mountain region, research has produced more information than is presently being used in day-to-day decision-making. Although a few summary publications and textbooks are available on the subject, most research results and observations during the past 40 years have been presented as individual articles, papers, and notes in a variety of publications. Moreover, much of what is presently known has not been documented in the literature. Accordingly, it is in the best interest of the profession to periodically synthesize and organize published as well as unpublished research results into one source.

The comprehensive status-of-knowledge summaries prepared for each vegetation type are intended to guide professional hydrologists and resource managers by providing information on: (1) what is known about the hydrology of the principal vegetation zones, and (2) how this knowledge can best be applied to meet multiresource management objectives. Supplemental benefits resulting from this effort include detailed literature reviews and identification of knowledge gaps where additional research is needed.

The purpose of this document is to provide a broad overview and evaluation of the more detailed status-of-knowledge reports. It is subdivided into five main sections: The Coniferous Forest Subalpine Zone, The Front Range Ponderosa Pine Zone, the Black Hills Ponderosa Pine Zone, the Alpine Zone, and finally, the Big Sagebrush Zone. Literature reviewed is not cited in this summary Paper, but is included in each of the five reports listed in the Preface.

THE CONIFEROUS FOREST SUBALPINE ZONE

Lodgepole pine and Engelmann spruce-subalpine fir forests characterize the subalpine zone (fig. 1). Lodgepole pine is the principal tree species in Wyoming, and occupies mountain slopes between 7,000 and 10,000 feet. Subalpine forests in Colorado range from 8,500 to 11,500 feet above sea level, and straddle the entire length of the Continental Divide from north to south across the State. Forest cover between 8,500 and 10,500 feet is lodgepole pine, quaking aspen, and Douglas-fir. Spruce-fir forests grow between 10,000 and 11,500 feet. In New Mexico, Douglas-fir and spruce-fir are the principal forest types. The former grows between 8,000 and 9,500 feet, whereas the latter is found above this elevation.

WHAT WE KNOW ABOUT SUBALPINE HYDROLOGY

Climate, Geology, and Water Yield

The climate of the subalpine zone is cool and humid. The mean annual temperature is less than 35°F, and precipitation, which falls largely as snow, averages about 28 inches.

Soils are derived from crystalline granites, and gneiss and schist rocks. Sedimentary and volcanic parent material are also common. Most valleys contain alluvial soils. Boggy areas, which owe their origin to seeps and springs, contain highly organic soils. For the most part, subalpine soils are relatively deep, permeable,

Figure 1.—Distribution of spruce-fir and lodgepole pine forests that comprise the subalpine zone in Wyoming, Colorado, and New Mexico.

and capable of storing modest quantities of water from snowmelt. Exceptions occur in those areas which have experienced intensive glacial activity. Here, soils are shallow, and runoff is concentrated during a short snowmelt period.

Snowmelt produces virtually all of the streamflow required by agriculture, industry, and municipalities. Spring runoff begins in late March or early April, peaks in early June, and recedes to base flow levels by mid-October. Streamflow averages between 12 and 15 inches annually. Mean annual water balances for typical subalpine watersheds in Colorado and Wyoming are summarized in table 1.

Table 1.--Mean annual water balances (inches) for typical subalpine watersheds in Colorado and Wyoming

Watershed	Seasonal snowpack, water equivalent	Precipitation	Evapotranspiration	Runoff
COLORADO:				
Soda Creek, Routt NF	42.6	55.2	16.7	38.5
Fraser River, Arapaho NF	15.0	30.3	16.9	13.4
Wolf Creek, San Juan NF	26.2	48.0	21.0	27.0
Trinchera Creek, Sangre de Cristo Mountains	9.5	19.6	14.5	5.1
WYOMING:				
South Tongue River, Bighorn NF	15.5	29.6	15.8	13.8

Snow Accumulation

Snow input can be precisely measured on accessible forested watersheds. Areal snow storage can be estimated from reconnaissance snow courses where one or two samples at most are taken at intervals along a trail which traverses the whole watershed. On uniformly forested watersheds, where melt rarely occurs during winter, snow storage can be estimated to within 5 percent of the true mean with 50 samples per square mile widely spaced over the drainage basin.

Where severe winds produce extremely irregular patterns of snow accumulation in forest margins and exposed parklike openings, reconnaissance snow courses can precisely estimate areal snow storage, provided that sampling intensities in and near the edge of large openings are 8 to 10 times greater than well inside the surrounding forest.

Partial cutting on areas less than 10 acres in old-growth lodgepole pine increases the snowpack in amounts proportional to the timber removed. Increases are optimum in clearcut patches five to eight times tree height and protected from wind. More snow is deposited in the openings and less under the adjacent uncut forest, so that total snow storage on an area basis is unchanged. Increased snow accumulation in the openings can be expected to persist for at least 30 years and longer, despite vigorous regrowth, due to the aerodynamic effect on snow distribution. After a typical snowfall event, wind-generated vortexes and eddies quickly strip intercepted snow from trees. In a short time, this airborne snow is redeposited at varying distances from where it was initially intercepted. Ultimately, virtually all the snow is removed from exposed tree crowns. The sequence of events in figure 2 illustrates the obvious importance of wind-caused snow redistribution in the subalpine zone.

Figure 2.—Significance of wind-caused snow redistribution in subalpine forest:

This photograph was taken during moderate snowfall that continued throughout the day on February 4, 1970 at the Fraser Experimental Forest. The storm ceased during the night.

The most exposed trees were already bare of snow by noon on February 5, 1970. Individual vortexes look like artillery bursts on the mountainsides. Vortexes were moving rapidly eastward (from right to left), and each one was visible for less than 60 seconds.

By 4:00 p.m. on February 5, 1970, all snow was gone from exposed tree crowns. The white patches are snow in the clearcut blocks on the upper portion of the Fool Creek watershed.

Evapotranspiration

Model studies of an unripened snowpack indicate that substantial amounts of water vapor are lost from the deepest layers of the pack. Free convection can take place within the pack during winter, and evaporation from surfaces can be relatively high during clear weather in late spring.

Both spruce and aspen can remove soil moisture to 8 feet in deep soils. The rate of water use by forest vegetation is related to availability. On low-elevation south slopes, soil-moisture deficits are sufficient to limit transpiration during dry years. Transpiration can occur early in the melt season when there is still considerable snow cover. Soil moisture is withdrawn largely from the upper part of the soil mantle during early spring. Later in the season, however, soil moisture in the deeper layers is required for transpiration demands.

Level-of-growing-stock studies have shown that only when a timber stand is thinned to approximately one-fifth of its original density, is soil-moisture withdrawal sharply reduced. Fall soil-moisture deficits in the top 6 feet of small patchcut openings are substantially less than in the surrounding uncut forest. Accordingly, less water is needed in spring to recharge soil moisture in cutover areas, and there is more available for streamflow.

Snowmelt and Runoff

Snowmelt rates on forested watersheds with generally east- and west-facing aspects are generally uniform at all elevations. In contrast, snowmelt rates on watersheds with north- and south-facing slopes differ considerably at low elevations. However, the time lag between maximum snowmelt rates on north and south slopes diminishes with increasing elevations.

Water-yield efficiencies are highest on watersheds that have (1) almost complete snow cover when seasonal snowmelt rates on all major aspects are uniform, (2) a delayed and short snow-cover depletion season, and (3) moderate recharge and evapotranspiration losses.

Water-yield efficiencies are least on low-elevation south slopes. Below 9,800 feet, streamflow can be less than 30 percent of that generated at higher elevations. Water yields from low-elevation north-south subdrainages can vary from near zero in poor runoff years to a maximum during good years of less than 60 percent of the flow generated from high-elevation subdrainages with north and south aspects.

Snowmelt rates are more rapid in patchcut areas than in uncut forest. Moreover, faster melt rates are offset by higher snow accumulation in small patchcuts so that open and forested areas become bare of snow simultaneously.

Accelerated snowmelt resulting from timber harvesting is conspicuous in the discharge hydrograph (figs. 3 and 4). At Wagon Wheel Gap in the headwaters of the Rio Grande (fig. 5), clearcutting a 200-acre aspen-mixed conifer watershed increased water yields about 22 percent. Stripcutting 40 percent of the old-growth lodgepole pine and spruce-fir forest on Fool Creek, in central Colorado (fig. 6), resulted in a 25 percent increase in runoff. Runoff increases may have begun to taper off since timber harvest in 1955, but current indications are that it will be at least 30 more years before the hydrologic impact from the initial cut is completely erased. Figure 7 compares seasonal runoff before and after stripcutting on Fool Creek.

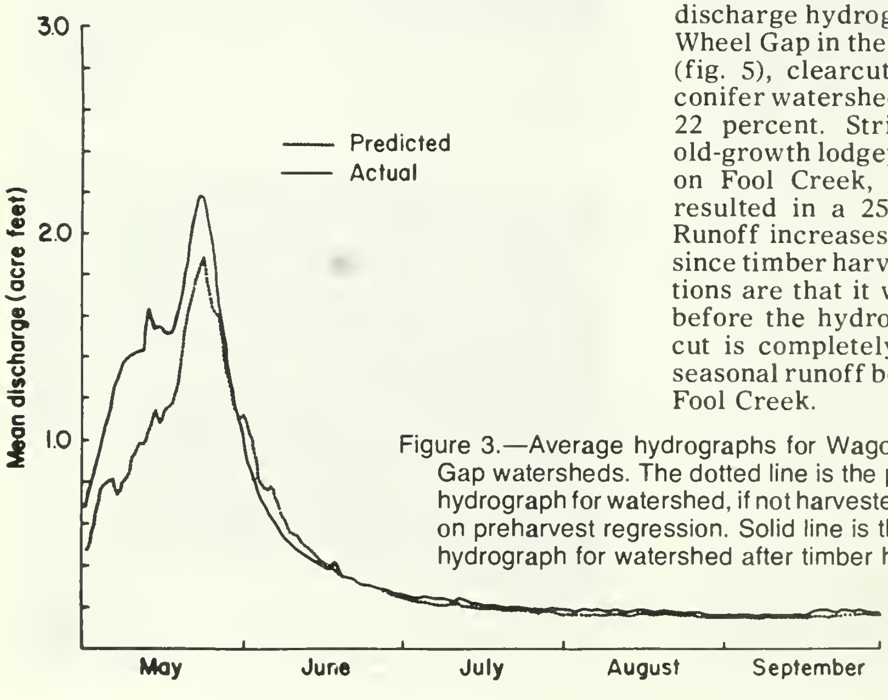


Figure 3.—Average hydrographs for Wagon Wheel Gap watersheds. The dotted line is the predicted hydrograph for watershed, if not harvested, based on preharvest regression. Solid line is the actual hydrograph for watershed after timber harvest.

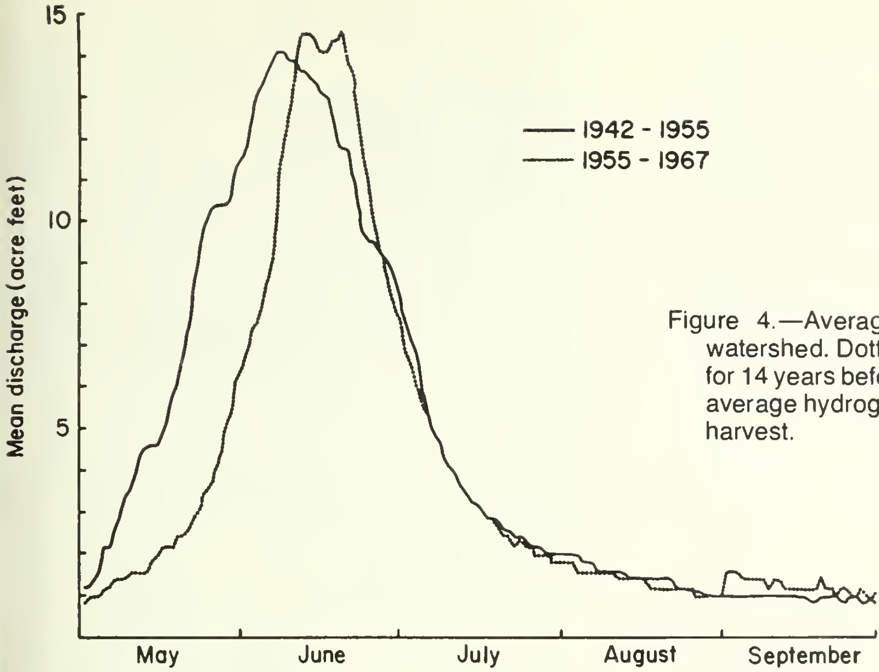
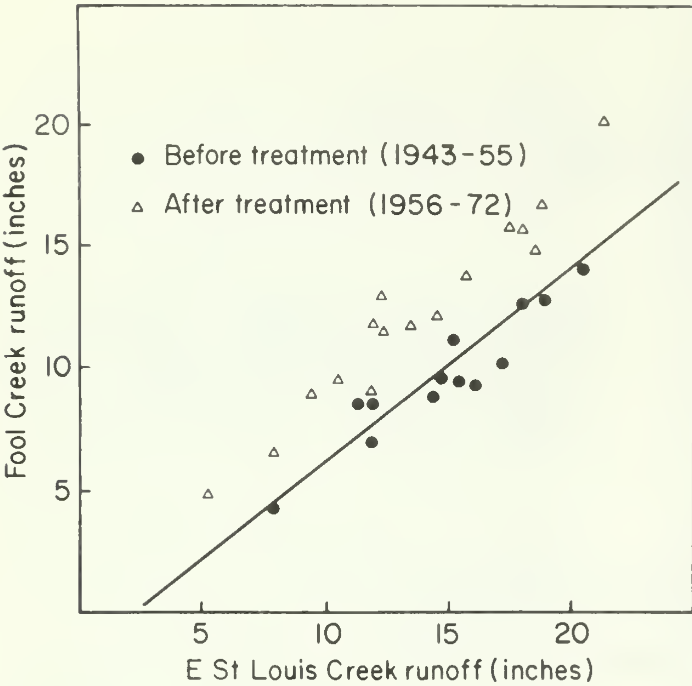


Figure 4.—Average hydrographs for Fool Creek watershed. Dotted line is the average hydrograph for 14 years before timber harvest. Solid line is the average hydrograph for 13 years following timber harvest.

Figure 5.—The Wagon Wheel Gap watersheds some 30 years after treatment. The regenerated forest cover on the clearcut watershed at right is aspen. The control watershed on the left is still vegetated with aspen and mixed conifers.

Figure 6.—
Fool Creek watershed, Fraser Experimental Forest. Control watershed is to the right of Fool Creek.



April - Sept.
Runoff Increase
Since Harvest

Year	Inches
1956	3.3
1957	5.2
1958	3.7
1959	4.6
1960	5.4
1961	3.4
1962	3.9
1963	2.9
1964	3.5
1965	4.0
1966	2.6
1967	3.1
1968	1.9
1969	2.5
1970	2.1
1971	3.6
1972	3.9
Mean	3.5 $\pm$0.8*

*95 Percent level of confidence

Figure 7.—Comparison of seasonal runoff before and after strip cutting on Fool Creek watershed.

Runoff probably is not significantly changed under accepted intensities of cattle grazing on watersheds with extensive grassland parks. Reasons for this are: (1) virtually all of the streamflow and sediment yield is produced during the snowmelt runoff season, (2) 60-minute rainfall intensities seldom exceed 1 inch per hour, and (3) grazing intensities are normally set up to obtain 25 to 60 percent utilization of range species, such as Idaho fescue.

Hydrologic Systems Analysis

Dynamic simulation models specifically designed to determine the short- and long-term hydrologic changes resulting from timber harvesting in the subalpine zone are now available for use by resource managers. Corollary models simulate timber yields. Emphasis is placed on the "planning unit," which is defined by environmental characteristics including slope, aspect, elevation, and forest cover. The hydrologic model (Subalpine Water Balance Model) simulates winter snow accumulation, the shortwave and longwave radiation balance, snowpack condition, snowmelt, and subsequent runoff in time and space.

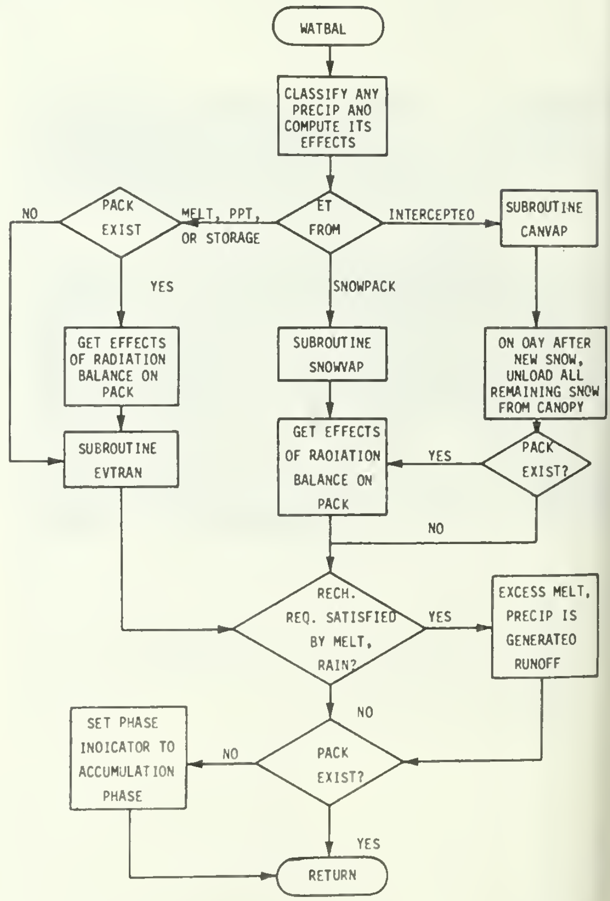


Figure 8.—Flow chart of dynamic model that simulates subalpine hydrology.

The model is capable of simulating the hydrologic impacts of a broad array of watershed management alternatives which can include weather modification, forest cover manipulation, or combinations of both practices. Figure 8 is a flow chart of the system. When timber is harvested, hydrologic change can be determined for intervals of time which can vary from a few years to the rotation age of subalpine forests. This is accomplished by means of time-trend functions in an expanded version (Subalpine Land Use Model) which computes changes in evapotranspiration, soil water, forest cover density, reflectivity, interception, and snow redistribution as the forest stands respond to management (fig. 9).

The models have been used to simulate the hydrologic impacts of forest and watershed management on five representative drainage basins in the Rocky Mountains. Detailed simulation analyses of hypothetical watershed management practices including weather modification and timber harvesting are presented in the conprehensive status-of-knowledge summary for the subalpine zone (RM-137).

The system developed for the subalpine coniferous forest zone represents our first step in providing the resource manager with planning tools which utilize our best technical understanding of fundamental hydrologic processes. The models have been designed so that they are no more complex than required to provide necessary information for planning. Moreover, use of the models is not unduly restricted by data requirements. Basic hydrologic data currently available are adequate for operational use in most areas.

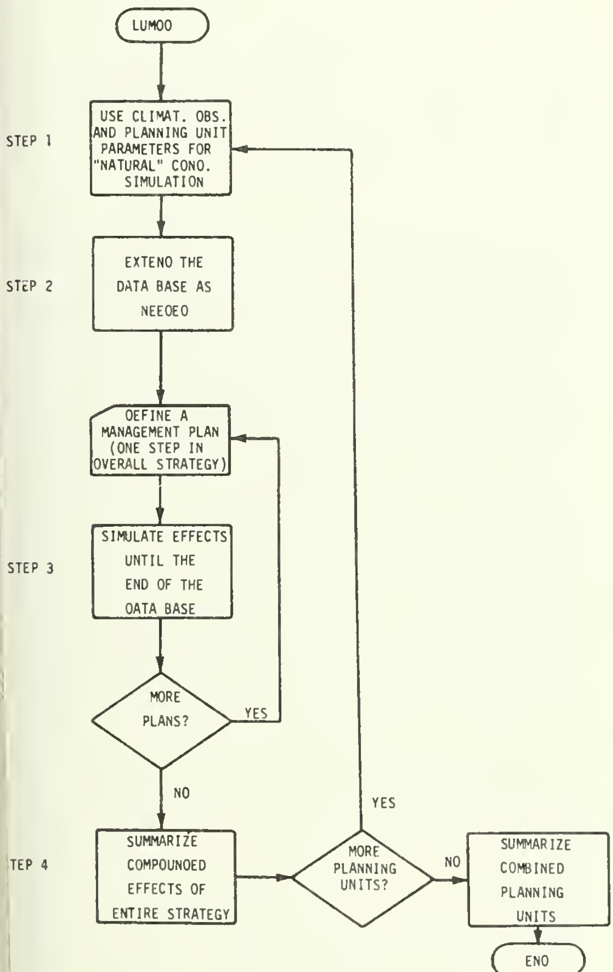


Figure 9.—Flow chart showing how the hydrologic simulation model is used to execute long-term alternative management strategies.

Erosion and Water Quality

Sediment Yield

Bedload and suspended sediment need not be excessive in central Colorado, provided reasonable erosion control measures are applied during logging and road construction. Sediment yields are increased in the years during and immediately after initial disturbance, but decrease rapidly in subsequent years toward preharvest levels.

Prediction equations which require erodibility indices based on rainfall intensity may be grossly in error when applied to much of the subalpine zone, where the runoff that transports much of the sediment load results from melting snow. Moreover, when rainfall-index equations are used, it is difficult to account for the obvious reduction of sediment yield with time. Accordingly, a simple model based on observed data has been developed to predict the impacts of secondary logging road construction.

The time-trend equation is used in combination with another expression which computes the area disturbed by road construction. This equation is formulated in terms of the following watershed and engineering design parameters: (1) width of roadbed, (2) average watershed sideslope, (3) number of miles of road system, and (4) angle of cut and fill. Because the model is formulated in terms of engineering design variables, its use should provide an estimate of the erosion impacts of alternative road systems. The model is based on field data collected from a stable subalpine watershed, and a carefully constructed secondary road system with a high standard of followup maintenance. Any direct application of the model should presume similar conditions.

Chemical and Bacterial Water Quality

In general, concentrations of all chemical water-quality components in subalpine streams are low. The pH values are near neutral, and water temperatures are cold (0° to 7°C). The chemical composition, in parts per million, of representative subalpine streams is summarized below:

Component	Concentration *(p/m)*
Ca	1.8 - 14.5
Mg	0.8 - 6.5
Na	1.0 - 4.5
K	0.4 - 1.0
CO_2	1.6
HCO_3	18.9
Cl	3.0 - 5.0
SO_4	10.0 - 14.6
NO_3	0.8 - 1.0
SiO_2	0.8

Bacterial counts can vary from several million colonies per milliliter down to less than 10,000 colonies per 100 milliliters. Generally, a strong positive bacteria-to-flow relationship can be expected. High bacterial concentrations associated with grazing and recreation impact appear to depend on the "flushing effect" during peak snowmelt and summer storm runoff periods. A seasonal trend for coliform, fecal coliform, and fecal streptococcus can be expected according to the following sequence: (1) low winter counts prevail while the water is near 0°C, (2) high concentrations appear during times of peak snowmelt, (3) a "post-flush" lull takes place as hydrograph declines in midsummer, (4) high concentrations are found again in the late summer period of warm temperatures and low flow, and (5) concentrations are sharply reduced in fall. All three bacteria can be expected in subalpine streams.

HYDROLOGIC PRINCIPLES IMPORTANT TO MULTIRESOURCE MANAGEMENT OF THE SUBALPINE ZONE

The task of recommending specific forest management practices is left to the resource manager after he has considered all feasible alternatives. The following paragraphs highlight technical aspects of the status of knowledge in watershed management, and summarize principles which should be considered in multiresource management of the subalpine zone.

- Patchcutting subalpine forests results in significant redistribution of the winter snowpack. An optimum pattern of snow accumulation results when openings are: (1) less than eight tree heights in diameter, (2) protected from wind, and (3) interspersed so that they are five to eight tree heights apart. More snow is deposited in the openings, but less snow accumulates in the uncut forest, so that total snow on headwater basins is not significantly increased.

- Snowmelt in patchcut openings on all aspects is more rapid than in the uncut forest. This accelerated melt causes streamflow to be higher on the rising limb of the hydrograph than during preharvest conditions. Where there is considerable natural regulation in the form of deep porous soils, recession flows apparently are not changed appreciably, and annual flood peaks are not significantly increased provided that the forest cover on no more than 50 percent of the watershed is removed in a system of small openings.

- When 40 percent of a densely forested subalpine watershed is occupied by small openings, and 60 percent is left uncut, annual water yields may increase as much as 2 to 3 inches above the norm. Interception loss is decreased, but increased evaporation from snow surfaces in the openings almost compensates for the decreased interception. Average fall soil-water recharge requirements are decreased, as is evapotranspiration during the growing season. Simulation analyses indicate that, under this alternative, water-yield increases on low-elevation south aspects in lodgepole pine forest are as large as corresponding increases from high-elevation north aspects in spruce-fir. Hence there is no reason to favor areas with the highest natural water yield if the objective is to maximize water yields from medium to dense old-growth forest.

- The pattern in which trees are harvested determines whether or not runoff will be increased. Highest increases in streamflow result when subalpine forests are harvested in a system of small forest openings. When the forest cover is removed in large clearcut blocks, or by selectively cutting individual trees, overall water increases are far less than that attained if an equivalent volume is removed in patches. When 40 to 50 percent of the mature spruce-fir timber volume is removed from north slopes on a selection-cut basis, water yields may actually decrease somewhat. In lodgepole pine forest, water yields can be increased somewhat by this method, provided that selection cuts are made on southerly aspects and at low elevations where the snowmelt season is short and begins relatively early in the spring.

- The harvesting measures recommended for maximum water yields are silviculturally sound and compatible with timber management guidelines recently developed and published in a comprehensive status-of-knowledge paper (RM-121). This paper, also published by the Rocky Mountain Station, carefully considers the ecology, silviculture, and management of subalpine forests; it recommends practices for water-yield improvement which would also enhance wildlife habitat, and preserve the natural landscape in areas where recreation and esthetics are important.

- It is not expected that the timber-harvest measures recommended for maximum water yields from the subalpine zone will be detrimental to water quality or excessively increase erosion, **provided that** timber is harvested with proper planning, engineering, construction, and followup maintenance. Although sediment yields can be expected to increase immediately following road construction, yields decrease rapidly toward preharvest levels after a short time. It is important to understand that these conclusions apply only to **surface erosion,** not **mass erosion,** which can occur if very steep and naturally unstable slopes are disturbed.

- Results from simulation analyses have indicated that, in central Colorado, a 15 percent increase in snow accumulation through successful weather modification will increase water yields 16 percent in the average year. In general, the increased snowpack will not extend the snowmelt season more than 3 to 5 days. Because water-yield benefits result from the last snowmelt at a given location, the bulk of the increased runoff is released during and just after peak streamflow. This would have a tendency to broaden the snowmelt hydrograph by increasing recession flows, and increase peak flows to some extent in small headwater streams. If increased snowfall due to weather modification is combined with patchcutting, water-yield increases will be even greater. In central Colorado, for example, where 40 percent of a given watershed is occupied by forest openings five to eight tree heights in diameter, water-yield increases can be doubled if the natural snowfall is increased by 15 percent.

- Dynamic simulation models have been developed from the best information we presently have about subalpine hydrologic systems. The models have been calibrated, using data from representative watersheds in old-growth lodgepole pine and spruce-fir forests throughout the Rocky Mountain region. They have been designed to predict the short- and long-term hydrologic impacts of a broad array of watershed management practices. Hydrologic changes can be determined for intervals of time which can vary from a few years to the rotation age of subalpine forest. The models produce expected results based on experience and our status of knowledge. We believe that the output from such models contains the type of information professional hydrologists and land managers need to know in order to make difficult management decisions. The ability of these and other similar models to integrate complex forest and water systems make them unique and powerful tools for evaluating the hydrologic and environmental impacts of a broad array of land management alternatives.

WHAT DO WE NEED TO KNOW

Techniques of precipitation measurement, including snow surveys and ground-based sensors, need to be improved. Although this problem has been researched for several hundred years, much of what has been done has largely reaffirmed past results without producing new knowledge. New and different systems, such as laser devices or particle counters, offer promise of better precipitation measurement in the future.

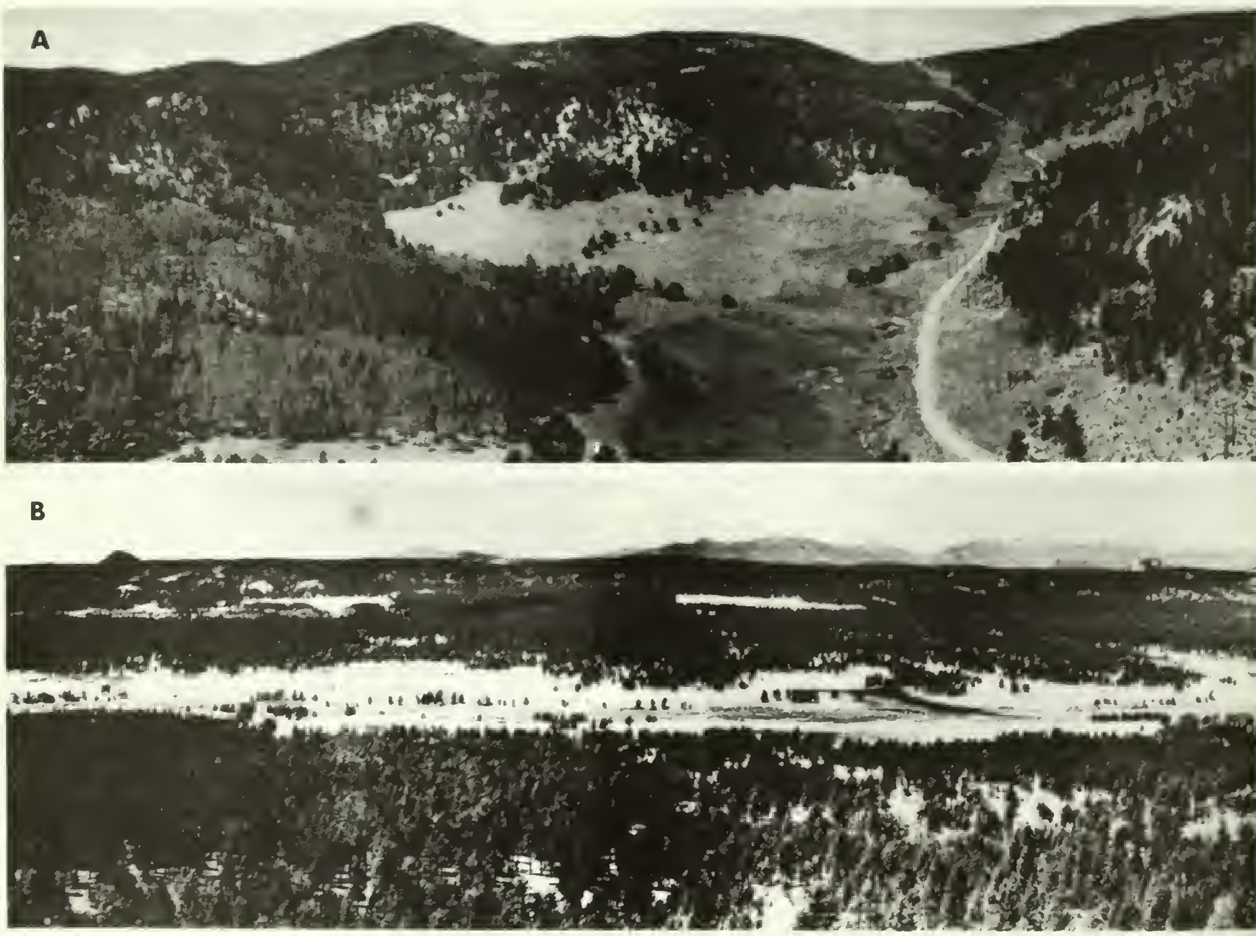
A novel simulation model recently proposed suggests that total snowfall in mountainous areas can be explained by the topographic slope which airmasses must traverse on the last 20 km of approach to a given station, and the number of mountain barriers upstream. Additional development of this and similar models which account for interactions between the topography and large airmasses will result in highly useful tools for explaining the seasonal snowfall distribution on a regional basis. Another important benefit from their use will be a better insight into the complex dynamic physical processes affecting mountain precipitation regimes.

A better knowledge of aerodynamic processes that affect interception and differential snow accumulation is yet to be gained. New work in (1) characterizing the aerodynamic characteristics of subalpine timber stands, (2) evaluation of the long-term effects of tree height growth on snow accumulation, and (3) sublimation losses from transported snow, will significantly add to what we have already learned from empirical studies.

At the present time, we do not have a complete understanding of evapotranspiration on an areal basis. While empirical methods have been useful for quantifying consumptive use, our knowledge of basic forest-water relationships is far from adequate.

The complex problem of quantifying the interaction of solar radiation with subalpine forest canopies needs more attention. This work should concentrate on the interrelated factors involved in the time-dependent variability of the radiation balance above and beneath forest canopies. It should consider solar geometry, the orientation of intercepting slopes, and the absorptive, transmissive, and scattering properties of canopies. Of highest priority are studies which objectively define the radiation balance in terms of such forest vegetation parameters as basal area, crown depth, stem density, and other indices of foliage mass and distribution.

One of the most controversial impacts of land use is road construction. Yet, little information is currently available on the natural levels of sediment yield from subalpine streams. Although some bedload data have been collected from experimental watersheds, more of this type of information is needed on representative watersheds throughout the Rocky Mountain region. There is much yet to be learned about other aspects of water quality, including suspended sediment, water chemistry, and bacterial water quality. These parameters are of interest in a wide range of problems which can vary from nutrient balance changes associated with timber harvesting to the disposition and survival of pathogenic bacteria resulting from winter recreation activities in wilderness areas.



THE FRONT RANGE PONDEROSA PINE ZONE

The Colorado Front Range, generally thought of as the eastern foothills region of the Rocky Mountains, extends from southern Wyoming to the vicinity of Canon City, Colorado. On the east, it is bounded by high plains; on the west it reaches the Continental Divide. The low-elevation (6,000 - 9,000 feet m.s.l.) forests and grasslands are generally and collectively called the ponderosa pine, or Montane Zone (fig. 10).

Commercially valuable tree species above 7,000 feet elevation are ponderosa pine, lodgepole pine, Douglas-fir, and Engelmann spruce. Much of the forest cover has been cutover, beginning with early settlement of the Front Range. Aspen is also an inportant tree species in young stands, particularly where fire has occurred. Brush species grow at the lower elevations on south exposures and on old burns. The interspersed grasslands are important forage producers for cattle (fig. 11). Many of the valleys were farmed near the turn of the century, but have since been abandoned because of low rainfall, erosion problems, and short grow-

Figure 10.—Distribution of the ponderosa pine type along the Colorado Front Range in relation to soil origin.

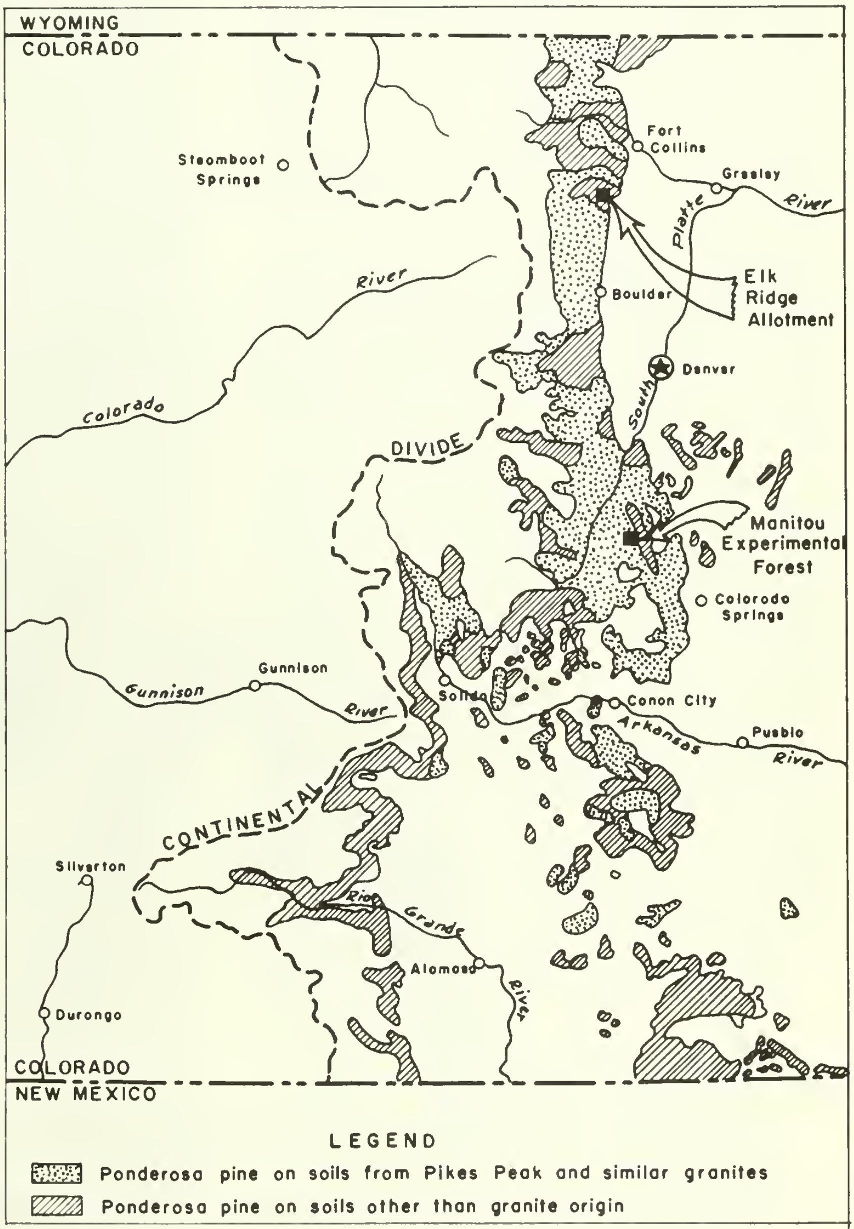


Figure 11.—Panoramas typical of the Front Range pine type: **A**, the North Fork of the Little Thompson watershed; **B**, the Manitou Experimental Ranges.

ing season. Today, recreation use and residential development in the Front Range probably have impacts as high as any other single use.

WHAT WE KNOW ABOUT FRONT RANGE HYDROLOGY

Climate, Geology, and Water Yield

The climate of the region is typically subhumid, with wide diurnal and annual temperature ranges and great variation in the amount and distribution of precipitation. Precipitation may be in the form of snow from late September through May, but snow commonly melts from areas exposed to radiation within a few days. The shallow snowpacks at high elevations and on protected north slopes generally disappear by mid-May. Annual precipitation probably averages between 15 and 20 inches. About two-thirds occurs in April to September, and thus accounts for the presence of grass over much of the area.

The Montane Zone is subject to intensive rainfall and infrequent but major floods. Flooding can occur from high-intensity rainfall confined chiefly below 7,000 feet and extending eastward from the foothills for a distance of about 50 miles. Such storms are generally confined to small areas and last for a short time. Perhaps the most devastating flooding can occur in May or June from moderate-intensity upslope storms which produce large quantities of precipitation over a period of 3 to 5 days. Above 7,000 feet, most of the precipitation from spring storms falls as snow.

Rainfall and flooding in the Front Range produce significant geologic as well as hydrologic effects. Geologic processes triggered by such floods can be intensified by improper land use, causing heavy property damage and even loss of life.

Land features along the Front Range are complex, and vary from steep rocky canyons to large openings and parks. Soils, for the most part, have developed from coarse granite rocks, alluvial deposits, sandstones, limestones, and quartzites. The most stable soils are developed from limestone, while the shallow and potentially unstable soils are derived from granite. Limestone and deep alluvium soils support more herbaceous vegetation and forest cover than do the less fertile granitic soils. The latter occur over about 90 percent of the area. Seeps, springs, and wet meadows are common throughout the Front Range, and occupy about 2 percent of the area.

The potential water balance for a typical Montane Zone watershed is shown in figure 12.

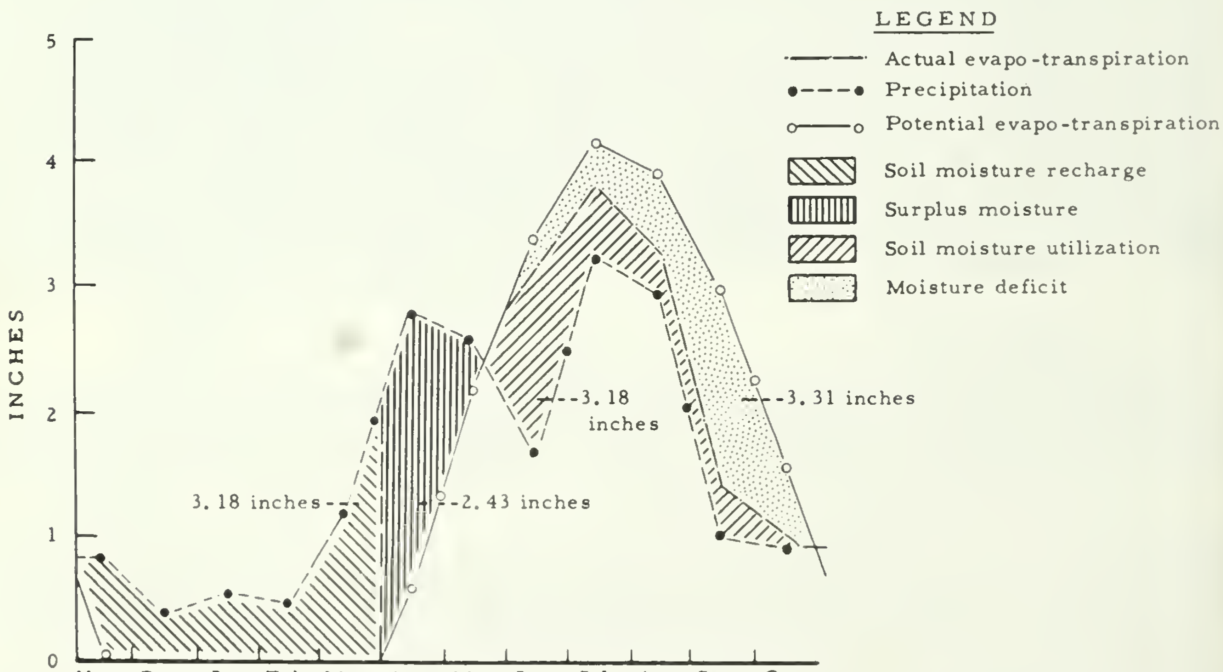


Figure 12.—Potential water balance for Missouri Gulch watershed, Manitou Experimental Forest.

The values indicate that annual precipitation is in excess of potential evapotranspiration from November through May. Thereafter, the balance is characterized by a substantial moisture deficit when evapotranspiration depletes soil-water storage. Accordingly, streams originating in the low-elevation pine type are usually intermittent and flow only during late fall, winter, and spring.

Average annual water yields can vary from approximately 12 inches in lodgepole pine and spruce-fir forests near the Continental Divide to less than 5 inches, or about 15 percent of the annual precipitation, in the Front Range pine zone. Near the upper limits of the ponderosa pine type, runoff is approximately 6 inches during the average year.

Figure 13.—Erosion channel through a Front Range meadow.

Watershed-Condition Criteria

Certain plant species and associations apparently have more effect than others on infiltration, runoff, and erosion. The effectiveness of any species or type is significantly influenced by organic materials and physical soil properties. Litter and porosity of the surface soil are the two factors most highly correlated with rainfall infiltration rates.

Cattle grazing and other land use affects infiltration by destroying plant cover and reducing the proportion of noncapillary pores. On-the-ground organic materials exceeding 2 tons per acre, exposed soil less than 30 percent, and noncapillary pores exceeding 20 percent in the upper 2 inches of soil constitute satisfactory watershed conditions from the standpoint of runoff and erosion from Montane grasslands.

On steep upland forested areas, organic materials exceeding 2 tons per acre or 1,000 to 1,300 pounds of live herbage per acre produce desirable watershed conditions. Quantity of litter is also an important hydrologic factor in the timber-grass types. Favorable watershed conditions result when 19,000 to 21,000 pounds of litter per acre are maintained.

Channel Erosion and Sediment Yield

Meadows and hillsides are typically lined with gullies throughout the Front Range pine zone (fig. 13). Guides for gully control have long been available, but many gully control structures apparently fail due to a lack of engineering and followup maintenance. Only a few summer storms produce gully flows. While some gully activity is caused by short-duration summer cloudbursts, the most severe erosion probably takes place during large-scale moderate-intensity upslope storms. Associated geologic activity such as rockfalls, slumps, and earthflows can also result from these events.

Reservoir sedimentation is also a significant factor. Sediment yields from one 69 square-mile drainage averaged approximately 0.3 acre-feet per square mile annually for an 11-year record period.

Watershed Management

Forest management in ponderosa pine offers possibilities for increasing water yields. Snow accumulation in small patchcuts five to eight times tree height can be expected to increase from 8 to 35 percent with an associated decrease in snowpack in the adjacent uncut forest, so that total snow storage is not changed. As discussed previously, research in the subalpine zone has shown that increased runoff and higher spring freshets can be expected after patchcutting; these changes affect the snow accumulation pattern and snowmelt timing, and reduce evapotranspiration. The same hydrologic principles apply in the Front Range pine zone.

Management of selected riparian and wet sites supporting trees or willows also offers considerable potential for increasing water supplies. Guidelines on this aspect of watershed management can be found in a recently published status-of-knowledge paper (RM-117) by Horton and Campbell.

Minimal responses in water yield can be expected on grazed lands where soils are deep and highly permeable. When deep-rooted plants are replaced by shallow-rooted species, significant savings in soil moisture are often realized. However, such replacement may not be compatible with the most desirable range management practices, since high forage-producing cover on moderately grazed range has a greater rooting depth and greater potential requirements for soil moisture.

HYDROLOGIC PRINCIPLES IMPORTANT TO MULTIRESOURCE MANAGEMENT OF THE COLORADO FRONT RANGE

- Research has shown that good range management practices and revegetation of depleted land with trees, shrubs, and grass will improve watershed conditions. However, such measures cannot offer complete protection against intense runoff, erosion, transport, and redeposition associated with infrequent severe hydrologic events. It must be recognized that, while improved range and forest management practices are essential in order to avoid triggering and compounding destructive geologic effects, no watershed management practice in itself can prevent normal geologic processes which are characteristic of the Front Range. The impacts of these normal processes will not be intensified, however, if the following watershed-condition criteria are adhered to:

  (1) For soils derived from granite and schist on slopes up to 40 percent, organic materials should exceed 2 tons per acre, or 1,000 to1,300 pounds of live herbage per acre. If any area on a 40 percent slope is capable of producing only 1,200 pounds of live herbage without being grazed, then it should be protected from grazing to meet satisfactory watershed criteria. Areas of lesser slope generally produce more than adequate herbage, and may be grazed to the extent that herbage is equal to or greater than the guide figure.

  (2) Approximately 19,000 to 21,000 pounds of litter per acre should be maintained on the timber-grass types. Tree cutting should be avoided on areas with lesser amounts of litter and on shallow soils. Areas with greater soil depth may be logged or grazed to the extent where the residual ground cover does not fall below the guidelines.

- Rapid urbanization of the Front Range is bound to increase watershed-protection problems. Of primary concern are hazards created by common land development practices such as road construction, drainage, steepness of natural slopes, building site location, and many related disturbances. Qualified professionals who can recommend those practices which avoid triggering geologic processes, thus compounding intensity and damage from severe hydrologic events, should be consulted prior to development.

- Water yields are important in the Front Range pine zone. Although the 3- to 5-inch yields are comparatively small in contrast to yields exceeding 12 inches from subalpine forests, watershed management practices can be expected to provide feasible solutions to many local water-supply problems with increased competition for this limited resource. The same hydrologic principles for water-yield improvement previously summarized for the subalpine zone are applicable to the Front Range. In forested areas, some form of patchcutting will produce highest runoff increases, whereas selective cuttings will result in small or negligible increases in streamflow.

WHAT DO WE NEED TO KNOW

Knowledge gaps discussed in the previous subalpine zone summary also apply to the Front Range. In addition, more research is needed on the best methods of plant establishment and kinds of plants most adaptable to the rehabilitation of naturally or artificially disturbed areas. The possibility that more livestock will be grazed in the Front Range pine zone raises new questions on improved grazing management and increased herbage production. Other land use practices in this zone, such as road construction, recreation, and urban development, will require additional study in order to formulate desirable multiple use management objectives.

THE BLACK HILLS PONDEROSA PINE ZONE

The Black Hills is an isolated forest area covering 5,150 square miles in southwestern South Dakota and northeast Wyoming. Ponderosa pine is the principal tree species. During the past 100 years, much of the area's commercial forests have been cutover at least once. Accordingly, most of the original old-growth stands have essentially been converted to a manageable second-growth forest.

The Hills, while dominated by ponderosa pine, also support almost pure stands of white spruce in stream bottoms and on north-facing slopes. Interspersed with these two conifer species are patches of quaking aspen and paper birch on the more moist sites. Willow, red-osier dogwood, and water birch are also found along many stream bottoms.

Open areas in the form of meadows, parks, and grassland are also common in the Black Hills. Kentucky bluegrass is a dominant grass species, and provides forage for livestock.

WHAT WE KNOW ABOUT THE HYDROLOGY OF THE BLACK HILLS

Climate, Geology, and Water Yield

The climate of the Black Hills is of the Continental type, with wide temperature ranges and nonuniform precipitation. Average annual temperatures are less than 50°F; annual precipitation varies from an extreme 30 inches in the high Hills to 14 to 16 inches toward the Plains. Greatest amounts fall as rain in the spring and early summer. Snow is generally a relatively minor component of annual precipitation, although heavy, wet snows are not uncommon in early to late spring.

During dry years there is little excess water for streamflow, while in average to maximum years, water is available for streamflow and increases with precipitation. Surface yields from the Sturgis watersheds are slightly greater than inches per year, or 25 percent of the annual precipitation. The Black Hills are also vulnerable to extreme flood events. The storm in June 972 caused unprecedented damage and loss of fe.

The area is an erosion remnant consisting of ranites which were pushed up beneath overlying sedimentary formations. The exposed granites, sedimentaries, and metasediments are the primary geologic features (fig. 14). The drainage network has a radial-dendritic pattern (fig. 15). Many streams originate on impervious crystalline rock formations and cut through the peripheral sedimentaries. These formations take in, store, and transmit large volumes of runoff, making them an important source of ground water. Much of the time, streamflow is diminished or completely disappears where streams cross sedimentary formations.

In areas of granitic and metamorphic parent material, soils are shallow, coarse textured, and porous. Valley soils are finer textured, deep, and more fertile. Clays and clay-loams are common, particularly where limestone is the parent material.

Water Quality

Concern for water in the Black Hills is focused primarily on quality. While the surface waters are of excellent quality, there are some problems related to the geochemistry of source areas and land and water use. Dissolved solids are low, but surface waters from limestone and related formations contain the largest amounts of essential nutrients.

One of the best-known water-quality problems involves "bog iron," present in some areas of metasediments. Some bog iron has been mined, leaving practically sterile conditions despite efforts at rehabilitation. Water from these areas is highly acid, and stream channels are a distinctive rust red. The effects of bog iron are detectable for considerable distances downstream from source areas.

The Black Hills are interlaced with an extensive road system; consequently, sediment yield is of concern to watershed management. Although many of the old roads have stabilized since construction, some problem areas are intensified after floods. Trouble spots are steep pitches in grade and channel bottom locations. Two types of areas are especially vulnerable—cohesionless permeable soils that are derived from granite bedrock, and soils that are medium to fine textured, easily compacted, and hence produce large quantities and intensity of runoff.

The undesirable effects of poor locations of old roads have been aggravated with the advent of various types of recreation vehicles. Erosion problems in a few places have intensified as the result of high recreation use. Once such problems are recognized, however, well-established methods are available for stabilization.

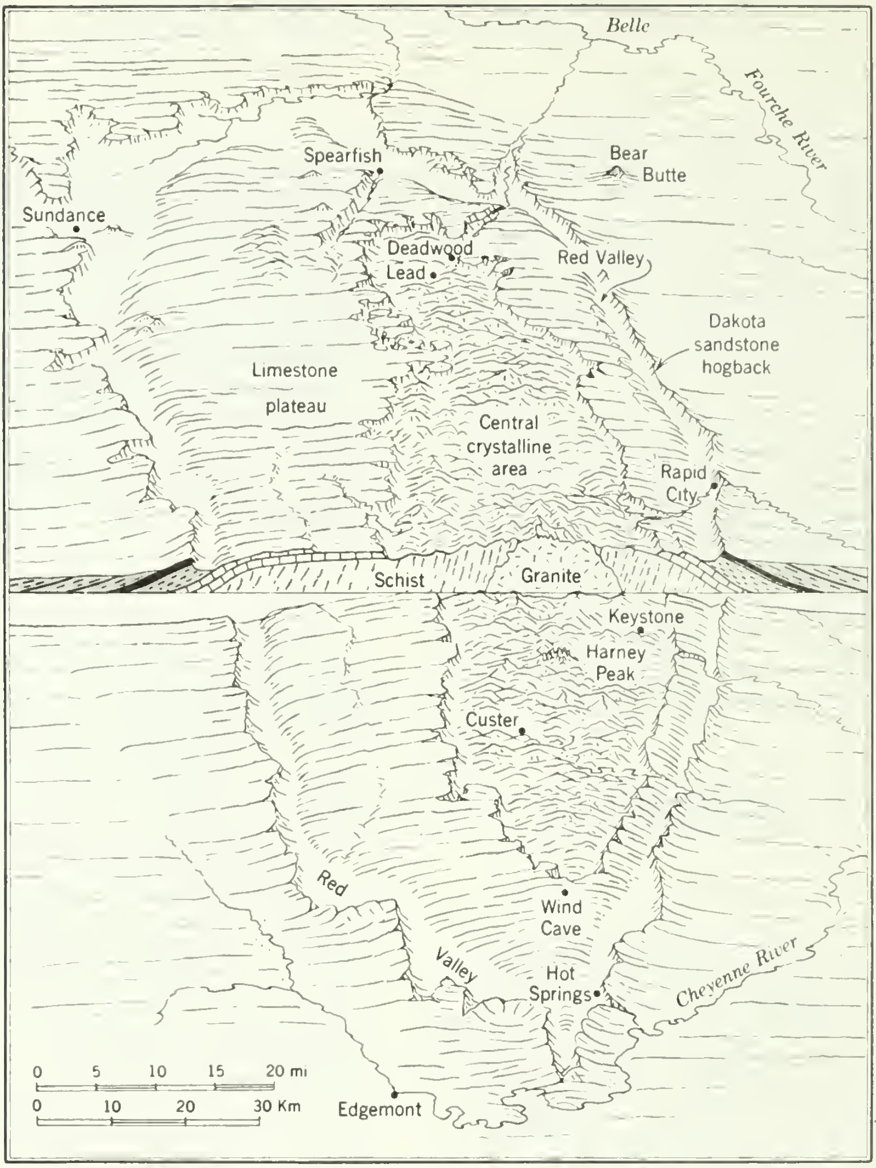


Figure 14.—Geologic map of the Black Hills (from Strahler's Physical Geography, 3rd ed., copyrighted 1969. Reprinted by permission of John Wiley & Sons, Inc., N.Y.).

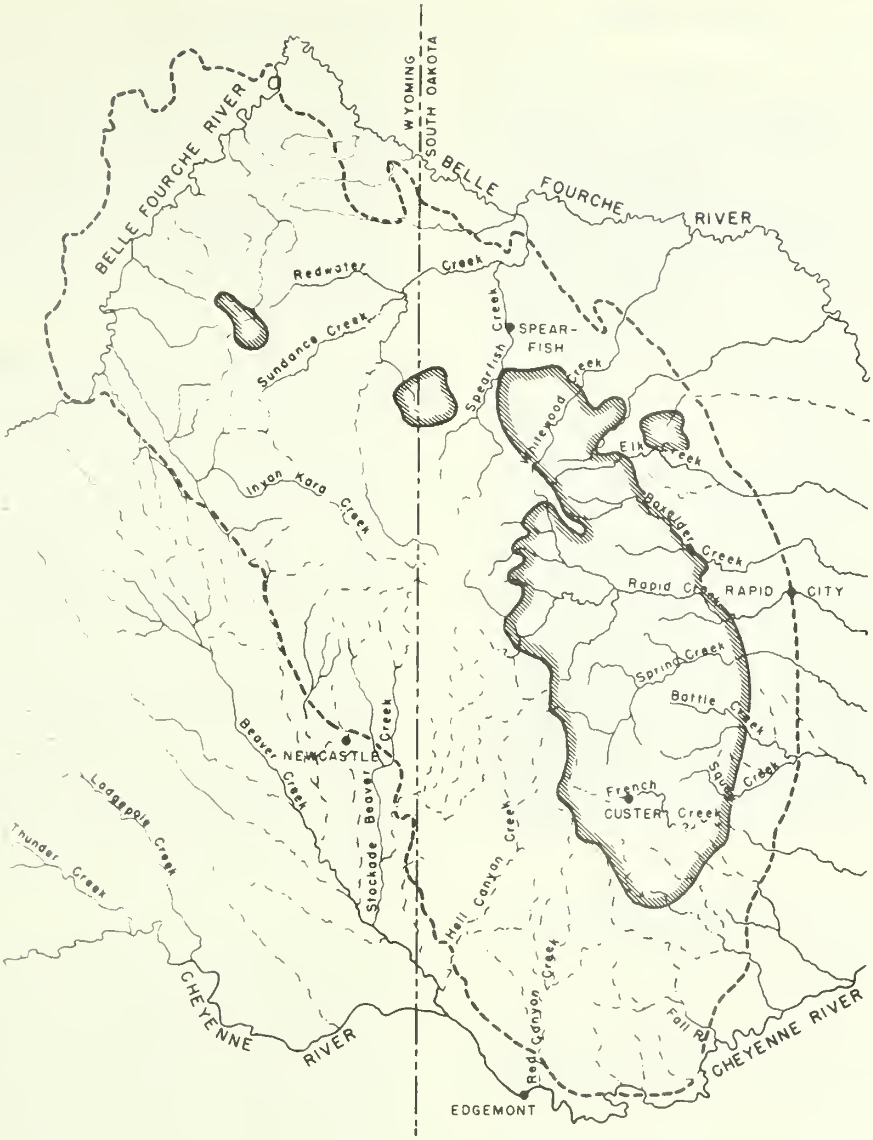


Figure 15.—Drainage map of the Black Hills and Bear Lodge Mountains. The heavy dashed line shows the extent of encircling sedimentary formations. The crosshatched lines show areas of metamorphic and igneous (crystalline) rock formations. Sedimentary formations are found in the remainder of the area.

Geology and Physiography

Geomorphology of the Sturgis watersheds has been carefully analyzed to better our understanding of the hydrology of headwater streams. Morphometric analyses have shown the relative hydrologic importance of several watershed form properties. For example, maximum length of master watershed and the average relief of first-order basins are highly correlated with volume yield and peak flow. Little is presently known about geophysical-hydrologic interactions in small watersheds; work is presently underway to better define soil and geologic properties.

Water-Yield Improvement

Research results from the Black Hills have contributed to the fund of knowledge on water-yield improvement in the central and southern Rocky Mountains. These data support the concept that irregular patchcutting will produce maximum increases in water yields. Small openings on first-order basins and interbasin areas will produce streamflow more efficiently by redistributing the snowpack and reducing consumptive use with minimum watershed and stream channel conveyance losses.

HYDROLOGIC PRINCIPLES IMPORTANT TO MULTIRESOURCE MANAGEMENT OF THE BLACK HILLS

Many of the principles outlined for the subalpine and Front Range zones also apply to the Black Hills. Those that are unique to the Black Hills are summarized below:

- The location of the Black Hills makes them especially attractive to the resident and nonresident public. Accordingly, esthetics are especially important, and water plays a key role. The Hills are an important source of ground water which still has a large untapped potential. Potential surface-water benefits from water-yield improvement exist on forested watersheds upstream from peripheral sedimentary formations. In these areas, irregular patchcutting will produce maximum water-yield increases without causing adverse ecologic effects. Thinnings will result in small or negligible increases in streamflow.

- The advent of recreation vehicles of various types, and the intensive network of old roads in the Hills, have created sedimentation problems in some areas. Most are small and relatively scattered. Where roads are located in stream bottoms or on steep grades, special measures must be taken to insure stability. Because vegetation reestablishes quite easily on most disturbed areas, sediment source areas should not be critical provided that land developments are well engineered and maintained.

- Chemical water quality is a problem in and downstream of a relatively few areas which have been mined for bog iron. Because restoration of such areas is difficult at best and perhaps ineffective, further mining should be discouraged until new methods are developed that will insure site restoration within a short period of time.

WHAT DO WE NEED TO KNOW

Knowledge gaps have been discussed in the previous summaries for the subalpine and Front Range Zones. In addition, there is still a need to adapt existing simulation modeling approaches to Black Hills management problems. To accomplish this, we need additional hydrologic inventory data on soils, geology, runoff, and precipitation to supplement our general knowledge of the area.

THE ROCKY MOUNTAIN ALPINE ZONE

The alpine zone (fig. 16) is that area above tree line which varies from about 10,000 feet in southern Wyoming to about 12,000 feet in southern Colorado and northern New Mexico. Estimates vary, but it is generally believed that alpine areas occupy more than 5 million acres in Colorado and Wyoming—about equally divided between each State—and about 250,000 acres in Utah.

The primary vegetation is composed of grasses, sedges, and a wide variety of forbs and lichens. Tree species reflect local soil-moisture conditions, and include dwarf willow, spruce, fir, and an occasional limber or bristlecone pine. Stunted, malformed coniferous trees occur in streamlined clumps at timberline. Wind-exposed ridges support only prostrate plants and cushion-type forbs and lichens. Terrain depressions on lee slopes accumulate blowing snow. Here, vegetation may be dense willow thickets in boggy areas, or nothing more than a few snow-tolerant forbs where snow accumulates to great depths.

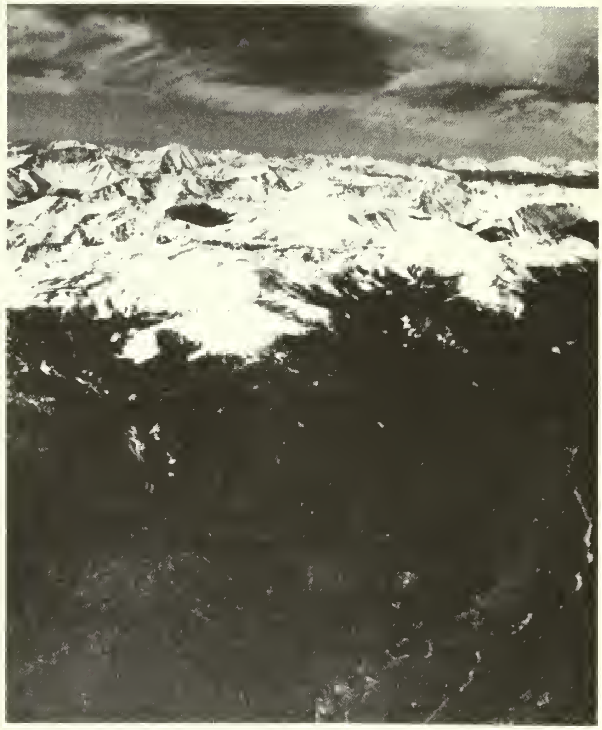


Figure 16.—The alpine zone in the vicinity of Berthoud Pass, Colorado.

WHAT WE KNOW ABOUT ALPINE HYDROLOGY

Landforms, Climate, and Streamflow

Landforms depend to some extent on bedrock geology, and vary from broad, gently sloping ridge crests and plateaus to steep and rugged peaks. Extensive glaciation has played a significant role in shaping the topography. Mass soil movement, patterned ground, and soil frost are also prevalent features.

Persistent winds and cold temperatures mark the climate of the alpine zone. Summer temperatures rarely exceed 70°F, and subzero days are common in winter. Over 75 percent of the annual precipitation occurs as snow, which is moved from exposed areas to wind-protected locations. Snow accumulates all winter and melts in early spring to early summer. The summer rainfall regime is similar to that in the subalpine zone.

Runoff data are scarce because few streams have been gaged in the rather hostile and inaccessible alpine environment. Estimates vary from 23 inches in Alberta, Canada, to 54 inches in Colorado. On the average, streamflow peaks in early summer, producing about 85 percent of the annual flow between May 1 and July 31. Less than 5 percent of the total flow occurs between December 1 and March 31.

Alpine drainages with more late-lying snowfields produce the most late-summer streamflow. Moreover, evaporation losses are low, so that watershed efficiencies (runoff expressed as a percentage of net input) can approach 90 percent during most years. Snowmelt runoff from alpine drifts produces surface runoff and contributes to water which is stored in fractured rocks deep within mountain massifs.

Alpine Snow Accumulation

Snow first accumulates at the windward edge of most fields and builds downward, rather than by initially filling in the deeper parts. The size and shape of the fields reflect the size and shape of barriers behind which they form, with the exception that very heavy or very light snow years make a difference in the size of the field. Some accumulation areas are not completely filled during dry years.

Most of the winter snow accumulates from a relatively few events. Between 55 and 70 percent accumulates during the 5 weeks of heaviest drifting, with between 30 to 40 percent accumulating in the 2 weeks of heaviest drifting. Generally, the first major storm of the season is also the largest snow accumulation period.

Evaporation, Condensation, and Melt

The onset of ablation varies from year to year in response to topography, the amount of snowpack, and spring weather conditions. Once spring melting is firmly established, the reduction in snowfield area progresses at a remarkably uniform rate, regardless of when the snowmelt season begins or the initial amount of snow.

In most cases, moisture exchange between the snow surface and overlying air is between 2 and 3 percent of the daily melt. Condensation dominates the nights and evaporation the mornings. Net losses in moisture generally occur in July, whereas net moisture gains can be expected in August. Carbon black, soil, sawdust, and gravel all affect snowmelt rates. Sawdust can retard melt, whereas carbon black will accelerate snowmelt, provided that it is applied evenly and in a thin layer.

Water-Yield Improvement

Extensive research under winter and summer conditions has shown that one feasible technique for improving water yields from the alpine zone is to build snowfences upwind of natural accumulation areas. The resulting increased snowpack, held in deep, high-elevation drifts that persist until late summer, will affect runoff. By trapping snow which would normally be lost to the atmosphere or blown into the subalpine zone below, streamflow timing is changed so that some runoff normally produced during the spring freshet is diverted to periods of low flow. The primary effect is to change the distribution of runoff, rather than to increase water yield.

Snow Accumulation

Studies of snowfence design features have shown that fence effect varies greatly with size of gap, and fence height and density (fig. 17). Relations have been established between gap size and the location and size of the lee drift. These are presented in Martinelli's detailed status-of-knowledge summary (RM-138).

Topography also exerts an important effect on fence performance. Pressure-gradient concepts provide a rationale for relating fence and terrain effects to snow accumulation. While pressure does not change in the lower layers for airflow over flat surfaces, irregular terrain or natural and artificial barriers will produce local pressure gradients. A favorable gradient (high pressure to low pressure) exists when air flows uphill, whereas an adverse gradient (low pressure to high pressure) exists when air flows downhill or against a barrier. Velocity and shear stresses in the lower layers increase downward, and maximum shear stress is at the surface along a favorable pressure gradient. Along an adverse gradient, velocity and shear stresses near the ground decrease and maximum shear stresses move up from the surface. The carry-

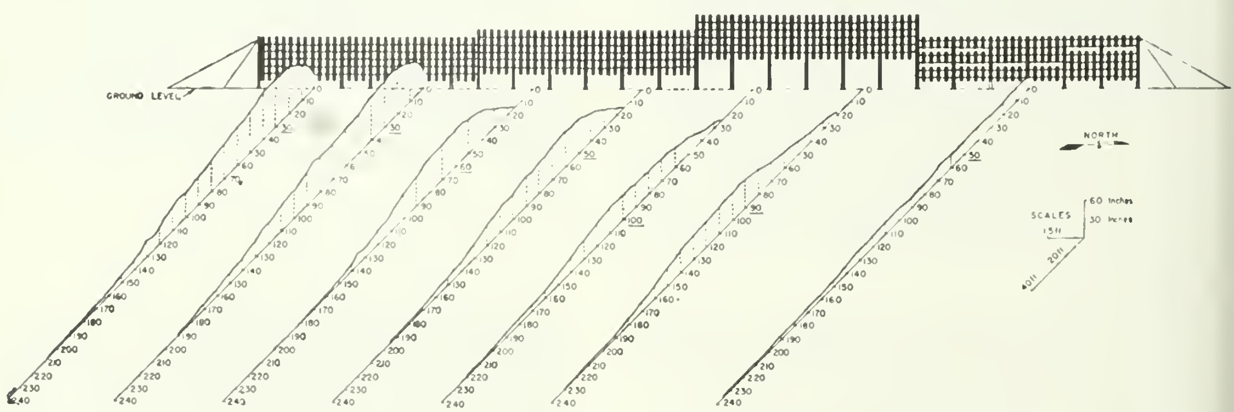


Figure 17.—Typical snowfence panel and snowdrift pattern at Pole Mountain, Wyoming. Snow depths of four locations. Right panel swings open in high winds; others are tests of bottom gap size. Note: There are three different scales in the diagram.

ing capacity of wind is directly related to the shear stresses in the lower layers. Accordingly, in an adverse gradient situation, velocities and shear stresses are reduced so that transported snow settles out of the airstream. Examples of how the above concepts help to explain total snow accumulation and maximum drift length observed in several typical terrain situations are presented in the comprehensive summary (RM-138). Five cases are discussed which include:

A snowfence on a uniform windward slope.
A snowfence on a uniform leeward slope.
A snowfence located leeward from a rounded ridge crest.
A snowfence at a sharp ridge crest.
A fence located at a break from horizontal to lee slope.

A method for estimating drift volume as a function of slope, fence density, and size of gap is also presented.

Snowmelt and Runoff

At the most efficient fence sites, approximately 60 to 120 feet of fence has a potential for producing an extra acre-foot of water at the start of the melt season. This holds for fences 10 to 12 feet tall, 40 percent fence density, bottom gaps of 2 to 4 feet, and snow density in the lee drifts of 500 kilograms per cubic meter. At such sites, the melt season is prolonged approximately 1 to 3 weeks. In general, an extra 2 feet of snow depth on July 1 increases the insuing melt season by 1 week.

PRINCIPLES IMPORTANT TO WATER-YIELD IMPROVEMENT IN THE ALPINE ZONE

- Ten years of study have shown that the best sites for increasing the amount of snow in alpine drifts will have: (1) ridge crest locations with the deep part of the natural drift not more than 8 to 10 times fence height to the lee, (2) upslope or level windward approach, (3) good orientation to prevailing drifting winds, (4) upslope or level terrain to the lee of the accumulation area, (5)a contributing distance upwind of the fence of at least 500 feet, (6) little natural accumulation upwind of the fence, and (7)adequate protection from direct solar radiation.

- Poor sites for snowfences have: (1) a downslope approach to the fence, (2) no natural catchment within 8 to 10 fence heights downwind of the logical fence location, (3) upwind accumulation sites to intercept snow or to throw a drift on the fence, (4) variable wind direction during drifting, and (5) a steep downslope exhaust zone that results in reverse windflow and erosion of the lee deposition.

- The following pressure-gradient concepts apply: (1) snowfences that obstruct flow in a favorable pressure gradient yield smaller and shorter drifts than expected over horizontal terrain, (2) the effects of fences located at the change from a zero or favorable to adverse pressure gradient should increase as the gradient increases up to the point where reverse flow in the eddy begins to erode the downstream edge of the drift, and (3) fences located within an average pressure region should show effects that follow those in the preceding statement, but the fences usually become buried in the drift.

- Details of snowfence construction, developed from long experience, present guidelines for structural stability, density, and gap width. The unique function of these structures, and the loads which they must withstand, require application of sound engineering principles to insure an adequate fence system.

- Snowfences also have a high utility for uses other than increasing late summer flows. Fences can help solve special problems, including avalanche control, highway and parking lot protection, wildlife habitat enhancement, and agricultural and domestic water development. Fence location, density, bottom gap, and height all vary, depending on the objective.

- Fences should be carefully located in alpine areas. They should not be placed indiscriminately along entire ridges. Visual impact should be minimized by careful design and use of materials which tend to blend in with the natural landscape.

- Use of snowfences for water-yield improvement from alpine areas should be considered as supplemental to other watershed management practices in forested or riparian zones. All hold promise for providing needed solutions to future water supply problems.

WHAT DO WE NEED TO KNOW

Several knowledge gaps must be filled before complete guidelines for snowpack management in alpine and other areas can be developed. First, we must be able to determine the mass flux of snow being transported past a given site to determine snow trapping efficiency. Particle counters will help to solve this problem. Secondly, we need better information on the combinations of terrain features which produce optimum snow accumulation sites. The pressure gradient concept is a promising way of developing initial criteria based on sound physical principles. Finally, more data are needed to further refine theoretical models which predict sublimation losses from blowing snow.

Other techniques should be explored for improving the timing and amount of water yield from the alpine zone. These include: (1) terrain modification, (2) intentional avalanching, and (3) artificially creating massive accumulations of ice from winter streamflow.

THE BIG SAGEBRUSH ZONE

Big sagebrush occupies almost 200 million acres in the 11 western States. Three subspecies—basin big sagebrush, Wyoming big sagebrush, and mountain big sagebrush—are recognized. Identification of big sagebrush to the subspecies level is important, since subspecies often indicate significant environmental characteristics of the site. Mountain big sagebrush typically grows above 7,000 feet on lands which receive a large proportion of the annual precipitation as wind-deposited snow. This subspecies affords a higher potential for water-yield improvement than does Wyoming big sagebrush, which grows below 5,000 feet on sites with less soil development and precipitation.

Sagebrush adapts to particularly dry conditions by shedding or reducing the size of its leaves to maintain a favorable internal water balance. Its root system enables big sagebrush to be a vigorous competitor for nutrients and soil moisture. The largest mass of roots is in the upper 2 feet of soil. When moisture has been depleted from the surface layers, its lateral and tap root systems are capable of utilizing water to depths that sometimes exceed 6 feet.

WHAT WE KNOW ABOUT BIG SAGEBRUSH HYDROLOGY

Climate and Water Yield of Mountain Sagebrush

The climate of the big sagebrush zone is characterized by a relatively warm and dry growing season where most of the precipitation is received as snow. Annual precipitation in the mountain big sagebrush zone is 15 to 20 inches per year, and approximately 9 to 12 inches of this total falls as snow. Snow does not melt during the winter months except in the lower portion of the zone on slopes that have a high energy input from solar radiation. Snowmelt generally begins in April or May. About 60 percent of the warm-season precipitation falls during June and September. Because of the combination of small storm size and high evaporation rates, most rainfall during July and August is ineffective in replenishing soil moisture. June rainfall is utilized by growing plants, whereas September rainfall begins to increase soil moisture levels.

Limited data collected at two research locations indicate most summer storms are small. Two-thirds of the rainfall events produce 0.10 inch or less. The duration of rainfall in excess of 1 inch per hour is usually less than 10 minutes, and average intensity for the entire storm period generally is less than 1 inch per hour. However, infrequent high-intensity thunderstorms can generate high rates of runoff and associated erosion.

Hydrologic data from mountain sagebrush are sparse. Annual precipitation of 15 inches produces approximately 3 inches of streamflow. Runoff during the snowmelt season is extremely sensitive to weather changes. The highly variable depth of snow accumulation on a watershed, and watershed orientation, also contribute to the volatile character of snowmelt runoff. Another phenomenon recently observed on sagebrush watersheds is "over-the-snow" flow (fig. 18), caused by a well-developed drainage network on top of dense snow in high accumulation areas. Figure 19 compares the snowmelt hydrographs from three watersheds representative of the mountain sagebrush type.

Figure 18.—Water flowing over the snow surface produced this channel into the dense snow filling a tributary. Such channels quickly route melt water with minimum conveyance losses. Dark material on the sides and bottom of this channel is soil deposited by runoff.

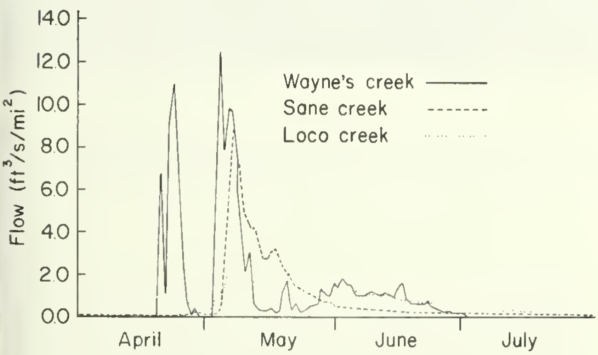


Figure 19.—Snowmelt runoff from the sagebrush type is sensitive to daily weather changes as shown by flow on Wayne's Creek, near Dubois, Wyoming. Water flowing on top of the snow caused high discharge rates on Sane Creek, near Saratoga, Wyoming, compared to those of Loco Creek, an adjacent watershed that did not develop "over-the-snow" flow.

Although telltale signs of severe runoff and erosion from intense rainfall have been observed, there is not yet enough information to completely define summer precipitation and runoff characteristics. Thirteen years of data from a 60-acre high-elevation drainage basin suggest that most high runoff events are caused by rain falling on premoistened soil rather than in response to high-intensity thunderstorms. It is reasonable to assume that infrequent flooding phenomena in the Black Hills, mountain sagebrush type, and Colorado Front Range are similar in nature.

Wind and Drifting Snow

One of the most distinctive features of the mountain sagebrush type is persistent wind, which significantly affects snow accumulation. Much of the snow is blown from windward slopes and ridgetops to protected areas on the lee side of ridges or into incised drainages. The threshold speed for transport of newly fallen snow is approximately 12 miles per hour; metamorphosed snow requires higher speeds. Although unknown but significant quantities of snow are sublimated, the remainder commonly accumulates in drifts 10 to 20 feet deep. This concentration of snow and subsequent ground water recharge results in springs and perennial streamflow from sagebrush lands (fig. 20). The magnitude of evaporation from the snow surface, and from moistened soil during melt is not known. Present indications are that it could comprise as much as one-half of the water volume for isolated drifts.

Watershed Management

Sagebrush Control

Sagebrush conversion is one of the primary tools utilized by range managers to increase forage for cattle and sheep. Burning was an early means of conversion, and is still effective. Plowing or disking is also effective, but limited to moderate slopes without numerous rocks. The discovery of phenoxy herbicides resulted in widespread use of 2, 4-D in the management of big sagebrush lands. Spraying has been the preferred method of sagebrush control since the early 1950's. Sprayed acreage in Wyoming increased from 319,000 acres in 1962 to between 1.3 and 1.4 million acres by 1970. This trend is indicative of sagebrush control practices throughout the West. Reseeding is a necessity in conjunction with control methods that destroy all vegetation, and is also recommended, regardless of the control method, where desirable plants comprise less than 20 percent of total original plant cover.

Native grass production commonly doubles immediately after sagebrush removal, and may triple that of unsprayed areas within 3 years (fig. 21). However, the level of increased production that can be expected over the long term has not been adequately established. Recent evidence indicates that production increases may persist for 15 to 30 years after conversion. The rate of sagebrush invasion after treatment depends most on the degree of initial brushkill and subsequent grazing

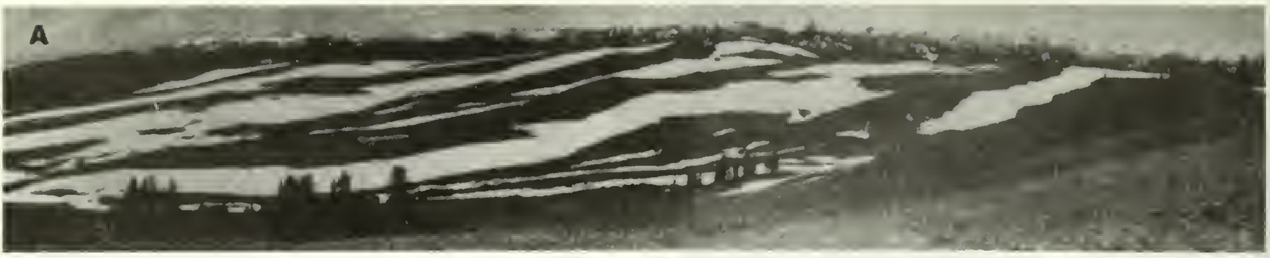


Figure 20.—Deep drifts persist long after the bulk of the snowpack has melted: **A**, snow conditions June 3, near the time of peak streamflow; **B**, snow conditions June 16, about 1 week after the hydrograph peak.

management. Uncontrolled grazing will generally result in rapid reinvasion, but with conservative grazing practices, the increased level of grass production will persist for a number of years, and the full benefits of sagebrush conversion can be realized.

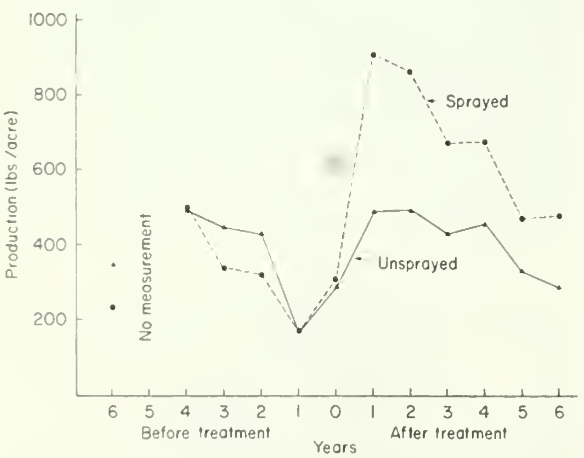


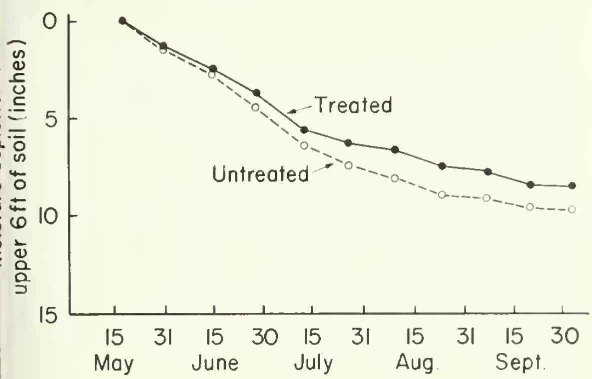
Figure 21.—Grass production (air-dry) for a sprayed and adjacent unsprayed high-elevation sagebrush watershed.

Burning, and mechanical methods that do not destroy the herbaceous vegetative cover, have little effect on herbaceous composition after treatment. Spraying strongly favors grasses over forbs, however. Spraying will drastically diminish forb production, and recovery is generally slow. Forb damage, a byproduct of spraying, should be carefully weighed against the benefits of increased grass production. Forbs are an essential ingredient in the diets of young sage grouse, and they are also sought by cattle.

The net effect of spraying on herbaceous vegetative composition depends upon the proportion of grasses and forbs in the sagebrush stand. If forbs comprise a substantial portion of untreated vegetation, much of the grass response takes place at the expense of forbs. Big sagebrush control will reduce total above-ground biomass production, even though combined grass-forb productivity may increase substantially after treatment. About one-third of the vegetative matter in climax stands is big sagebrush, but on sites where it is sprayed as a range improvement practice, young sagebrush may contribute two-thirds or more of the annual production. The fact that the increase in herbaceous production does not fully replace sagebrush herbage indicates a diverse mixture of life forms more fully utilizes site resources than does a limited number of species or life forms.

Soil Moisture

The conversion of a mountain sagebrush stand to herbaceous vegetation reduces soil moisture withdrawal about 15 percent. This difference takes place while vegetation is actively growing, and not uniformly through the summer season. After midsummer, the rate of use is similar for both treated and untreated vegetation (fig. 22). Soil-water use declines sharply on :reated areas when herbaceous vegetation reaches maturity, and after the midsummer eaf drop by big sagebrush in sagebrush stands.



igure 22.—Sagebrush conversion reduces soil-water use about 15 percent during the time of active vegetation growth. The rate of use after midsummer is similar for both treated and untreated vegetation.

The root systems of big sagebrush are capble of extracting water deep in the soil after ıoisture near the surface is depleted. Accordıgly, about 80 percent of the water savings ıkes place at depths between 3 and 6 feet when ıgebrush is removed. Moisture to support herıaceous vegetation on treated land is derived ıainly from the top 3 feet of soil. Soil-water use ı the surface 2 feet equals or exceeds that of ndisturbed sagebrush vegetation. Some soil oisture is used by both treated and untreated egetation until late fall. Once snow begins to ccumulate, however, soil-moisture content oes not change through the winter months.

Snow Accumulation

Sagebrush plants trap snow since the leaves and twigs promote snow deposition by reducing windspeed. Live sagebrush plants, and the skeletal remains of sprayed plants, are more effective snow-trapping agents than herbaceous vegetation. Snow accumulates faster in sagebrush than grass stands as long as the brush remains above the snow surface.

Sagebrush control reduces snow accumulation most strongly on windward slopes and to a lesser extent on leeward slopes. Sagebrush removal may reduce the rate of accumulation early in the winter, before vegetation is covered, but have little effect on final depth where natural snow deposition exceeds the height of sagebrush. Snow accumulation is governed by the interaction of the wind with topography once vegetation is covered. Sagebrush removal can affect snow deposition at a given point, but may not affect total storage on a watershed since large-scale snow accumulation is governed more by topography than by vegetation.

Streamflow

Results from one paired watershed study in mountain sagebrush suggest that total annual water yields can be increased approximately 13 percent by converting the shrub-dominated vegetation to a herbaceous type. While these results are not statistically significant at the 95 percent level of confidence, the apparent increase in water yield closely approximates measured differences in soil moisture withdrawal. Accordingly, the streamflow increase suggested by watershed comparisons is probably a real response. Treatment has no effect on the yearly maximum discharge rates, mean daily discharge rates, or recession flows in summer.

The 13 percent streamflow increase is considered to be about maximum for the big sagebrush type, and is attained only: (1) on sites where there is significant precipitation to rewet the soil throughout its profile, and (2) where the soil mantle is sufficiently thick so that the rooting zone of replacement vegetation lies above the deep root system of the sagebrush which formerly occupied the site.

Blowing Snow Control

Snow transported by wind is subjected to large sublimation losses. Snowfences, previously discussed, can also be effectively used in sagebrush and grasslands to reduce sublimation, and thereby tap this heretofore unavailable water source. A mathematical model has been developed to determine the quantity of water equivalent that sublimates while snow is being transported by wind. This model assumes that the annual volume of sublimated snow is a function of: (1) the mean annual snow transfer coefficient, or the ratio of the quantity of snow transported by wind to that which falls during the winter drift period; (2) mean winter precipitation received during the time snow is subjected to drifting; and (3) the average distance a snow particle travels before sublimating(transport distance) during the winter drift period.

In southcentral Wyoming, the snow transfer coefficient is approximately 0.7 for mountain big sagebrush 8 to 16 inches tall. This means that 70 percent of the precipitation that falls during the drifting season returns directly to the atmosphere when no barriers exist to induce snow deposition. The residual 30 percent is stored in the crown space, which protects the snowpack from wind. Average transport distances vary from 3,300 feet at a 7,500-foot elevation to 5,000 feet at the 8,500-foot level. These large distances, and a drift period which extends from November 1 to March 30, suggest a high potential for exploiting this drifting-snow resource with minimal impact on the environment and other land uses. Snowfences properly located provide an effective means to capture and retain wind-borne snow with high efficiency (fig. 23). Engineering guidelines are available for determining proper fence size and spacing. Specific design criteria and references to pertinent literature are found in the comprehensive status-of-knowledge summaries (RM-138 and RM-140).

Erosion and Sediment Yield

There is general agreement that watershed cover—including litter, rock, and live vegetation—is an important factor influencing infiltration, erosion, and subsequent sediment yield. From the standpoint of watershed management, practices that increase litter and vegetation promote soil stability.

Little factual information on sedimentation from big sagebrush lands is available. Measurements on two areas in Wyoming suggest that both suspended sediment and bedload movement are typically low. High sediment movement occurs only during extreme precipitation events. The over-the-snow flow phenomenon previously discussed, may also increase sediment movement.

Sagebrush-conversion techniques which minimize soil disturbance are preferred. Spraying will produce the least soil disturbance. Plowing should be used only when there is a high likelihood of establishing a seeded stand quickly.

HYDROLOGIC PRINCIPLES IMPORTANT TO MULTIRESOURCE MANAGEMENT OF THE BIG SAGEBRUSH ZONE

- More than 90 percent of big sagebrush vegetation is killed by burning, mechanical removal, or chemical herbicides, when these techniques are properly implemented. Reseeding is recommended on sites where the population of desirable species is depleted, and must accompany those methods which destroy all vegetation.

Figure 23.—Windborne snow that otherwise returns to the atmosphere can be trapped and stored behind snowfences. There is an opportunity to improve water yield wherever a large quantity of snow is transported by wind.

• The composition of herbaceous vegetation is largely unaffected by burning or mechanical sagebrush control methods which leave existing herbaceous cover intact. Spraying, however, can reduce forb production 45 to 65 percent. Forb damage caused by spraying with phenoxy herbicides should be carefully weighed against increased grass production, since forbs constitute an important food source for certain wildlife species as well as livestock. The land manager controls plant composition when reseeding is necessary following sagebrush removal. Planted species can be selected to optimize vegetation composition to meet specific management objectives.

• Grass production commonly doubles after spraying, but declines with time as sagebrush gradually reoccupies the site. The duration of treatment effect is strongly influenced by grazing management practices following sagebrush control. Most projects probably have an effective life of between 15 and 30 years, if initial sagebrush kill is high and conservative grazing practices are followed.

• The production of above-ground herbaceous biomass (including production by sagebrush) is reduced by sagebrush removal. While combined grass-forb production can increase approximately 50 to 200 percent, this is not sufficient to replace the herbage produced by the original sagebrush. When sagebrush is sprayed, forbs as well as sagebrush are killed, so that part of the grass response simply compensates for decreased forb growth.

• Techniques which cause the least soil disturbance are recommended for converting big sagebrush to a herbaceous vegetation type. Plowing or disking should be restricted to lands with little natural erosion and where there is a high probability of establishing a seeded stand quickly. A high erosion potential also exists after sagebrush stands are burned until residual vegetation regrows sufficiently to provide soil protection.

• Soil-moisture withdrawal can be decreased approximately 15 percent by sagebrush removal (1) if the rooting depth of residual vegetation is less than that of the sagebrush which formerly occupied the site, and (2) if snowmelt is sufficient to recharge the entire soil mantle. Soil-moisture use is reduced at depths greater than 2 feet and during the time that vegetation is actively growing. Water use in the surface layers of soil is unchanged or may increase, since treatment shifts the rooting zone to the upper part of the soil profile.

• The interaction of wind with vegetation and topography controls snow deposition. Live sagebrush crowns which protrude above the snowpack collect snow more efficiently than do defoliated sagebrush crowns or herbaceous vegetation. Sagebrush removal can reduce snow accumulation on windward slopes; basin-wide snow storage may not be significantly affected, however, since wind and topography are the primary factors controlling snow accumulation.

• Indications are that annual runoff from mountain sagebrush can be increased a maximum of 15 percent through extensive sagebrush eradication. Again, water yield can be increased only when rooting depths of replacement vegetation are less than the original sagebrush, and snowmelt exceeds soil-water recharge requirements. Treatment apparently does not affect peak or recession flows appreciably.

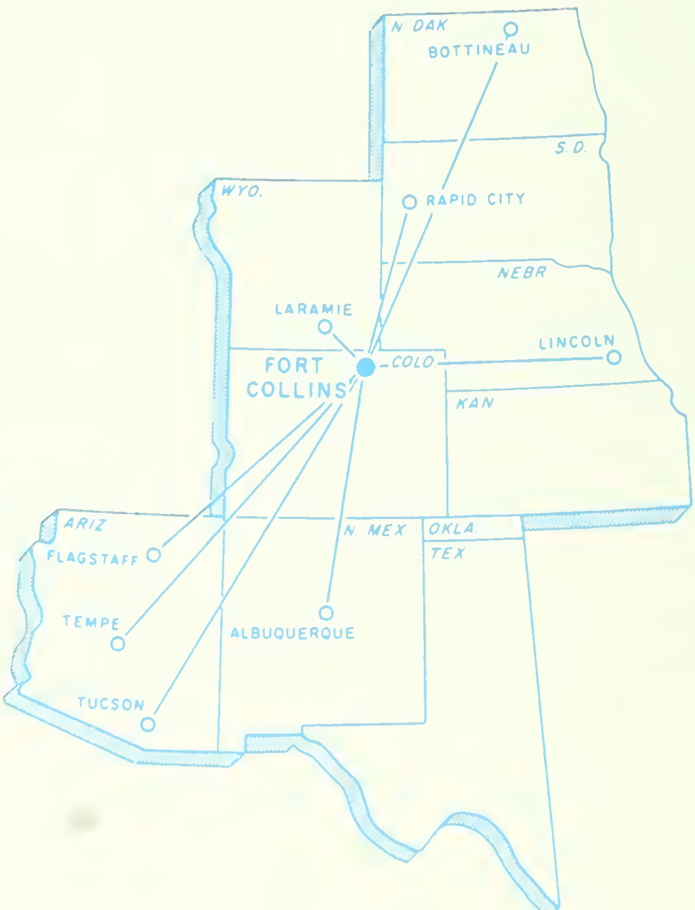
• Drifting snow represents a large, untapped water resource on sagebrush and grasslands. As much as 70 percent of this snow is lost to the atmosphere under natural conditions. Snowfences provide an efficient means of capturing drifting snow with little impact on the environment or other uses of the land. Snowfences can be used to develop water sources or to augment existing supplies; however, sublimation and evaporation can extract as much as 50 percent of the water stored in isolated drifts behind snowfences.

WHAT DO WE NEED TO KNOW

More documentation is needed on the long-term effectiveness of sagebrush removal, particularly after spraying, since the majority of sprayed land has been treated during the past 15 years. Range management practices that utilize the increased grass production most efficiently also need to be determined.

The factors that govern infiltration and sediment movement are complex and their interrelationships are poorly understood. More research is needed to identify those soil, cover, topographic, and hydrologic parameters which determine infiltration and erosion. Perhaps the biggest knowledge gap is the lack of direct measurements of bedload and suspended sediment for any length of time in sagebrush lands.

Present techniques for gathering such basic hydrologic information as the quantity of winter precipitation, the flux and timing of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Jack Pine Provenance Study in Eastern Nebraska

John A. Sprackling and Ralph A. Read

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Rocky Mountain Forest and
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Forest Service
U.S. Department of Agriculture
Fort Collins, Colorado 80521

Abstract

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1975. Jack pine provenance study in eastern Nebraska. USDA For. Serv. Res. Pap. RM-143, 8 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

A 9-year provenance test of jack pine in eastern Nebraska, with 28 origins, indicated that height, form, cone production, and needle length of southern origins exceeded northern origins. Foliage color during winter was yellow green on northern origins but green on southern origins. Fast-growing origins developed dense, compact, well-shaped crowns because of the multinodal growth characteristic of jack pine. A Petawawa, Ontario origin, of rapid growth and superior form, is recommended for plantings in Nebraska.

Keywords: *Pinus banksiana*, provenances, growth, tree form, windbreaks.

Preface

The provenance study described in this paper is one of a dozen experimental plantations of various tree species established on the Horning State Farm near Plattsmouth, Nebraska, which is administered by the Department of Forestry of the University of Nebraska. The USDA Forest Service, through its Rocky Mountain Forest and Range Experiment Station Research Work Unit at Lincoln, cooperates with the Nebraska Agricultural Experiment Station on this research.

The purpose of this work is to find and develop better adapted trees for use in all kinds of plantings, environmental and commercial, throughout Nebraska and the central Great Plains. These provenance studies of different species provide basic materials of known origin for evaluation of adaptability, for study of genetic variation, and for selection, propagation, and breeding for resistance to disease and insect pests.

The diversity of tree planting materials under study at this and many other locations in the Plains was made possible through cooperation in a Regional Tree Improvement Project (NC-99, formerly NC-51) of the North Central States Agricultural Experiment Stations.

Credits are due the Petawawa Forest Experiment Station, Canadian Forestry Service, for seed of their All-range Experiment No. 255; Jonathan W. Wright, Professor of Forestry, Michigan State University, for initiating the Regional study and providing the planting stock; and Walter T. Bagley, Associate Professor of Forestry, University of Nebraska, for cooperation in planting and maintenance of the plantation.

USDA Forest Service
Research Paper RM-143

May 1975

Jack Pine Provenance Study in Eastern Nebraska

John A. Sprackling, Forestry Research Technician

and

Ralph A. Read, Principal Silviculturist

Rocky Mountain Forest and Range Experiment Station[1]

[1] *Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University. Research reported here was conducted at the Station's Research Work Unit at Lincoln, in cooperation with the University of Nebraska.*

Contents

Trade and company names are used for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the U.S. Department of Agriculture to the exclusion of others that may be suitable.

Jack Pine Provenance Study in Eastern Nebraska

John A. Sprackling and Ralph A. Read

Provenance tests are used to determine the natural variation within a species, as well as the relative adaptability of various seed sources throughout a species' natural range to areas outside that range. Knowledge of the genetic variation within the natural geographic range of a species provides a foundation for further tree breeding programs. Moreover, information derived from provenance tests can insure maximum success in introducing trees to the relatively treeless prairies of the central Great Plains for windbreaks, landscaping, and Christmas tree plantations.

The objective of this study was to determine the natural variation, adaptability, and growth in eastern Nebraska of a wide range of seed origins of jack pine (*Pinus banksiana* Lamb). The primary goal was to determine which seed origins are well adapted for use in future plantings in the Plains. The study was conducted as part of a cooperative Regional Tree Improvement Project (NC-99) of the North Central States Agricultural Experiment Stations.

Previous Work

The natural range of jack pine extends from Nova Scotia west to the foothills of the Northern Rockies in Alberta and Northwest Territory, Canada, where it reaches 65° north latitude. It occurs throughout the Lake States and as far south as northern Indiana (fig. 1). This species is believed to be very diverse genetically because of its wide distribution in the boreal forests of North America (Fowells 1965). Past research has indeed indicated important differences within the species, which can be attributed to genetic variation.

The earliest record of jack pine planting in the central Great Plains was in 1891 on the Bruner property in the sandhills of Holt County, Nebraska (Pool 1953). That planting, which included other conifers, was judged a success after 10 years. It provided the stimulus for the creation, in 1902, and the subsequent tree planting program of the Nebraska Forest Reserves (now the Nebraska National Forest) in the sandhills along the Middle Loup River in central Nebraska. In 1903, 70,000 jack pine seedlings were dug in the native forests of Minnesota and planted in this Forest Reserve. Planting of jack pine seedlings of Minnesota and Wisconsin origins was continued through the 1920's until about 4,600 acres were established.

The drought of the 1930's caused high mortality in the Nebraska National Forest jack pine plantations, particularly in poorly stocked areas (Christiansen 1940). However, timber sales which began in 1929 in the 19-year-old plantations produced corral poles, fenceposts, cabin logs, turkey roosts, and fuelwood for local use (Dayharsh 1940). Growth and development through a 48-year period, including response to thinning at age 12, and comparisons with native sites in the Lake States, were described by Boldt (1969). Despite the large area planted to jack pine outside its natural range, it is not possible to evaluate those plantations for performance of seed origins with any degree of reliability. Origin was not specifically documented, and no statistical design was used in the plantings.

Provenance tests in other regions indicate that height growth of jack pine from southern seed origins exceeds that of northern origins. Schantz-Hansen and Jensen (1952) determined that a provenance from the Bass River State Forest, New Jersey, grew faster than all others at a Cloquet, Minnesota test site. Canavera and Wright (1973) found that jack pines from southern Michigan and Wisconsin seed origins were three times as tall as those from the Northwest Territories of Canada after 4 years of growth in two Michigan plantations. A comparison of Lake

Figure 1.—Location of jack pine (*Pinus banksiana*) origins.

States provenances by Arend and others (1961) at three test sites in lower Michigan indicated that lower Michigan seed origins grew fastest, whereas upper Michigan Peninsula origins produced slow-growing trees. An Indiana study demonstrated that trees from the southern half of a seed-collection area covering Michigan, Wisconsin, and Minnesota averaged 4.8 feet in height after 7 years, while those from the northern half averaged 4.2 feet (Williams and Beers 1959).

Seedling foliage of northern seed origins turned purple during winter through the third year, and yellow thereafter. Those of southern origins remained green during winter (Stoeckeler and Rudolf 1956, Canavera and Wright 1973).

Other characteristics positively correlated with southern seed origins were abundant flowering, lammas growth, and a high degree of stem crook (Canavera and Wright 1973). King and Nienstaedt (1965) concluded that, among Lake State provenances, lower Michigan stock was most resistant to jack pine needle cast (*Hyperdermella ampla* Dearn.), whereas northern Minnesota stock was least resistant. Northern seed origins produced trees with many serotinous cones, but southern seed sources had a large proportion of open cones (Schoenike and others 1959). Survival of field plantings ranged from 82 to 100 percent in the above studies.

Methods

Seeds from 96 geographic origins throughout the natural range of jack pine were collected over a 5-year period under the direction of Mark Holst, Petawawa Forest Experiment Station, Chalk River, Ontario. Samples of these seeds were planted by J. W. Wright in a Michigan State University nursery at East Lansing, Michigan, and 1-year-old seedlings were distributed to North Central States cooperators in 1965. Seedlings of 28 of the 96 origins, representative of the species range, were planted in spring 1965 at the Horning State Farm experimental area of the Department of Forestry, University of Nebraska, near Plattsmouth, Nebraska (fig. 1 and table 1). Location is latitude 41° North, longitude 96° West, and 1,100-foot (330 m) elevation. The plantation is located on a gentle southwest-facing slope of silt loam soils derived from loess. Growing season averages 170 days, and mean annual precipitation is 30 inches.

Seedlings were machine planted in randomly placed four-tree linear plots of each of the 28 seed origins in each replicate. The plantation contains six replications in 18 rows, spaced 12 feet apart on the contour; trees in each row were spaced 6 feet apart. The plantation has been maintained by mowing between rows and applying Simazine (4 pounds per acre) in a 20-inch band on both sides of each tree row for 6 years following planting.

Table 1.--Data on seed origin locations of jack pine tested in eastern Nebraska

Petawawa origin number	State or Province	Place	North latitude	West longitude	Elevation	
			degrees	*degrees*	*feet*	*meters*
07	Prince Edward Island	East Bideford	46.6	63.9	100	30
08	New Brunswick	Turtle Creek	46.0	65.0	250	76
09	New Brunswick	Grand Lake	46.0	66.1	25	8
21	Quebec	Little Calumet R.	49.7	67.2	100	30
20	Quebec	Toulnoustook R.	49.7	68.4	250	76
29	Quebec	Murray Bay	47.6	70.2	300	91
33	Quebec	Lake Valade	47.3	73.9	1,350	412
49	Quebec	Capitachouane R.	47.8	76.7	1,500	457
48	Quebec	Baskatong Lake	46.8	76.1	800	244
47	Quebec	Harry Lake	46.4	76.2	600	183
44	Quebec	Fort Coulonge	45.8	76.7	400	122
46	Ontario	Petawawa Plains	45.8	77.4	600	183
42	Ontario	Douglas	45.5	76.9	500	152
43	Ontario	Constance Bay	45.5	76.1	250	76
40	Ontario	Claire River	44.6	77.0	700	213
39	Ontario	Twin Lakes	44.6	77.9	800	244
56	Ontario	Wasaga Beach	44.5	80.0	600	183
84	Ontario	Vermillion Bay	49.8	93.4	1,300	396
89	Saskatchewan	Nipekamew R.	54.2	104.9	2,000	610
99	Northwest Territory	Wrigley	63.2	123.4	550	168
23	New York	Upper Jay	44.3	73.8	950	290
73	Michigan (LP)	Marl Lake	44.5	84.7	1,193	364
74	Michigan (LP)	Marl Lake	44.5	84.8	1,145	349
71	Michigan (LP)	Freesoil	44.1	86.1	900	274
75	Michigan (UP)	Gladstone	46.0	86.5	650	198
69	Wisconsin	Mosinee	44.8	89.7	1,200	366
67	Wisconsin	Nekoosa	44.3	89.7	970	296
78	Minnesota	Brainerd	46.3	94.2	1,150	351

Height and survival were measured at the end of growing seasons from 1966 through 1971. Severe rains 6 weeks after the plantation was established in 1965 washed out 35 percent of the seedlings. These were not included in survival counts, and were replaced with 1+1 stock from on the site in the spring of 1966. Periodically, the plantation was checked for damage by insects, disease, or heavy snow. Current measurements made in November 1973 included the following:

- Total height
- Average annual height growth for the past 6 years
- Form rating (a numerical rating from 0 to 40 given each tree based on straightness of stem, crown density, crown balance, and branch angle[2])
- Winter foliage color
- Average length of 1-year-old needles
- Cone production

Data were subjected to analysis of variance with multiple range tests, to determine significant differences among means. Correlation analyses were made to determine the degree of association between measured characteristics and origin latitude. An isodata cluster analysis was made to determine if geographical ecotypes could be delineated.

Results

Seedling Survival

Overall plantation survival was 94 percent after two growing seasons and 92 percent after three (table 2). Thereafter, mortality was negligible. Survival rates of origins were so influenced by the heavy rains that they could not be correlated with latitude, longitude, or elevation.

Height and Growth Rates

Trees from northern latitudes were shorter and slower growing, while those from southern latitudes were taller and grew faster (table 2). Computed correlation coefficients were -0.78 and -0.79. The average plantation height after 9 years was 12.4 feet. Trees from Fort Coulonge, Que. (44), were tallest, averaging 14.3 feet. The tallest individual tree was 17.1 feet (fig. 2). The shortest trees, averaging 7.6 feet, were from Wrigley, N.W.T. (99) (table 2). An analysis of variance showed significant differences in heights among the 28 origins. Multiple range tests indicated that the tallest origin (Fort Coulonge, Que.—44) was significantly taller than the 14 origins averaging 12.5 feet or less. Trees from Murray Bay, Que. (29), Little Calumet River, Que. (21), Nipekamew River, Sas. (89), and Wrigley, N.W.T. (99) were significantly shorter than all others tested (table 2).

Figure 2.—After 10 growing seasons, this tree from Fort Coulonge, Quebec (44), was tallest in the plantation at 17.1 feet.

Plantation height growth rates averaged 1.7 feet per year. Marl Lake, Mic. (74) and Mosinee, Wis. (69) trees averaged 2.0 feet in height growth per year over the last 6 years, faster than all other origins.[3] Trees from these two origins grew significantly faster than all origins which grew 1.8 feet per year or less. Height growth rates for individual trees varied widely. A tree from Wrigley, N.W.T. (99) averaged 0.03 foot per year, whereas a Fort Coulonge, Que. (44), tree averaged 2.45 feet per year (fig. 2).

[2]*Branch angle refers to the angle of the lateral branches relative to the main stem. Crown balance refers to the uniformity of lateral branching on all sides of a tree. Each of the four morphological characteristics was given a numerical rating from 0 to 10. The sum of the four equals the form rating. Trees with acute branch angles, straight stems, and dense, balanced crowns were given the highest form ratings.*

[3]*The fastest growing origins were not necessarily the tallest, because growth rates were based on the last 6 years in the plantation and heights were based on 9 years.*

Table 2.--Survival and height of jack pine origins in eastern Nebraska

Petawawa origin number	3-year survival	Height: 9-year total	Height: Percent of plantation mean	Mean annual height growth 1968-1973	Basis: trees
	percent	*feet* [1]	*percent*	*feet*	*no.*
QUE 44	100	14.3	115	1.9	23
WIS 69	100	14.2	114	2.0	22
MIC 71	88	14.1	113	1.9	16
ONT 56	96	14.0	113	1.9	21
ONT 46	92	13.9	112	1.9	22
MIC 74	96	13.8	112	2.0	21
WIS 67	86	13.7	111	1.9	18
ONT 39	83	13.6	110	1.8	19
MIN 78	98	13.4	108	1.8	22
MIC 75	96	13.3	107	1.9	21
ONT 43	96	13.2	107	1.8	22
MIC 73	83	13.2	106	1.8	21
ONT 84	92	12.8	104	1.8	22
NY 23	100	12.8	103	1.7	23
QUE 47	96	12.5	101	1.7	22
QUE 42	79	12.3	99	1.7	20
QUE 33	100	11.8	95	1.7	23
NBR 08*	96	11.7	95	1.6	24
ONT 40	71	11.6	94	1.6	15
QUE 48	92	11.6	93	1.6	22
NBR 09	96	11.5	93	1.6	22
QUE 49*	88	10.9	88	1.5	19
PEI 07*	96	10.5	85	1.5	22
QUE 20*	100	10.4	84	1.4	20
QUE 29*	96	9.9	80	1.4	26
QUE 21*	100	8.9	72	1.2	25
SAS 89*	76	8.6	69	1.2	15
NWT 99*	92	7.6	61	1.0	11
Plantation average	92	12.4		1.7	

[1] Duncan's range test: Means within same bracket do not differ at 5% level. Means of equal value may be separated by brackets due to rounding off.

*Northern origins

Form

Slow-growing trees from northern origins definitely had the poorest form, while fast-growing trees from southern origins generally developed dense, well-balanced crowns (tables 2 and 3). The average form rating was 28.8 (best possible=40). Trees with the best forms were from Petawawa, Ont. (46), averaging 31.6. One tree from this origin rated 37, the highest form rating in the plantation (fig. 3). Nipekamew River, Sas. (89), trees had the poorest form, averaging 25.3. The seven origins of poorest form were also the shortest. Conversely, origins displaying above-average form were generally the tallest.

Other Characteristics

Average length of 1-year-old needles was 1.3 inches. The shortest, slowest growing trees had the shortest needles (tables 2 and 3). The correlation between needle length and latitude of origin was fairly weak. Trees from southern origins had green foliage during winter, whereas northern origins were yellow green.

Winter foliage color was the characteristic found to be most strongly correlated with latitude of origin:

Characteristic	Correlation coefficient r
Yellow winter foliage	0.80
Average annual height growth	-0.79
Height	-0.78
Cone production	-0.75
Form rating	-0.72
Needle length	-0.41

Cone production was very high relative to other species of pine of the same age in this experimental area. At 10 years of age, the average tree had approximately 40 cones. Trees from the two extreme northern origins (Nipekamew River, Sas.—89 and Wrigley, N.W.T.—99) were noticeably less prolific, averaging 25 cones per tree. Cone production was negatively correlated with latitude of origin.

No damage from insects or diseases was detected. Heavy snow and freezing rain, which frequently break limbs on trees in the central Great Plains, caused no noticeable damage to the jack pines. The top 10 inches of some termi-

Table 3.--Form, needle length, winter needle color, and cone production of jack pine origins 9 years after planting in eastern Nebraska

Petawawa origin number	Average form rating[1]	Needle characteristics: Mean length	Needle characteristics: Winter color	Average cone production[2]
	[3]	*inches*	*percent yellow*	*per tree*
ONT 46	31.6	1.3	0	H
ONT 40	31.2	1.2	0	H
WIS 67	30.4	1.3	0	H
ONT 39	30.3	1.4	11	H
MIC 71	30.0	1.3	0	H
ONT 43	29.9	1.4	0	H
MIC 74	29.9	1.4	5	H
WIS 69	29.7	1.4	0	H
ONT 56	29.7	1.4	0	H
MIC 73	29.6	1.4	14	H
ONT 84	29.5	1.2	59	M
QUE 47	29.5	1.3	5	H
MIN 78	29.4	1.3	5	H
MIC 75	29.2	1.4	10	H
ONT 42	29.2	1.3	10	H
NBR 09	29.1	1.1	9	H
NY 23	28.8	1.3	4	H
QUE 44	28.3	1.3	4	H
QUE 33	28.3	1.1	39	H
QUE 48	28.3	1.3	36	H
NBR 08*	27.7	1.2	25	M
QUE 20*	27.4	1.1	25	M
PEI 07*	27.3	1.1	9	M
QUE 29*	27.2	1.1	31	M
QUE 21*	26.4	1.1	40	M
QUE 49*	26.0	1.1	53	M
NWT 99*	25.4	1.2	73	M
SAS 89*	25.3	1.1	93	M
Plantation average	28.8	1.3	19	

[1] 0 = lowest 40 = highest
[2] M = 20 to 40. H= >40
[3] Duncan's range test: Means within same bracket do not differ at 5% level. Means of equal value may be separated by brackets due to rounding off.
* Northern origins

Figure 3.—The dense, compact crown and acute branch angle displayed by this tree from Petawawa, Ontario (46) are characteristics desirable in Christmas trees.

ıals on the tallest trees had lost their needles, probably as they were whipped by the wind during late summer.

Genetic Variation Among Provenances

Variations in the measured characteristics of trees from different origins growing in the relatively uniform environment of this Nebraska plantation are probably reasonable expressions of genetic variation across the natural range of the species. Data for total height, last 6 years of growth, and form rating were therefore combined in a cluster isodata analysis. The 28 origins tended to fall into two major groups: eight northern origins (asterisks in tables 2 and 3) were distinct from all other origins. This supports Yeatman's (1974) statement that jack pine has well-defined adaptational gradients (clinal variation) associated with latitude. No further geographic division appeared plausible. Additional data on more provenances, particularly from the northern and western range of jack pine, are necessary for a complete analysis of genetic variation within the species.

Discussion

The excellent survival of all origins confirms that jack pine is well adapted to climatic conditions in eastern Nebraska. Provenance studies elsewhere in the United States have found that jack pine survival rates exceed other species tested. Although jack pine is known to excel on sandy soils, it had no problem adapting to the silty clay loam soils of eastern Nebraska.

The study area was in extreme eastern Nebraska, where growing season and precipitation are highest for the State. Therefore, growth rates at the study site are maximum to be expected in Nebraska.

Jack pine has been growing in the sandhills of west-central Nebraska, on the Bessey Division of the Nebraska National Forest, since the early 1900's. Of the 25 conifer species planted there during the last 75 years, only three have passed the test of time and drought, and are considered adaptable. Jack pine is one of these. The species has proved successful because of high rates of survival and rapid juvenile growth, despite attacks by the pine tip moth (*Rhyacionia* sp.), a serious pest of pines in central and western Nebraska. Jack pine seedlings have become established following fires, which have periodically wiped out other species. The greatest threat to jack pines in the sandhills has been extreme drought, such as occurred in the 1930's and again in the mid-1950's.

The absence of damage from insects and disease, and better-than-average growth rates at the Horning plantation, were highly encouraging.

Southern origins had greener winter foliage and grew faster than northern origins, which reaffirms the results from jack pine provenance tests in the Lake States (Schantz-Hansen and Jensen 1952, Canavera and Wright 1973, Williams and Beers 1959). Consequently, northern origins of jack pine are not recommended for plantings in Nebraska.

Seven of the eight tallest origins had form ratings among the top nine (tables 2 and 3). This positive relationship between rapid growth and superior form differs from previous experiences with other species of pine. Generally, the fastest growing trees have sparse, limby crowns containing gaps between whorls of laterals. The fastest growing jack pines developed dense, compact crowns, however, with foliage that remained green during the dormant season. This is most likely a function of the multinodal type of growth, a strong genetic trait of the species. These form and color characteristics are highly desirable in trees used for windbreaks, Christmas trees, and landscaping purposes. The following seven origins, which combined rapid growth with esthetic appeal, have great potential for various types of plantings in Nebraska: Mosinee, Wis.—69, Freesoil, Mic.—71, Wasaga Beach, Ont.—56, Petawawa, Ont.—46, Marl Lake, Mic.—74, Nekoosa, Wis.—67, and Twin Lakes, Ont.—39.

Trees from Petawawa, Ont. (46) display superior form, comparable to the best Scots pines (*Pinus sylvestris* L.), which are so popular for Christmas trees. Their main stems are among the straightest in the plantation. Crowns of these trees are exceptionally compact, because the lateral branches consistently sweep upward from the main stem (fig. 3). Thus, seedlings of Petawawa, Ont. (46) origin are recommended over all others in the plantings for posts, poles, windbreaks, greenbelts, Christmas trees, or landscaping purposes. Hopefully, superior jack pine seedlings from this origin will be grown and made available through the Clarke-McNary program for future planting programs.

Jack pine can be expected to grow best in eastern Nebraska, where precipitation is maximum and tip moth has not been a serious problem. Slower growth rates can be expected in central Nebraska because of tip moth damage and less precipitation. Tip moth can be controlled, however, by spraying trees with insecticides (Roselle 1973, Sexson and Roselle 1974). Where average annual precipitation is less than 20 inches, it is suggested that jack pine be planted only where irrigation facilities are available in case of extreme drought.

Lower branches of jack pines planted in the middle of stands or rows tend to die back from lack of light. Therefore, to obtain wind protection to ground level, jack pine should be planted in the outside rows of windbreaks containing several rows. Shade-tolerant shrubs or trees (such as eastern redcedar, *Juniperus virginiana* L., and lilac, *Syringa vulgaris* L.), which retain lower branches and foliage, should be planted in adjacent rows.

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A 9-year provenance test of jack pine in eastern Nebraska, with 28 origins, indicated that height, form, cone production, and needle length of southern origins exceeded northern origins. Foliage color during winter was yellow green on northern origins but green on southern origins. Fast-growing origins developed dense, compact, well-shaped crowns because of the multinodal growth characteristic of jack pine. A Petawawa, Ontario origin, of rapid growth and superior form, is recommended for plantings in Nebraska.

Keywords: *Pinus banksiana*, provenances, growth, tree form, windbreaks.

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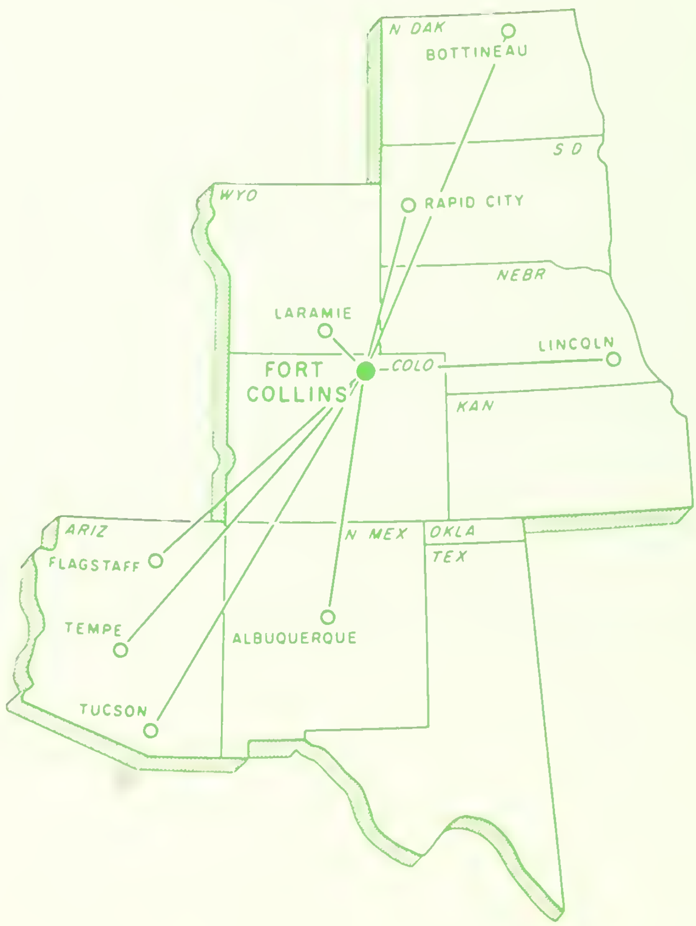
Although this report discusses research involving pesticides, such research does not imply that the pesticide has been registered or recommended for the use studied. Registration is necessary before any pesticide can be recommended. If not handled or applied properly, pesticides can be injurious to humans, domestic animals, desirable plants, fish, and wildlife. Always **read** and **follow** the directions on the pesticide container.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Red Pine Provenance Study in Eastern Nebraska

John A. Sprackling and Ralph A. Read

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Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture
Fort Collins, Colorado 80521

Abstract

Sprackling, John A., and Ralph A. Read.
1975. Red pine provenance study in eastern Nebraska. USDA For. Serv. Res. Pap. RM-144, 7 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521

An 11-year provenance test of red pine in eastern Nebraska, with 54 rangewide origins, revealed that heights and growth rates differed significantly among origins, but tree form, needle length, and foliage color were uniform. No geographic patterns of variation were identifiable. A fast-growing St. Philomene, Quebec origin is recommended for windbreak and landscape plantings in eastern Nebraska.

Keywords: *Pinus resinosa*, provenances, windbreaks, ornamentals, growth, tree form.

Preface

This provenance study is one of a dozen experimental plantations of various tree species established on the Horning State Farm near Plattsmouth, Nebraska, which is administered by the Department of Forestry of the University of Nebraska. The USDA Forest Service, through its Rocky Mountain Forest and Range Experiment Station Research Work Unit at Lincoln, cooperates with the Nebraska Agricultural Experiment Station in research conducted on this experimental area.

The specific purpose of this work was to find and develop better adapted trees for use in all kinds of plantings, environmental and commercial, throughout Nebraska and the Central Plains. Such provenance studies of different species provide plants of known origin for evaluation of adaptability and genetic variation, and for selection, propagation, and breeding for resistance to disease and insect pests.

The diversity of tree planting materials under study at this and many other locations in the Plains was made possible through cooperation in a Regional Tree Improvement Project (NC-99, formerly NC-51) of the North Central States Agricultural Experiment Stations.

Credits are due Jonathan W. Wright, Professor of Forestry, Michigan State University, for initiating the Regional study and providing the planting stock, and to Walter T. Bagley, Associate Professor of Forestry, University of Nebraska, for cooperation in planting and maintenance of the plantation.

USDA Forest Service
Research Paper RM-144

May 1975

Red Pine Provenance Study in Eastern Nebraska

John A. Sprackling, Forest Research Technician
and
Ralph A. Read, Principal Silviculturist

Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University. Research reported here was conducted at the Station's Research Work Unit at Lincoln, in cooperation with the University of Nebraska.*

Contents

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Red Pine Provenance Study in Eastern Nebraska

John A. Sprackling and Ralph A. Read

Red pine (*Pinus resinosa* Ait.) grows in the northern forest region of North America in an east-west belt approximately 1,500 miles long and 500 miles wide from Newfoundland and Pennsylvania to northwestern Minnesota and southeastern Manitoba (fig. 1). The species is considered to be relatively old, with little variation in morphology throughout its range (Fowler and Lester 1970).

Red pine progeny for this provenance test in eastern Nebraska encompassed a wide range of seed sources. Objectives of the study were to determine the variation, adaptability, and growth of red pine when introduced to the Central Plains. Information thus gained can be used to recommend better-adapted red pine origins for windbreaks, Christmas tree plantations, and landscaping projects in this area. This study also provides information and materials necessary for future tree breeding programs with red pine.

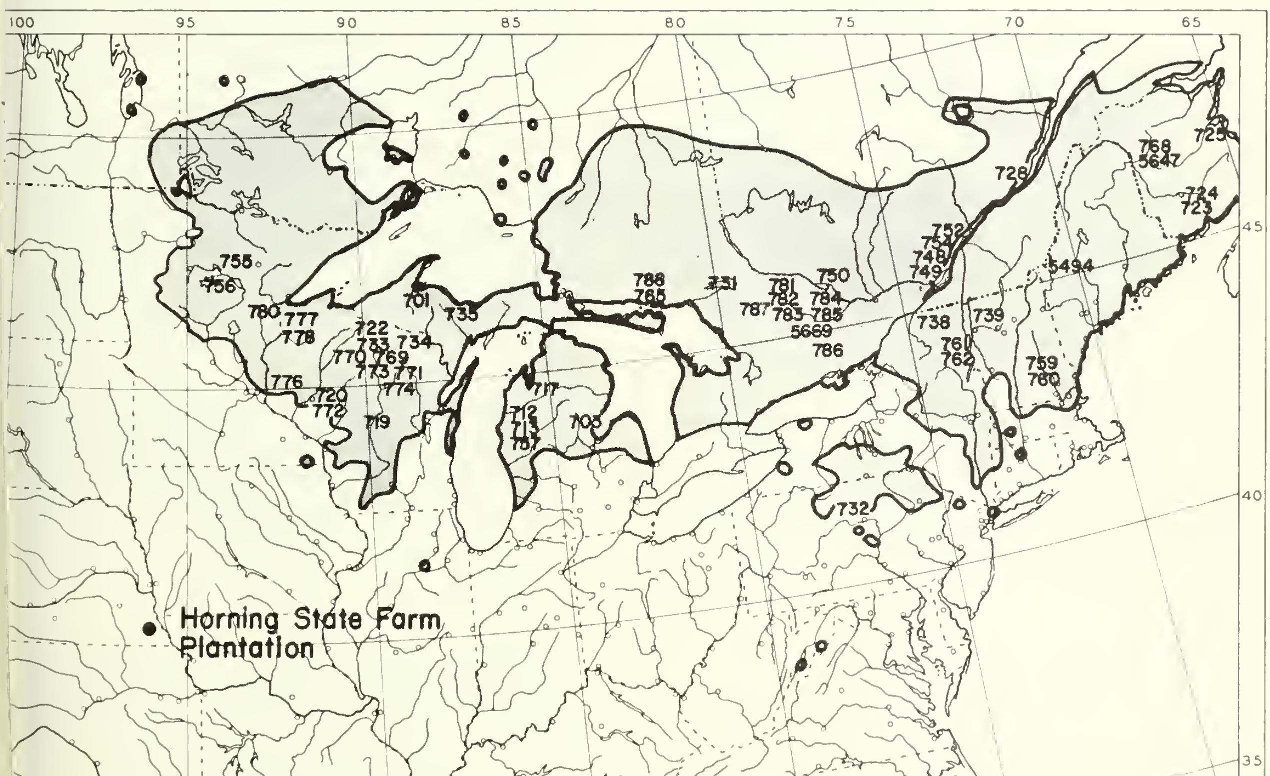

Figure 1.—Seed origins tested from within the natural range of red pine.

Previous Work

Although morphology of red pine is relatively uniform, some research has indicated that ecotypes have developed in the northern half of the Lake States, central Wisconsin, lower Michigan, the Northeast, and West Virginia (Rudolf 1957). Hough (1967) concluded, after a 25-year test in Pennsylvania of rangewide origins, that trees from southern origins generally were taller than those from northern origins, while tree forms were extremely uniform throughout. Sweet (1963) tested seven provenances in New Zealand for 6 years, and found that origins from climates with high mean annual temperatures and long growing seasons grew faster than others, and a Sturgeon Falls, Ontario, origin grew fastest.

Trees from lower Michigan were 8 percent taller than average at age 11 in 8 plantations of 77 provenances in the North Central States (Wright et al. 1972), whereas trees from New Brunswick, Manitoba, and western Ontario seed sources were 8 percent shorter than average. (The experimental planting reported here is one of the plantations studied by Wright et al., but additional years of growth are now available for more detailed information on performance in Nebraska.)

A Statewide provenance study in Michigan found lower Michigan trees 10 percent taller than upper Michigan trees after 10 years in a lower Michigan plantation, but only 3 percent taller when grown in an upper Michigan plantation (Yao et al. 1971).

Fowler (1965) compared cone length, number of seeds per cone, percent full seed, seed weight, percent germination, number of days to germinate, hypocotyl length, and number of cotyledons of 34 red pine trees from 9 climatic zones within their natural range. Number of cotyledons per seedling was the only characteristic correlated with provenance latitude: northern origins had fewer cotyledons than southern origins.

Other characteristics of red pine such as foliage color, needle length, bud characteristics, and hardiness are uniform among provenances (Wright et al. 1963).

Methods and Materials

Seeds of 77 origins were sown in the Michigan State University nursery at East Lansing during the spring of 1960. The 3+0 seedlings of 54 origins (fig. 1, table 1) were lifted, shipped by air, and planted in May 1963 at the Horning State Farm experimental area near Plattsmouth, in southeastern Nebraska. The planting site, at 96° west longitude and 41° north latitude, is on a gentle northfacing slope of silt loam soils derived from loess. Growing season averages 170 days and mean annual precipitation is 30 inches. Because the site had not been cultivated for several years, it was plowed and fallowed in 1962 in preparation for planting.

Seedlings were machine planted 5 feet apart in 16 rows spaced 10 feet apart. Each of the 54 provenances were replicated 8 times in 4-tree linear plots, which were randomly allocated in each replication. Surplus trees of all provenances were planted adjacent to the plantation. Maintenance of the plantation from 1963 through 1967 involved mowing between rows during the growing season, and applying Simazine spray in early spring at a rate of 4 pounds per acre in a 20-inch band along both sides of each tree row. The plantation was not mowed or sprayed after 1968.

Tree heights were measured following the growing season from 1965 through 1969 and again in 1971. Survival of initial plantings was checked after the first and second years, and dead seedlings were replaced by hand planting surplus stock. The trees were checked periodically for presence of insects and diseases and possible winter damage. The following additional measurements and observations were made during September 1973:

- Total height.
- Form rating—A numerical rating from 0 to 40 based on the sum of four characteristics: (1) branch angle, (2) stem straightness, (3) crown density, and (4) crown balance.[2]
- Average length of 1-year-old needles.
- Cone production.
- Average annual height growth for the last 7 years.

Analysis of variance and multiple-range tests were performed to determine any significant differences in total height, growth rate, or form among seed sources. An isodata cluster analysis[3] was made to determine and geographical patterns of variation.

[2]Branch angle refers to the angle of the lateral branches relative to the main stem. Crown balance refers to the uniformity of lateral branching on all sides of a tree. Each of the four morphological characteristics was given a numerical rating from 0 to 10. The sum of the four equals the form rating. Trees with acute branch angles, straight stems, dense crowns, and balanced crowns were given the highest form ratings.

[3]An isodata cluster analysis groups seed sources that are morphologically similar.

Table 1.--Data on seed origin locations of red pine tested in eastern Nebraska

Michigan State Univ. origin no.	State or Province	Place	North latitude	West longitude	Elevation	
			degrees	*degrees*	*feet*	*meters*
768	New Brunswick	Hamilton Brook	47.0	67.4	400	122
5647	New Brunswick	Limestone	46.8	67.6	450	137
725	New Brunswick	Despres Lake	46.6	65.6	300	91
724	New Brunswick	Grand Lake	46.0	66.1	75	23
723	New Brunswick	Camp Gagetown	45.8	66.3	--	--
728	Quebec	Loretteville	46.9	71.4	475	145
754	Quebec	Rawdon	46.2	73.9	202	62
752	Quebec	St. Philomene	46.1	73.3	62	19
748	Quebec	Berthierville	46.1	73.3	54	16
749	Quebec	Berthierville	46.1	73.3	54	16
788	Ontario	Sand Lake	46.6	82.2	1,400	427
731	Ontario	Sturgeon Falls	46.4	79.9	--	--
765	Ontario	Massey	46.1	82.2	--	--
731	Ontario	Deep River	46.0	77.4	--	--
782	Ontario	Chalk River	46.0	77.4	--	--
784	Ontario	Chalk River	46.0	77.6	--	--
785	Ontario	Chalk River	46.0	77.4	--	--
750	Ontario	Ft. Coulonge	46.0	76.6	447	136
5669	Ontario	Chalk River	46.0	77.5	--	--
783	Ontario	Chalk River	45.9	77.4	--	--
787	Ontario	Niven	45.8	78.0	750	229
786	Ontario	Griffith	45.2	77.2	850	259
5494	Maine	Flagstaff Lake	45.2	70.1	1,200	366
759	New Hampshire	Henniker	43.2	71.8	400	122
760	New Hampshire	Weare	43.1	71.7	600	183
739	Vermont	Checkerberry	44.6	73.1	200	61
738	New York	Paul Smiths	44.5	74.3	1,675	511
761	New York	Upper Jay	44.3	73.7	--	--
762	New York	Upper Jay	44.3	73.7	--	--
732	Pennsylvania	Renova	41.3	77.8	1,300	396
717	Michigan (LP)	Fife Lake	44.5	85.5	1,200	366
713	Michigan (LP)	Yuma	44.5	86.0	1,000	305
712	Michigan (LP)	Pomona	44.5	86.0	900	274
757	Michigan (LP)	Boon	44.2	85.5	1,300	396
703	Michigan (LP)	Gladwin	43.8	84.5	--	--
701	Michigan (UP)	Baraga	46.9	88.4	560	171
735	Michigan (UP)	Marquette	46.6	87.5	725	221
777	Wisconsin	Brule	46.5	91.6	974	297
734	Wisconsin	Boulder Junction	46.4	89.6	--	--
778	Wisconsin	Gordon	46.3	91.6	1,060	323
733	Wisconsin	Woodruff	46.1	89.7	--	--
722	Wisconsin	Sayner	46.0	89.5	--	--
770	Wisconsin	Worcester	45.8	90.4	1,500	457
769	Wisconsin	Three Lakes	45.8	89.1	1,650	503
771	Wisconsin	Crescent	45.6	89.7	1,100	335
773	Wisconsin	Bradley	45.5	89.8	1,100	335
774	Wisconsin	Post Lake	45.5	88.8	1,000	305
776	Wisconsin	Cylon	45.2	92.0	1,100	335
720	Wisconsin	Washington	44.8	91.4	1,000	305
772	Wisconsin	Fall Creek	44.8	91.4	1,000	305
719	Wisconsin	Pittsville	44.3	89.8	1,030	314
755	Minnesota	Winnibigoshish Lake	47.5	94.3	1,350	412
756	Minnesota	Leech Lake	47.3	94.5	1,350	412
780	Minnesota	Cloquet	46.7	92.5	1,265	386

Results

Seedling Survival

Overall survival was 79.4 percent after one growing season, and 78.7 percent after two growing seasons. Survival varied from 97 percent for three origins (Niven, Ont.—787, Berthierville, Que.—748, and Baraga, Mic.—701) to 34 percent (Limestone, N.B.—5647) (table 2). Mortality after the second year was negligible, except that caused by a surface fire in 1968 which spread from adjacent land through a portion of the plantation. All trees damaged by fire were subsequently excluded from analysis. Survival rates were unrelated to latitude or longitude of seed origin.

Height and Growth Rates

Trees from St. Philomene, Quebec (752) were the tallest after 11 years. They averaged 18.9 feet in height, 11 percent taller than the plantation average of 17.1 feet (table 2). Individual trees of this origin varied in height from 20.5 feet, the second tallest tree in the plantation, to 16.2 feet. Height measurements taken in 1966, 4 seasons after planting, showed these Quebec origin trees to be tallest even at the that time, averaging 4.4 feet.

Over the last 7 years,[4] the fastest height growth rate was 2.1 feet per year for eight origins, compared to a plantation average of 1.9 feet per year. The fastest growing individual tree, from Upper Jay, New York (762), averaged 2.4 feet in annual height growth for the last 7 years.

Analyses of variance indicated that some differences in total heights and height growth rates between origins were significant. Multiple range tests showed that trees of the tallest origin (St. Philomene, Que.—752, which averaged 18.9 feet) were significantly taller than trees of some 27 origins, which averaged 17.2 feet or less. Similarly, the fastest rate of height growth (2.1 feet per year for 8 origins) was significantly greater than the 1.8 feet per year or less of the 10 slowest growing origins. Neither heights nor growth rates were correlated with latitude, longitude, or elevation of seed origin.

[4]*Average annual height increments were based on the last 7 years, whereas total heights were measured after 11 years. Thus the tallest trees did not necessarily have the fastest growth rates.*

Table 2.--Survival and height of red pine origins in eastern Nebraska

Michigan State Univ. origin number		2-year survival	Height: 11-year total[1]	Height: Percent of plantation mean	Mean annual height growth 1967-73	Basis: trees
		percent	*feet*	*percent*	*feet*	*no.*
QUE	752	91	18.9	111	2.1	16
WIS	772	78	18.8	110	2.1	9
MIC	735	78	18.7	109	2.1	2
VT	739	84	18.6	109	2.0	4
ONT	788	69	18.5	108	2.1	6
MIC	712	84	18.3	107	2.1	10
WIS	720	72	18.1	106	2.0	5
NY	762	88	18.1	106	2.0	11
ONT	731	81	18.0	105	2.1	3
ONT	781	88	18.0	105	2.1	2
WIS	777	78	17.9	105	2.0	7
ONT	765	84	17.9	105	2.0	4
MIC	703	84	17.9	105	2.0	8
WIS	773	81	17.9	105	2.0	9
NH	760	84	17.9	105	2.0	8
ONT	785	75	17.8	104	2.0	10
NY	761	84	17.8	104	2.0	12
ONT	787	97	17.8	104	2.0	10
QUE	749	62	17.8	104	2.0	8
MIC	713	84	17.8	104	2.0	11
QUE	754	69	17.7	104	2.0	3
ONT	5669	53	17.6	103	2.1	12
ONT	783	81	17.6	103	2.0	14
QUE	748	97	17.3	101	2.0	8
WIS	734	81	17.3	101	2.0	10
WIS	776	64	17.2	101	2.0	8
MIN	780	72	17.2	101	2.0	3
WIS	722	84	17.2	101	2.0	10
WIS	733	72	17.2	101	2.0	6
WIS	778	91	17.1	100	1.9	13
MIN	756	84	17.1	100	2.0	10
ONT	782	82	17.1	100	1.9	9
WIS	770	84	17.1	100	2.0	12
ONT	750	84	17.0	99	1.9	6
ONT	784	78	17.0	99	1.9	5
ONT	786	81	16.9	99	1.8	5
WIS	771	88	16.7	98	1.8	8
WIS	774	72	16.7	98	2.0	7
MIC	757	75	16.7	98	1.8	9
NBR	768	75	16.7	98	1.9	9
WIS	719	84	16.4	96	2.0	6
NBR	724	88	16.4	96	1.9	11
NY	738	78	16.2	95	1.8	6
NBR	723	84	16.1	94	1.8	3
MIN	755	75	16.1	94	1.8	1
MAI	5494	50	15.8	92	1.9	13
MIC	701	97	15.6	91	1.7	10
NBR	5647	34	15.6	91	1.9	11
QUE	728	81	15.3	89	1.7	1
NH	759	67	14.7	86	1.5	6
NBR	725	78	14.3	84	1.6	4
WIS	769	--	14.1	82	1.7	10
MIC	717	--	12.5	73	1.4	4
PA	732	--	12.0	70	1.4	7
Plantation average		79	17.1	100	1.9	

[1]Duncan's range test: Means within same bracket do not differ at the 5% level. Means of equal value may be separated by brackets due to rounding off.

Form

Form ratings for origins ranged narrowly from 26 to 33, with a plantation average of 29.3 (table 3). Individual trees rated as high as 37 (fig. 2) and as low as 18. Trees from Cape Gagetown, New Brunswick (723), had the highest form ratings. An analysis of variance indicated no significant differences in form among the 54 origins. Multiple range tests showed only four origins with form ratings significantly lower than the other 50.

Figure 2.—A Gordon, Wisconsin, tree exhibits a straight stem, dense foliage, and a compact crown. Form rating was 37.

Other Characteristics

Average needle length also ranged only slightly among origins, from 5.0 to 6.0 inches (table 3). Foliage color during the growing season was uniformly dark green throughout the plantation; during dormancy foliage was a duller green, but still uniform.

Table 3.--Form, needle length, and cone production of red pine origins 11 years after planting in eastern Nebraska

Michigan State Univ. origin number		Average form rating[1]	Average needle length	Average cone production[2]
		[3]	*inches*	*per tree*
NBR	723	33.0	5.3	M
MIC	735	32.5	6.0	L
ONT	765	31.5	6.0	M
NBR	725	31.2	5.4	L
WIS	720	31.0	5.9	L
NBR	5647	30.7	5.6	L
QUE	754	30.7	5.5	L
ONT	787	30.6	5.7	L
ONT	784	30.4	5.5	L
MIC	713	30.3	5.9	L
ONT	788	30.2	5.6	L
NH	760	30.1	5.5	L
NBR	768	30.1	5.6	L
WIS	772	30.0	5.7	L
ONT	750	30.0	5.5	L
ONT	781	30.0	5.0	M
WIS	774	29.9	5.8	L
QUE	752	29.8	5.7	M
NBR	724	29.7	5.6	L
QUE	748	29.6	5.6	L
NY	761	29.6	5.5	L
ONT	783	29.5	5.7	L
QUE	749	29.5	5.6	L
MIC	703	29.5	5.2	L
ONT	786	29.4	5.6	M
MIC	712	29.4	5.5	L
ONT	731	29.3	5.5	M
NH	759	29.3	5.3	L
MIC	701	29.2	5.4	L
NY	762	29.2	5.8	L
ONT	785	29.1	5.7	L
WIS	778	29.0	5.6	M
WIS	773	29.0	5.2	L
QUE	728	29.0	5.0	L
ONT	5669	28.9	5.6	L
WIS	770	28.9	5.5	L
VT	739	28.8	5.9	M
WIS	771	28.8	5.8	L
WIS	719	28.7	5.9	L
NY	738	28.7	5.7	M
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MIN	756	28.4	5.4	L
WIS	777	28.3	5.3	L
MIC	757	28.2	5.6	M
WIS	722	28.1	5.8	L
MAI	5494	28.1	5.8	L
ONT	782	28.0	5.5	M
MIC	717	28.0	5.2	L
WIS	776	27.8	5.1	L
PA	732	27.3	5.9	L
WIS	769	27.2	5.6	L
MIN	755	26.0	6.0	H
Plantation average		29.3	5.6	

[1] 0 = lowest 40 = highest
[2] L = <20 cones; M = 20 to 40 cones; H = >40 cones.
[3] Duncan's range test: Means within same bracket do not differ at the 5% level. Means of equal value may be separated by brackets due to rounding off.

Cone production for all origins was relatively low. Only 13 of the 54 origins averaged more than 20 cones per tree (table 3). Individual trees of the same origin often ranged from less than 20 to well over 40 cones per tree, however. Cone production was not correlated with seed origin.

No damage from insects or disease has been observed in the plantation. Heavy wet snow or freezing rain caused greatest physical damage (fig. 3). In no instance did this breakage cause mortality, however, and generally the tree crown was not noticeably deformed.

The isodata cluster analysis, which compared total height, growth rates, and form ratings of all origins, revealed no clearly defined geographical ecotypes within the species. On the contrary, all measurements except height and growth rates portrayed a uniform species.

Discussion

The separate ecotypes referred to by Rudolf (1957) were not identifiable in this study. Heights and growth rates varied sufficiently, however, that certain origins can be selected for tree planting programs where rapid height growth is desired.

The plantation average growth rate of 1.9 feet per year is excellent for conifers, and compares favorably with broadleaf species in eastern Nebraska. Seven tests of the same red pine origins, conducted simultaneously in Michigan, Wisconsin, Minnesota, and Indiana, produced slower growing trees (Wright et al. 1972). Shorter growing seasons and less fertile soils in the Lake States were probably responsible for slower growth, although four of the test sites in southern Michigan and eastern Indiana had growing seasons only 10 days shorter than Nebraska. However, those sites averaged 5 more inches of precipitation per year than at Horning, Nebraska.

Height measurements of the Nebraska plantation in 1971 indicated that, collectively, four of the five lower Michigan origins were taller than other geographically related origins, averaging 106 percent of the plantation mean height. In 1973, these same origins averaged only 103 percent of the plantation mean, and only one origin (Pomona, Michigan—712) from lower Michigan was among the 10 tallest. No permanent pattern of superior height growth by geographically related origins has been established in the plantation. It is unlikely that any such pattern will develop because of the uniformity among origins displayed thus far.

Trees in the plantation were vigorous, and the absence of disease and insect damage was encouraging. Christmas tree growers near Lincoln, Nebraska, 50 miles west of the study area, have reported young red pines damaged by tip moths (*Rhyacionia* sp.) when planted near infested stands of ponderosa pine (*Pinus ponderosa* Laws.) Tip moth infestations appear to increase further west in Nebraska. These insects, which do not cause mortality but will re-

Figure 3.—Severe snow damage which bent lower branches and caused some breakage.

duce terminal growth, can be chemically controlled (Roselle 1973, Sexson and Roselle 1974).

Information regarding the ability of red pine to grow in central and western Nebraska is scanty. Only small portions of red pine stands planted early in this century on the Bessey District, Nebraska National Forest, are still living. High mortality resulted from periods of drought, severe tip moth damage during juvenile growth, and a 1965 fire. For these reasons other species are considered more suited for conditions in central and western Nebraska.

In eastern Nebraska, on the other hand, all of the tallest 27 origins (table 2) should be satisfactory for windbreak plantings. The St. Philomene, Quebec, (752) origin, tallest in this study, also grew rapidly in most of the Lake States studies (Wright et al. 1972). It was tallest, 19 percent above average, in the Indiana provenance test; second tallest, 20 percent above average, in the Wisconsin provenance test; and 11 and 12 percent above average height in two Michigan plantations. Because of its consistent performance, this seed origin is recommended over all others for use in eastern Nebraska windbreaks. Landowners interested in growing trees for posts, poles, and lumber should also consider obtaining seedlings of this fast-growing origin. Correspondence with the nursery supervisor at Berthierville, Quebec, indicates that seeds of this origin can be obtained.

New Brunswick origins, in contrast, averaged only 92 percent of plantation average heights in both the Lake States and Nebraska, and are not recommended for eastern Nebraska.

Average form ratings for the plantation were very high (29.3). The uniformly dense, oval, dark green crowns give the red pine plantation an esthetic advantage over some of the other pine plantations at Horning. Stems were consistently straight and crowns symmetrically balanced in all origins. Lower branches were persistent to ground level. These factors, combined with an average needle length of 5.6 inches, created a dense, compact crown that is desirable for windbreaks. Because there were no significant differences in form, all origins tested can be used for plantings in eastern Nebraska where high esthetic value is desirable, but rapid height growth is less important, such as for Christmas trees. St. Philomene (752) and Fall Creek, Wisconsin (772), seed origins are recommended where both rapid growth and superior form are desired, as in greenbelts, parks, roadsides, and landscaping projects. Although the Marquette, Michigan (735), origin grew rapidly, there were insufficient trees remaining on which to base a reliable recommendation.

The good survival, rapid growth, excellent form, and high esthetic value demonstrated by red pine in this study proves that it can be successfully grown for shelterbelts, Christmas trees, and landscaping purposes in eastern Nebraska. Red pine is not recommended for central and western Nebraska, however. For maximum success, red pine should not be planted adjacent to stands of pines infested with tip moth.

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An 11-year provenance test of red pine in eastern Nebraska, with 54 rangewide origins, revealed that heights and growth rates differed significantly among origins, but tree form, needle length, and foliage color were uniform. No geographic patterns of variation were identifiable. A fast-growing St. Philomene, Quebec origin is recommended for windbreak and landscape plantings in eastern Nebraska.

Keywords: *Pinus resinosa*, provenances, windbreaks, ornamentals, growth, tree form.

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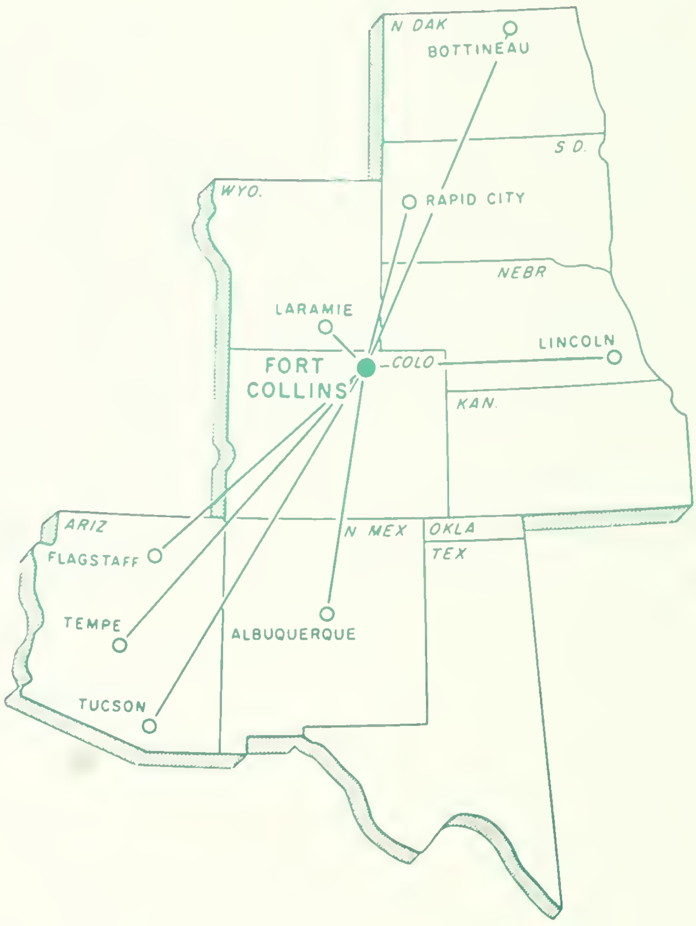
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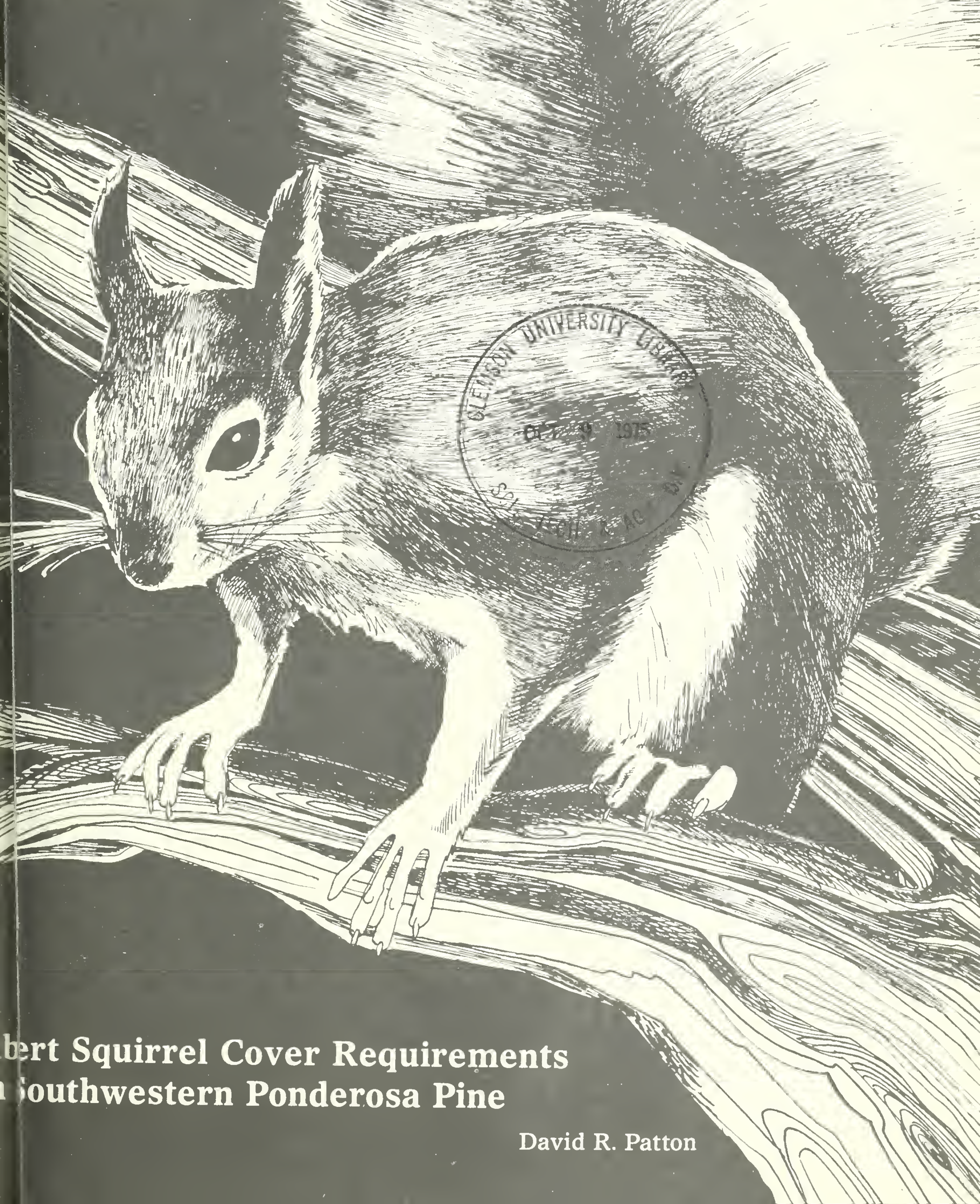

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bert Squirrel Cover Requirements
Southwestern Ponderosa Pine

David R. Patton

Abstract

Patton, David R.

1975. Abert squirrel cover requirements in southwestern ponderosa pine. USDA For. Serv. Res. Pap. RM-145, 12 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521

Describes the characteristics of ponderosa pine trees and stands selected by the Abert squirrel for cover. Presents data on basal area, tree density and size, tree vigor, dominance and age class, nest location and nest tree density in a pine forest. Discusses the data's relevance for evaluating the quality of Abert squirrel habitat.

Keywords: Abert squirrel, ponderosa pine, habitat evaluation, squirrel cover.

PREFACE

Criteria for optimum squirrel cover presented in this study were from data obtained in an area where man had not overcut the forest. The trend for forest management in ponderosa pine is going toward large single-aged stands, with trees spaced more evenly. In such a stand the effect of tree grouping and great diversity could be destroyed, and I suspect Abert squirrel habitat also.

Keith (1965) pointed out the dependence of Abert squirrels on ponderosa pine, McKee (1941) alluded to the evolutionary aspects of pine and squirrels, and implicit in this study is the close association of tree size, density, and grouping to provide squirrel nest cover. These factors cannot be denied if the Abert squirrel is to remain part of the ponderosa pine ecosystem. There will need to be trade-offs between wood production and squirrel habitat. Biologists and foresters must work together to insure that future timber stands and squirrel habitat start with ponderosa pine seedlings.

Special recognition is due Dr. D.I. Rasmussen, U.S Forest Service (retired). His observations and many years of field experience provided a background from which I could draw to develop research concepts.

USDA Forest Service
Research Paper RM-145

May 1975

Abert Squirrel Cover Requirements in Southwestern Ponderosa Pine

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[1]Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University; author is located at Station's Research Work Unit at Tempe, in cooperation with Arizona State University.

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Abert Squirrel Cover Requirements in Southwestern Ponderosa Pine

David R. Patton

INTRODUCTION

Ponderosa pine[2] is the most widely distributed pine in North America; it ranks second in timber production in the western United States. Commercial ponderosa pine in the Southwest occupies about 11 million acres mostly in Arizona, Colorado, and New Mexico (fig. 1). Of the many wildlife species inhabiting the ponderosa pine forest, none are more dependent on pine for food and cover than the Abert squirrel. The relationship is even more interesting because the distribution of Abert subspecies coincides with disjunct ponderosa pine forests. Since pine is an important timber species, increasing national demand for wood products will increase timber harvesting in the southwestern ponderosa pine type, which will directly affect squirrel habitat. Abert squirrel management depends on a knowledge of squirrel food and cover requirements, and how these requirements are changed by changes in the physical and spatial characteristics of the pine forest.

Food habits of this handsome squirrel generally have been determined, and studies still in progress will add to our knowledge, but factual information about cover is lacking. Cover, defined as vegetative shelter, includes the nest, nest tree, and vegetation surrounding the nest tree of an Abert squirrel. The vegetation characteristics preferred for cover need to be identified and quantified so guidelines can be developed to evaluate the quality of squirrel habitat and how quality is affected by forest succession and forest management practices.

The objectives of this study were to determine: (1) density of squirrel nests in a ponderosa pine forest stratified by physical characteristics, (2) physical characteristics of trees selected for nests, and (3) the physical and spatial characteristics of trees surrounding the nest tree. Data collected to satisfy these objectives would be the basis for developing a technique to evaluate Abert squirrel habitat. With this technique the forest wildlife manager could evaluate land management practices that alter the squirrel's environment, and recommend changes in cutting practices to insure that some areas will remain good squirrel habitat.

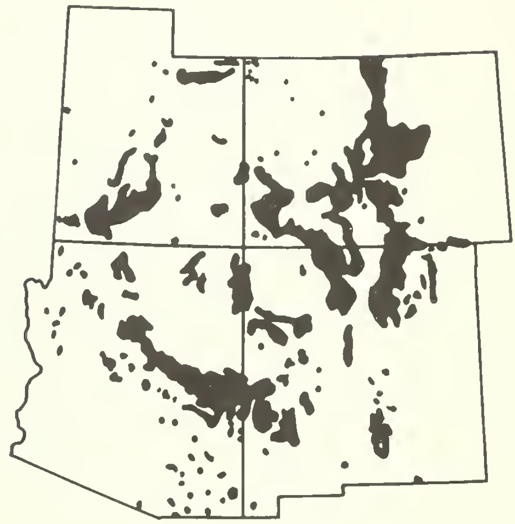

Figure 1.—Occurrence of ponderosa pine in the Southwest.

The Abert Squirrel

The Abert squirrel type specimen was collected from the San Francisco Mountains in Arizona in October 1851 by S.W. Woodhouse. It was named in honor of Lt. James W. Abert, who made natural history observations while on a military expedition to the Southwest (Merriam 1890). Collectively the Abert squirrel sub-

[2]*Scientific names of plants and animals mentioned are listed inside the back cover.*

species (including *Sciurus kaibabensis*) have been described in a subgenus (*Otosciurus*) as tassel-eared squirrels. Opinions differ on whether the Kaibab squirrel is a separate species or a subspecies of the Abert. Merriam (1904) gave the Kaibab squirrel species status, but Cockrum (1960) considers it a subspecies of Abert. The difference in the two squirrels is based on color variation; both appear to have similar habitat requirements.

Abert squirrels are found only in the interior ponderosa pine forests where temperatures are cool and rainfall is moderate (McKee 1941). The interior pine type has been described by the Society of American Foresters (1954) as a separate forest type—Type 237. It differs from other ponderosa pine, particularly in coastal areas, in that it occurs mostly in pure or nearly pure stands at middle elevations where rainfall is less than 25 inches. In Arizona and New Mexico, Gambel oak is a common associate of ponderosa pine. The type occurs just above the pinyon-juniper and below the Douglas-fir zone.

This pine distribution restricts the Abert to Arizona, Colorado, New Mexico, Utah, and parts of Mexico. McKee (1941) believes the present squirrel distribution came about as a result of ponderosa pine disappearing from low elevations because of changes in climate. The Abert did not adapt to other vegetation types, and over thousands of years moved upward with the receding pine forests. Keith (1965) suggests that squirrel populations fluctuate over short periods and that there has been a general downward trend in squirrel numbers. He relates the changes to logging and a failure of ponderosa pine to regenerate.

Keith (1965) published the first factual information on the food and cover requirements of the Abert squirrel. His paper provided evidence the Abert depends solely on ponderosa pine for most of its life necessities. In 1964 I began a study on the Apache National Forest to learn more about the Abert squirrel and its habitat (Patton and Green 1970). The objective of that earlier study was to determine sizes of ponderosa pine selected by squirrels for feed trees to provide data to forest managers to coordinate squirrel management with timber harvesting.

The Abert Squirrel's Habitat

Research indicates trees between 11 and 30 inches diameter at breast height (d.b.h.) are preferred for feed trees (Patton and Green 1970). The frequency distribution of tree diameters used by squirrels on the Kaibab National Forest[3] is close to that reported on the Apache National Forest (Patton and Green 1970).

Feed tree density varies considerably and probably reflects different squirrel numbers and different measurement techniques. Squirrels used from 0.6 to 4.7 trees per acre on the Manti-LaSal National Forest in Utah depending on whether the stand was cut or uncut.[4] On the Kaibab National Forest, Hall[5] found number of trees used per acre varied by year from 0.5 to 6.0. Computations from Arizona Game and Fish Department surveys, however, showed 2.4, 14.1, and 11.7 feed trees per acre for 1968, 1969, and 1970, respectively.[3]

Although there is some indication that squirrels prefer certain trees for feeding[5] (Goldman 1928, Keith 1965, Pearson 1950), the criteria for choice of feed trees has not been determined. A qualitative difference in trees has been suggested by Keith (1965), but Hall[5] could not validate this difference in his chemical analyses.

Cover preference of Abert squirrels has not been established except for casual observations and some limited data. Several people[5] (Bailey 1931, Cahalane 1947, Goldman 1928, Patton and Green 1970, Warren 1910) indicate that squirrels most frequently nest in ponderosa pine. Other tree species have been used for nests, mainly Gambel oak (Patton and Green 1970). Nest trees in Arizona vary in size from 12 to 41 inches d.b.h. at Fort Valley (Keith 1965), from 10 to 24 inches d.b.h. in Castle Creek (Patton and Green 1970), and from 11 to 28 inches d.b.h. on the Kaibab National Forest.[3]

The habitat surrounding the nest tree is probably more important than the nest tree itself. At Castle Creek, Patton and Green (1970) identified a tree density factor that suggested minimum amounts of cover for maintenance of squirrel habitat. A squirrel nest is generally found in a tree that is one of a group of trees of similar size, but sometimes nests are found in

[3]*Rasmussen, D.I. 1972. National and international interest in the Kaibab squirrel: A problem analysis. 91 p. (Unpublished report prepared by Reg. 3, USDA For. Serv., Albuquerque, N. Mex., on file at Rocky Mt. For. and Range Exp. Stn., Tempe, Ariz.)*

[4]*Butler, J.J , and G. Richardson. 1969. Abert squirrel activity in the Arch Canyon and Babylon timber sales, Monticello Ranger District, Manti-LaSal National Forest, Price, Utah. 5 p. (Unpublished report on file at Rocky Mt. For. and Range Exp. Stn., Tempe, Ariz.)*

[5]*Hall, J.G. 1967. The Kaibab squirrel in Grand Canyon National Park: A seven seasons summary 1960-1966. 54 p. (Unpublished report prepared by Natl. Park Serv., U.S. Dep. Inter., Grand Canyon, Ariz., on file at Rocky Mt. For. and Range Exp. Stn., Tempe, Ariz.)*

isolated trees. All nest trees on the Kaibab National Forest were located in groups of trees that provide access to the nest tree by interlocking or close tree crowns.[3] Such a grouping provides protection from weather plus alternate escape routes.

Ponderosa pine exists mainly as a climax forest in the Southwest (Pearson 1950). Although tree species composition in the pine type is rather simple, the spatial distribution of trees is very complex. Cooper (1961) described four scales of patterns, from a large scale induced by topography to a small scale of individual arrangement of trees in a stand. Characteristically, ponderosa pine in the Southwest grows in irregular uneven-aged stands, with even-aged groups within the stands (Schubert 1973). Groups vary from a few trees of similar size occupying about 1/100 acre to many trees on areas of 1/20 to 1/5 acre. Cooper (1961) suggests reasons for this group pattern: the species is intolerant to shade and natural fires oppose a random vegetation distribution.

Availability of squirrel food items is directly associated with the morphology and phenology of ponderosa pine. Ponderosa has both staminate and pistillate flowers on the same individual (monoecious). Flowering usually begins in May, and pollen is shed in June. After pollination the female flower develops slowly the first summer. Although the female conelet has been pollinated, fertilization is delayed until the following spring. The cone then develops rapidly and reaches maturity in August and September.

Staminate flowers are eaten by the Abert in May and June, and squirrels are often seen with a yellow "pollen" face. Ovulate cones are consumed from May to November when the last seed generally has been shed. Inner bark and apical buds become the squirrel's main food source during winter months, especially when snow covers the forest floor. Acorns and fungi are readily eaten when they are available.

STUDY AREA

Squirrel-pine relationships were studied on watershed 8 of the Beaver Creek Pilot Watershed, 25 miles south of Flagstaff, Arizona, on the Coconino National Forest (fig. 2). This area was selected because it had a good squirrel population, a variety of ponderosa pine stand conditions, and easy access. Also, supporting information in the form of maps, aerial photographs, timber inventory, and a soil survey was available.

Landscape

Watershed 8, an area of 1,765 acres, varies from 6,900 feet elevation at the lower end to 8,020 feet on top of Lake Mountain. It is part of the Grand Canyon section of the Colorado Plateau physiographic province (Fenneman 1931). Slopes are gentle in the center of the watershed, but become steep around Lake Mountain and along the stream drainage below Butch Tank. Drainage is west into the Verde River. The watershed had been logged twice, once in 1930 and again in 1950. The latter was a selection cut which removed approximately half of the commercial volume.

Climate

Climate in watershed 8 is similar to that of Flagstaff. The coldest month is January, with an average minimum of 14° F and an average maximum of 40° F. August is the warmest month; the average minimum temperature is 50° F and the average maximum is 81° F. Two distinct precipitation seasons are evident: summer rains come in July and August in thunderstorms, while winter precipitation is in the form of snow. Average precipitation is 24 inches; about 5 inches of this falls during July and August.

Soils

There are five soil series (Brolliar, Cabezon, Friana, Siesta, and Sponseller) within the watershed boundary (Williams and Anderson 1967). Brolliar, the most important, covers 70 percent of the study area. It consists of moderately deep and deep, well-drained, noncalcareous material on nearly level to hilly uplands, formed from weathered porous basalt. The surface layer of Brolliar is dark brown, soft when dry, and has a blocky structure. Basalt bedrock is at a depth of 2 to 5 feet. Stones and cobbles cover 20 to 60 percent of the surface of most areas. Litter of decomposed and partly decomposed pine needles overlies the mineral soil.

Flora and Fauna

Ponderosa pine is the dominant plant species in the study area. Small clumps and single trees of Gambel oak and New-Mexican locust are scattered throughout the pine. Aspen occurs along cool drainages, but is not a major component of the overstory.

Figure 2.—Location of study area—watershed 8 (1,765 acres) of the Beaver Creek Pilot Watershed, Coconino National Forest, Arizona.

Understory species include Arizona fescue, Junegrass, blue grama, mountain muhly, geraniums, peavine, and clovers. Woody understory species are not abundant, but oak, locust, and Fendler ceanothus are present.

Common mammals found in the watershed are mule deer, elk, cottontail rabbit, bobcat, coyote, raccoon, and red squirrel.

Many species of birds inhabit the study area, but those seen most often are the pygmy nuthatch, violet-green swallow, gray-headed junco, mourning dove, red-tailed hawk, goshawk, and wild turkey.

METHODS

My approach to experimental design was to inventory and describe areas used by squirrels for cover. Each area was located by the presence of a nest.

An existing timber inventory system for watershed 8, consisting of 180 points identified on the ground and on a base map, was used by a field crew to search systematically for squirrel nests. The crew marked each nest tree with a numbered aluminum tag and orange flagging, plotted its location on the base map, and then used it as the center of a 1/10-acre plot to inventory the trees surrounding the nest tree.

Species and diameter, measured at 4.5 feet (d.b.h.), were recorded for all trees on the plot. Diameters were rounded to the nearest inch for computing basal area and average tree diameter for trees over 7.5 inches d.b.h. Basal area is the total cross-sectional area in square feet of trees on a per-acre basis. Average diameter generally is determined from basal area, but in this study I averaged the diameters for all trees on the plot.

Plot slope was recorded to the nearest percent and categorized in one of five classes: 5 or less, 6 to 10, 11 to 15, 16 to 20, or greater than 20. Plot exposure was recorded to the nearest degree and assigned to one of eight classes: N, NE, E, SE, S, SW, W, and NW. Plot slope position was recorded as lower, middle, or upper one-third of the total slope. Canopy coverage at the plot was estimated from four spherical densiometer readings taken at the plot center facing north, east, south, and west.

Other factors recorded at the plot were number of trees with the main trunk forked and the amount of ground cover. Ground cover was estimated on five 8- by 20-inch plots systematically spaced at 3-foot intervals along the north radius of the 1/10-acre plot. Cover to the nearest percent was recorded for rock, litter, grass, forbs, bare soil, and woody plants less than 2 feet high.

Age of each nest tree was determined from an increment core removed at d.b.h. Mistletoe-infected nest trees were rated using Hawksworth's (1961) 6-class system. The tree crown is divided into three vertical sections and assigned a value:

0 - No infection
1 - Light infection
2 - Heavy infection

The value for each section is added to obtain a composite rating for the tree.

Nest location (trunk, fork, or limb), nest distance from the ground, nest exposure from the tree trunk, nest tree height, and number of trees interlocking the crown of the nest tree were recorded at the inventory plot.

Nest trees were described by recording age-vigor, tree position, and tree dominance. Age-vigor was recorded by using criteria for ponderosa pine in the Southwest (Thompson 1940):

Age I—Young blackjack pine, seldom over 12 inches d.b.h. and usually less than 75 years old.

Age II—Blackjack pine seldom over 24 inches d.b.h. and usually less than 150 years old.

Age III—Intermediate or young yellow pine less than 36 inches d.b.h. and between 150 and 225 years old.

Age IV—Yellow pine over 225 years old with bark plates long, wide, and smooth.

Vigor AA—Crown is over 70 percent of the tree height.

Vigor A—Crown is between 55 and 70 percent of the tree height.

Vigor B—Crown is between 35 and 55 percent of the tree height.
Vigor C—Crown is between 20 and 35 percent of the tree height.
Vigor D—Crown is less than 20 percent.

Nest tree position indicates the horizontal location of a tree in a group of trees (Pearson 1950). The classifications used were:

Isolated—Tree is free to grow on all sides and is 30 or more feet from other trees.
Open—Tree is detached from a group of trees, but is closer than 30 feet.
Marginal—Tree is growing on the edge of a group of trees.
Interior—Tree is growing inside a group of trees.

Tree dominance indicates vertical position of the tree crown in a stand (Pearson 1950). For ponderosa pine in the Southwest the criteria are:

Isolated—Trees with crowns that receive full light from above and from all sides through the life of the tree.
Dominant—Trees with crowns extending above the general level of the crown cover and receiving full light from above and partly from the side; larger than average trees in the stand.
Codominant—Trees with crowns forming the general level of the crown cover and receiving full light from above, but comparatively little from the sides, usually with crowns crowded on all sides.
Intermediate—Trees shorter than those in the two preceding classes, but with crowns either below or extending into the crown cover formed by codominant and dominant trees. These trees receive little direct light either from above or from the sides.
Overtopped—Trees with crowns entirely below the general level of the crown cover that receive no direct light either from above or from the sides.

RESULTS AND DISCUSSION

Data analysis consists of two parts. First, nest tree density and ponderosa pine crown density classes are compared. Second, physical characteristics of nest trees and physical and spatial characteristics of trees surrounding the nest tree are described from data collected on the 1/10-acre inventory plots. The terms cover site, nest site, plot, and stand all refer to the 1/10-acre inventory plot.

Density of Squirrel Nests

The pine forest in watershed 8 was stratified into three crown density classes. These classes could be identified under a stereoscope using a crown density scale on color aerial photographs. Five acres was the smallest area included in a class. Tree diameters for the three crown density classes were estimated from a dot grid sample within each class by comparing the tree crown under the dot to a crown diameter scale graduated in thousandths of an inch. The measurement was then converted to tree diameter from a regression of tree crown to tree diameter for ponderosa pine. Within each density class, differences in sizes of stands and clumping of trees could be seen on the photographs, but these areas were not delineated because of their small size. These small areas also were the areas that would be described in the nest tree inventory. Thus, the crown density classes are described at a scale large enough to be interpreted from aerial photographs, using standard photographic techniques and aids:

Low Crown Density (Class I)—This class contains mature yellow pine with somewhat homogeneous spacing of single trees. In some areas trees may be grouped. Small stands of saplings (1 to 5 inches d.b.h.) and poles (5 to 9 inches d.b.h.) sometimes are scattered between large groups of mature trees. Trees are generally above 18 inches d.b.h. Crown density is 35 percent or less.

Moderate Crown Density (Class II)—A class containing mature yellow pine mixed with stands of intermediate pine. An open effect results from space between large stands. Large stands may contain subgroups of trees from 1/10 to 1/4 acre in size. Openings between large groups sometimes have evenly spaced single trees. Average diameter of trees in the stands ranges from 14 to 17 inches d.b.h. Crown density is between 36 and 70 percent.

High Crown Density (Class III)—Intermediate and blackjack pines occur in this class in a mixture of densities and diameters. Many stands have one layer, but two and sometimes three layers are formed by several mature trees (15 to 17 inches) protruding through the canopy. Average d.b.h. of these stands is between 11 and 13 inches. Crown density is over 70 percent.

The nest tree distribution map compiled from field locations was used as an overlay to compare nest tree density with the crown density map delineated from aerial photographs. The highest density of nest trees is in Class III (table 1). Open stands (Class I) contain the lowest density. Within the watershed there were 414 nest trees representing a crude density of one nest per 4.3 acres. However, some areas totaling 144 acres should be excluded because they are different vegetation types: locust thickets (23 acres), meadows (99 acres), and riparian (22 acres). After deducting these 144 acres, the nest tree density in ponderosa pine becomes one per 3.9 acres. Farentinos (1972) found one nest for each 4.4 acres on an area of 178 acres in Colorado.

Table 1.--Nest tree density by crown density classes for ponderosa pine, watershed 8

Crown density class	Average d.b.h. (inches)	Acres	Nest trees No.[1]	Nest trees Density
I	18≥	297	33	1 per 9.0 acres
II	14-17	989	219	1 per 4.5 acres
III	11-13	335	159	1 per 2.1 acres
Total or average		1,621	411	1 per 3.9 acres

[1]Nest trees totaled 414, but three nests were in ponderosa pine trees in riparian vegetation.

The 414 nest trees counted in the census is a minimum figure. A check of three areas within 2 weeks after they were inventoried by the field crew indicated the crew missed about one nest tree in 20 (5 percent). This is a low error, however, with little impact on number of nests in the three crown density classes.

An average nest density for the entire watershed does not adequately describe the squirrel-tree relationships. Even within classes, different densities can be found on small areas depending on how close the area is to the upper or lower limit of the class. Class I had an area with a density of one nest per 20 acres, and Class III has an area with one nest per 0.5 acre. Nevertheless, if nest tree density is an indicator of quality, then the tree crown density classes —which are relatively related to tree size —characterize pine stands with poor, fair, and good squirrel nesting habitat, respectively.

Characteristics of Nest Trees

Variation within the three classes could not be examined in detail from aerial photographs. The next step was to analyze cover site data to describe squirrel habitat in more specific terms. If many different combinations of diameter and density of trees are available such as in watershed 8, a squirrel should select those that best meet its requirements. By examining a large number of nest sites, some condition or combination of habitat components may be described as representing optimum nest cover.

Although 414 nest trees were found within the watershed, not all of them could be completely described because of time constraints. The 302 nest sites selected represent a 73 percent sample of 414 nest trees within the watershed boundary.

Nest Tree Diameter

Nest tree diameter provides insight into the selection of an individual tree within a stand. When the data are grouped into 3-inch diameter classes, four classes (those from 11 to 22 inches d.b.h.) include 80 percent of the nest trees:

Diameter class *Inches d.b.h.*	Nest trees *Number*	Nest trees *Percent of total*
8-10	13	4.3
11-13	64	21.2
14-16	99	32.8
17-19	45	14.9
20-22	33	10.9
23-25	15	5.0
26-28	16	5.3
29-31	7	2.3
32-34	6	2.0
35≥	4	1.3
Total	302	100.0

The mean d.b.h. (17.4 inches) is in the lower limit of the 17- to 19-inch class interval. The model class of nest trees is the 14- to 16-inch d.b.h. with 33 percent of the trees.

No nest trees were smaller than 8 inches, and trees above 22 inches diameter (older mature trees) account for 16 percent of the total. The largest tree selected for a nest was 38 inches. If trees of all diameters are available in the watershed, those from 14 to 16 inches d.b.h. with an optimum of 15 inches are most likely to be selected for nest trees by squirrels.

The largest trees selected for nests were found on plots with the largest average tree diameters (table 2). Eighty-four percent of the nest inventory plots had trees whose diameters were larger than that of the nest tree. The tabulation below presents the frequency distribution of average d.b.h. of all trees on the plots:

Table 2.--Plots classified by density, with average diameter at breast height (d.b.h.) of the stand and of the nest trees

Stand density (trees/acre)	Plots	Average d.b.h. of-- Stand	Nest tree
	No.	- - - *Inches* - - -	
≤ 50	12	20.2	22.7
51-100	44	17.1	22.7
101-150	50	14.0	20.0
151-200	52	12.3	16.7
201-250	76	12.0	14.7
251-300	47	11.6	14.8
301-350	13	11.4	14.4
351≥	8	10.8	12.9
Total	302		

Diameter class	Nest inventory plots	
Inches d.b.h.	*Number*	*Percent of total*
8-10	17	5.6
11-13	195	64.6
14-16	50	16.6
17-19	21	6.9
20-22	13	4.3
23≥	6	2.0
Total	302	100.0

Of 302 plots, 195 (65 percent) had an average d.b.h. in the 11- to 13-inch class and 50 (16 percent) were in the 14- to 16-inch class. These two classes account for 81 percent of all inventory plots. This high percentage indicates squirrels have a strong tendency to select the smaller stands for cover, particularly those in the 11- to 13-inch d.b.h. range. Trees in this diameter class generally have a denser crown and would provide more protection from weather than large older trees.

Vigor and Position

Two vigor classes (B and C) account for 76 percent of the trees used for nests:

Vigor class	Nest trees *Number*	*Percent of total*
AA	17	5.6
A	55	18.2
B	125	41.4
C	105	34.8
Total	302	100.0

A tree did not need a large crown volume to be selected for a nest tree; B and C classes have from 20 to 55 percent of the total tree height in crown.

Each nest tree was classified by its postion relative to other trees on the plot. Ninety-two percent of all nest trees were located in interior positions.

Position	Nest trees *Number*	*Percent of total*
Isolated	0	0.0
Open	12	4.0
Marginal	12	4.0
Interior	278	92.0
Total	302	100.0

A nest tree located in a group of trees, with crowns interlocking or only a few feet apart, offers protection and many escape routes as opposed to a nest tree in a less dense stand.

An indication of tree grouping was obtained by recording the number of trees with crowns interlocking the crown of the nest tree. Results show 75 percent of the nest sites had three or more trees interlocking the crown of the nest tree. Trees interlocking to this extent would provide easy access to and from the nest. Some nest trees had as many as six interlocking trees, and every nest tree had at least one. Also there is an additive effect of crown volume when trees are clumped. A clump of young trees with interlocking branches forms a compact area—more so than older trees with less volume.

Age and Age Class

Annual rings indicate that 66 percent of the nest trees were between 51 and 100 years of age. Only 5 percent of the nest trees were over 200 years old. For management purposes, age of nest trees may be indirectly classified by qualitative characteristics associated with tree age. Age Class II (blackjack) accounted for 53 percent of the nest trees. Eighteen percent were in the youngest age class (Class I). Age Classes III and IV accounted for 29 percent of the nest trees.

Mistletoe Infection

The amount of mistletoe contained in the nest trees was small. Ninety-three percent of the trees had a zero rating. Only two trees had a rating of heavy mistletoe infection. Six percent of the trees recorded in the timber inventory had some mistletoe in their crowns, which would indicate a light infection in the watershed.

Dominance Class

Tree dominance indicates the amount of light a crown receives at different levels in the forest canopy. Nearly three-fourths of the 302 nest trees were codominants, again indicating squirrels prefer a crowded tree within a group for cover:

Dominance class	Nest trees Number	Percent of total
Isolated	4	1.3
Dominant	65	21.5
Codominant	217	71.8
Intermediate	15	5.0
Overtopped	1	.4
Total	302	100.0

Nest Location

Abert squirrels seldom built more than one nest in the same tree. Only four trees were found with two nests; none had more. One large pine containing two nests was found in an open area surrounded by several large Gambel oak. Otherwise, the nest trees were not different from those normally selected.

Eighty percent of the nests were located on a limb next to the tree trunk (fig. 3). Only 5 percent were located in the fork of a tree, even though 80 percent of the inventory plots had forked trees. Those nests (15 percent) located further out on a limb were mostly in "witches' brooms" of ponderosa pine twigs.

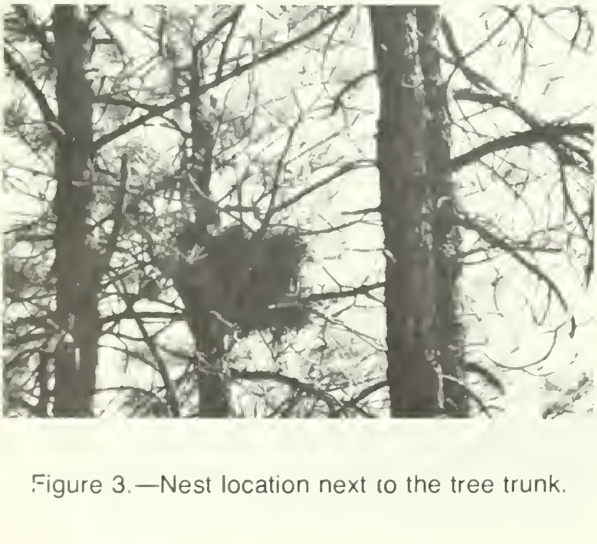

Figure 3.—Nest location next to the tree trunk.

A second location factor is height of the nest in a tree. Comparing tree height to nest distance from the ground indicates a favored zone for nest location within the forest canopy from 30 to 50 feet above the ground (fig. 4). Seventy-six percent of the nests were located in this 20-foot-wide zone. Equal numbers (12 percent) were located below 30 and above 50 feet. The lowest nest was 18 feet above the ground in a tree 53 feet tall. A tree 90 feet tall had the highest nest (84 feet).

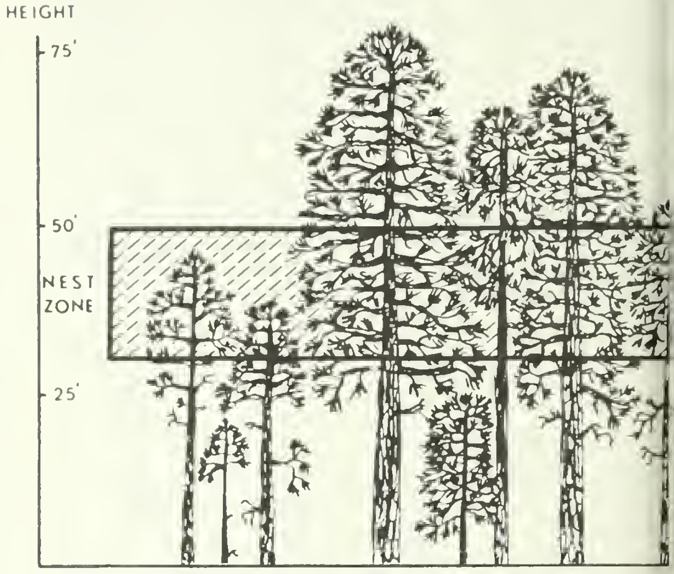

Figure 4.—Nest zone within the ponderosa pine canopy.

Nest Size and Construction

At each nest tree an estimate was made of the nest size in thickness and diameter. Ninety-one percent of the nests were between 10 and 18 inches diameter with an average of 14 inches. Most (90 percent) of the nests were between 6 and 12 inches thick with an average of 10 inches.

Construction material consisted of interwoven twigs and needles from ponderosa pine. In three cases, nests were built from oak leaves instead of ponderosa pine twigs. Material for lining the nest almost always includes dry grasses. Other materials used were plastic bags, horse hair, rabbit fur, and Spanish moss.

Characteristics of Trees Surrounding the Nest Tree

Experience gained while locating the nest trees suggested that the probability of finding a nest was directly related to tree density and tree diameter. If squirrels purposely were selecting cover sites with high tree densities, tree density on areas they have selected should be higher than the watershed average.

Density

Nest tree inventory plots had greater density of trees than timber inventory plots for every tree diameter class but one (30 inches d.b.h., table 3). The greatest difference was in the 12-inch class.

Table 3.--Average number of trees per acre on timber inventory plots and nest tree inventory plots, by d.b.h. class

Size class (Inches d.b.h.)	Timber inventory	Nest-tree inventory	Difference
	- - - - *Trees/acre*	- - - -	
8	36.0	51.8	+15.8
10	29.9	47.4	+17.5
12	16.8	35.0	+18.2
14	10.1	23.4	+13.3
16	4.6	13.7	+ 9.1
18	3.9	6.8	+ 2.9
20	2.5	4.9	+ 2.4
22	1.6	3.0	+ 1.4
24	1.1	2.0	+ .9
26	1.1	1.3	+ .2
28	.7	1.0	+ .3
30	.7	.5	- .2
32	.1	.5	+ .4
Total	109.1	191.3	+82.2

Nest inventory plots were separated into eight classes based on the number of trees per acre. Stand densities from 51 to 300 trees per acre account for 89 percent of all nest sites:

Trees per acre	Nest trees	
Number	*Number*	*Percent of total*
≤ 50	12	4.0
51-100	44	14.6
101-150	50	16.6
151-200	52	17.2
201-250	76	25.2
251-300	47	15.5
301-350	13	4.3
351≥	8	2.6
Total	302	100.0

The distribution is moderately uniform in this density range.

Basal area is the most frequent measure used by foresters to express tree density (Husch 1963). When nest inventory plots are stratified by basal area, the frequency distribution shows three classes from 101 to 250 square feet per acre accounting for 84 percent of the nest sites. The highest percentage (36 percent) of plots was in the 151 to 200 square-foot-per-acre class:

Basal area per acre (*square feet*)	Nest inventory plots	
	Number	*Percent of total*
≤ 50	0	0.0
51-100	18	6.0
101-150	69	22.8
151-200	108	35.8
201-250	77	25.5
251-300	22	7.3
301≥	8	2.6
Total	302	100.0

Canopy Coverage, Exposure, and Ground Cover

Data presented so far have indicated that most nest trees should be found in areas with a high crown density. Of 300 inventory plots, 88 percent had over 61 percent canopy coverage. Average canopy coverage increased from 58 percent with 75 trees per acre to 88 percent at 300 trees per acre. These figures are probably a little high (5 to 10 percent) due to a tendency to overestimate canopy coverage when using a spherical densiometer.

Some investigators (Keith 1965, Farentinos 1972) have suggested there is an association between exposure and nest location in a tree. Both the nest site and percent slope affect the amount of radiation received at the nest.

A chi-square test indicated no interaction, however, between nest exposure in a tree and exposure of the nest tree on a site. Thus, nest selection within a tree crown is probably independent of exposure and is not affected by slope of the site.

Woody and herbaceous understory vegetation is conspicuously absent from the nest sites. Litter comprised in excess of 81 percent of the ground cover on 96 percent of the plots, giving the forest floor a clean appearance. The lack of grasses, forbs, and shrubs is associated with the high tree density and canopy coverage, which inhibits herbaceous growth.

Tree densities that prevent herbaceous growth accumulate large amounts of tree litter. As this material decomposes it apparently creates a favorable condition for certain fungi that are sought by squirrels for food throughout the year (fig. 5).

Figure 5.—An Abert squirrel has been digging in pine litter for fungi.

Slope and Position on Slope

Fifty-nine percent of the plots were on slopes of less than 10 percent. Fifteen percent were on slopes greater than 20 percent. The steepest slope with a nest tree was 45 percent. The middle slope position accounted for 42 percent of the nest sites. A middle position may be selected by squirrels because it is not subject to as much wind as the upper slopes (Buck 1964) and is less affected by nighttime cooling than lower slopes (Rosche 1958, Bergen 1969). The lower slopes had 23 percent of the nest trees; the upper had 35 percent.

Oak Associated with Cover Sites

Patton and Green (1970) have shown that hollow Gambel oaks are used by squirrels for nests (dens). In watershed 8, none of the leaf nests were in oak trees, even though 124 (41 percent) nest inventory plots had oak trees over 8 inches in diameter that presumably could be used as nest trees. One reason for not building nests in oak trees is because they are deciduous and the nest would be exposed in the winter.

During the nest inventory, no Gambel oak den trees were found. After the inventory was completed, however, squirrels instrumented with radio transmitters were tracked and found to be staying overnight in hollow oak. Thus, oaks may be used more than can be determined by inventory methods or relying on sight observations.

Oaks are probably more important to squirrels as a source of food than for nest trees. Acorns constitute as much as 40 percent of the fall diet when a good crop is available (Stephenson 1974). Trees in the 12- to 14-inch d.b.h. class are considered the best acorn producers (Reynolds et al. 1970). Timber inventory data from watershed 8 indicate 2.9 oaks per acre in the 12- to 14-inch d.b.h. class. The average diameter of 297 oaks over 8 inches d.b.h. on 124 sites selected by squirrels was 13.4 inches d.b.h. At present, there are no data available to compare the number of squirrel nest trees in ponderosa pine stands with and without oak.

Oak trees in watershed 8 were frequently used for den trees by red squirrels. On one occasion when a red squirrel had just placed a cone in a large hollow tree, an Abert came in behind him and removed the cone.

Cone Production at Cover Sites

Larson and Schubert (1970) have determined that cone production of single ponderosa pine trees is a function of tree size and vigor. The largest and most vigorous isolated trees are the best cone producers. A 40-inch tree produces over 20 times more cones than a 20-inch tree:

Diameter class	Cone production
Inches d.b.h.	*Number*
12-16	6
16-20	21
20-24	75
24-28	139
28-32	218
32-36	306
36-40	446

Although the best cone producers are the largest trees, they are not present in high numbers. Trees 20 inches d.b.h. and larger account for 7.8 trees per acre in watershed 8. In the nest tree inventory the same tree sizes amounted to 13.2 trees per acre (table 3).

Fifty-six percent of the sites selected for nests had one or more trees over 20 inches capable of producing cones. Although small trees do not produce many cones, when present at high tree densities, their combined production could be significant. A stand table prepared for sites most often selected for cover shows that 74 percent or 720 cones per acre are possible from trees 12 to 20 inches d.b.h. (table 4). In reality cone production would probably be less than indicated because most of the trees will have an interior position. The significant factor is that nest sites had some trees either at or adjacent to the site that were capable of producing cones.

Table 4.--Cone production at sites most often selected for cover

Size class (Inches d.b.h.)	Cones per tree	Trees[1] per acre	Cones per acre	Cumulative percent
	- - - *Number* - - -			
12-16	6	99.0	594	61
16-20	21	6.0	126	74
20-24	75	2.3	173	92
24-28	139	.4	56	98
28-32	218	.1	22	100
Total		107.8	971	

[1]Trees between 8 and 12 inches d.b.h. account for 135 trees per acre, but they do not contribute to the cone crop.

Figure 6.—Good squirrel cover contains a large number of small groups of trees (crown density class III), but with some groups of larger trees in the stand.

CONCLUSIONS AND MANAGEMENT APPLICATIONS

The evidence in this study indicates tree density, diameter, and a grouped distribution of trees are the most important components of Abert squirrel nest cover. In the right combinations these factors provide squirrels with optimum conditions necessary for nest protection. Cover factors for nest site selection have well defined upper and lower limits. Data collected in the nest inventory can be brought together to describe the conditions most often selected by the Abert squirrel for cover in watershed 8 of the Beaver Creek Watershed, an area reasonably representative of both "pine country" and "squirrel country" in Arizona.

A Description of Abert Squirrel Cover Sites

The best cover conditions are found in uneven-aged ponderosa pine stands with trees spaced in small even-aged groups within the stand. These pine stands have densities between 201 and 250 trees per acre (fig. 6). Average tree diameter for the stand is between 11 and 13 inches d.b.h., but small groups of larger trees are present which produces a mosaic of height groups. Basal area of trees over 8 inches d.b.h. in the stand is between 151 and 200 square feet per acre. Gambel oak is found in the stand in densities of one to two trees per acre in the 12- to 14-inch d.b.h. class.

A typical nest tree within a stand is a codominant, interior pine with its crown making up 35 to 55 percent of the tree height. It is usually a blackjack pine between 50 to 100 years old with a diameter of 14 to 16 inches d.b.h., but may not be the largest tree in the stand. Several adjacent trees of similar size have their crowns touching or interlocking, thereby forming a group with several escape routes.

The nest itself is most often located on a limb against the tree trunk between 30 and 50 feet above the ground. It can face in any direction. The nest site has a canopy coverage greater than 80 percent on a slope of 10 percent or less. Optimum site characteristics include ground cover of at least 80 percent litter on a middle slope position.

Evaluating Squirrel Habitat

Wildlife biologists need to be able to determine the quality of squirrel habitat and how quality is changed by forest succession and forest management practices. Criteria describing cover in this study are being combined with food habits data from other studies to develop an Abert squirrel habitat model. This model will emphasize the ranking of habitat quality (poor, fair, etc.) as determined by different combinations of tree sizes and densities.

The criteria used in the model must be validated in different areas before they can be applied in general to all ponderosa pine forests. In the meantime biologists can use the description of optimum cover as a standard for comparing squirrel habitat in other areas.

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Describes the characteristics of ponderosa pine trees and stands selected by the Abert squirrel for cover. Presents data on basal area, tree density and size, tree vigor, dominance and age class, nest location, and nest tree density in a pine forest. Discusses the data's relevance for evaluating the quality of Abert squirrel habitat.

Keywords: Abert squirrel, ponderosa pine, habitat evaluation, squirrel cover.

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Keywords: Abert squirrel, ponderosa pine, habitat evaluation, squirrel cover.

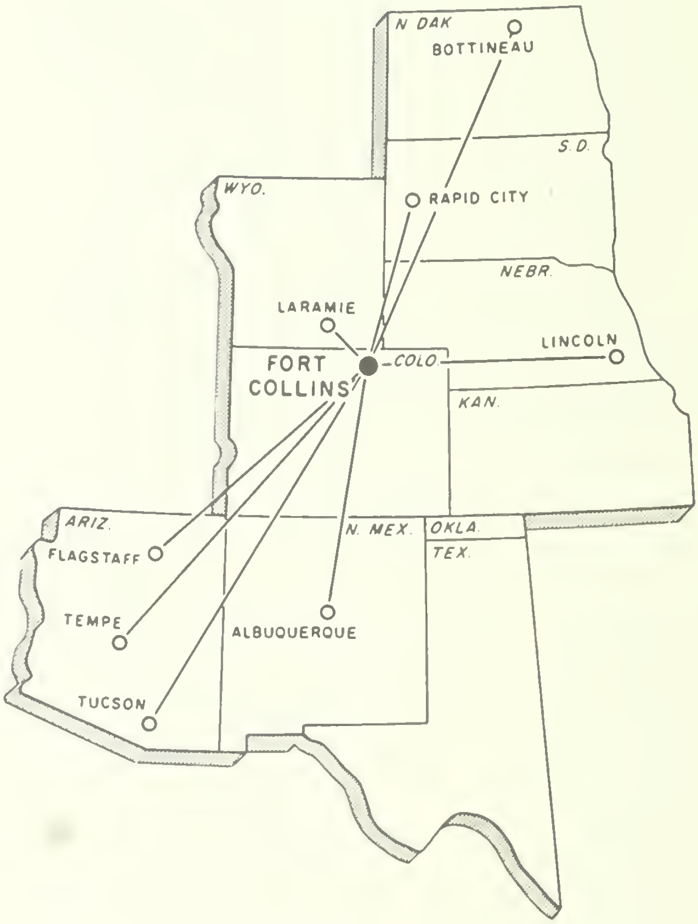
COMMON AND SCIENTIFIC NAMES OF PLANTS AND ANIMALS MENTIONED

Plants

Aspen	*Populus tremuloides*
Ceanothus, Fendler	*Ceanothus fendleri*
Clovers	*Trifolium* spp.
Fescue, Arizona	*Festuca arizonica*
Geraniums	*Geranium* spp.
Grama, blue	*Bouteloua gracilis*
Junegrass	*Koeleria cristata*
Locust, New-Mexican	*Robinia neomexicana*
Muhly, mountain	*Muhlenbergia montana*
Oak, Gambel	*Quercus gambelii*
Peavine	*Lathyrus* spp.
Pine, ponderosa	*Pinus ponderosa*

Animals

Bobcat	*Lynx rufus*
Coyote	*Canis latrans*
Deer, mule	*Odocoileus hemionus*
Dove, mourning	*Zenaidura macrocura*
Elk	*Cervus canadensis*
Goshawk	*Accipiter gentilis*
Hawk, red-tailed	*Buteo jamaicensis*
Junco, gray-headed	*Junco caniceps*
Nuthatch, pygmy	*Sitta pygmaea*
Rabbit, cottontail	*Sylvilagus nuttallii*
Raccoon	*Procyon lotor*
Squirrel, Abert	*Sciurus aberti aberti*
Squirrel, Kaibab	*Sciurus aberti kaibabensis*
Squirrel, red	*Tamiasciurus hudsonicus*
Swallow, violet-green	*Tachycineta thalassina*
Turkey, Merriam's	*Meleagris gallopavo merriami*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lark Martin

USDA Forest Service
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Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture
Fort Collins, Colorado 80521

June 1975

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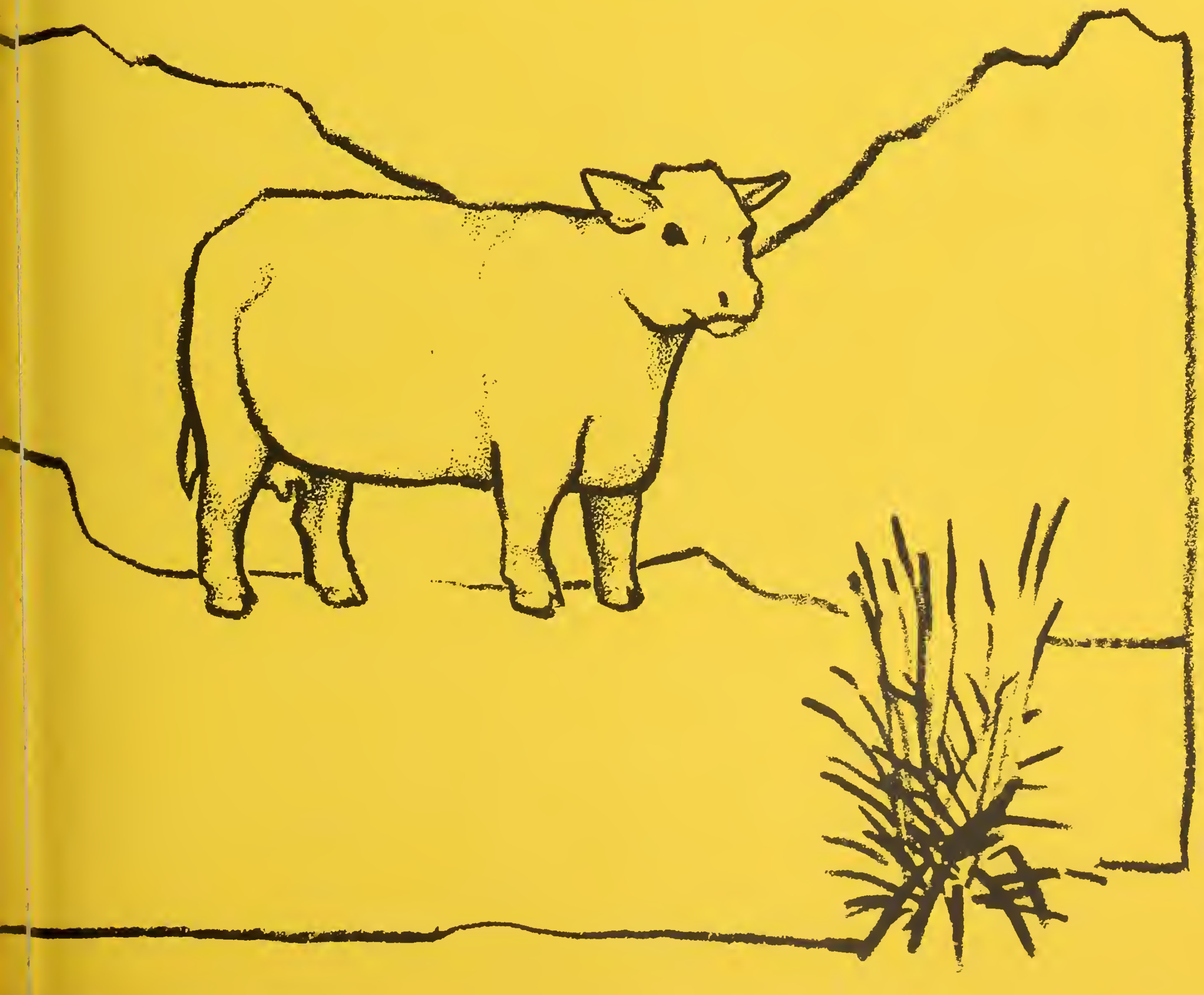

Abstract

Martin S. Clark.
1975. Stocking strategies and net cattle sales on semidesert range. USDA For. Serv. Res. Pap. RM-146, 10 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521

The impact of variable forage yields on income from semidesert range was simulated over a 29-year period for several stocking strategies. Stocking factors evaluated were cull age for cows, age of cows at first calf, number of cows per 100 animal units total stocking, several levels of constant stocking, and two plans of flexible stocking. Results indicate that the cow herd should be maximized, that cows should be bred to calve at age 2 and culled at age 8, and that constant stocking at 90 percent of average proper stocking produces relatively high income as well as relatively low risk of overstocking.

Keywords: Range management, semidesert ranges, ranch income.

USDA Forest Service
Research Paper RM-146

June 1975

Stocking Strategies and Net Cattle Sales on Semidesert Range

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[1]Central headquarters maintained at Fort Collins, in cooperation with Colorado State University; author is located at the Station's Research Work Unit at Tucson, in cooperation with the University of Arizona.

Contents

Research Summary

- The impact of variable forage yields on average ranch income was simulated under several stocking strategies for a southern Arizona range over a 29-year period. Stocking factors evaluated included cull age for cows, age of cows at first calf, number of cows per 100 animal units total stocking, several levels of constant stocking, and two plans of flexible stocking.

- Culling at age 8 is recommended, because pregnant 8-year-old cows can be held over and substituted for replacement heifers that should be culled, or for other cows that have failed to conceive. Average net sales were about the same if cows were culled at age 8 as at age 10.

- There is real merit in calving at age 2 if it can be done successfully. Average net sales for herds calving at age 2 exceeded those of herds calving at age 3 by from $223 to $765. The relative advantage increased as the number of cows increased. Yearling heifers should be bred to bulls of a small-boned breed, and first-calf heifers should be pregnancy tested in the fall. Heifers not with calf should be sold.

- The cow herd should be maximized. Net sales per 100 animal units total stocking increased as the number of cows increased under all stocking plans. Net sales for 70-cow herds were about $1,000 greater than for 40-cow herds. If yearlings are rated at 0.6 animal unit, the maximum number of cows per 100 animal units total stocking would be 87, with 4 bulls and 15 replacement yearling heifers. Under price conditions of the study, income from cow-calf production would exceed that of cow-yearling production unless calf crops dropped to 60 percent. At the same price per pound, yearlings would have to weigh 550 pounds to equal their value as 400-pound calves.

- A general shift from cow-calf to cow-yearling operations would reduce the amount of grain fed to cattle and could improve prices by reducing beef production and cattle inventories.

- Flexible stocking (60 to 140 percent of average) is difficult to administer, and the hazards of overgrazing that it imposes are too great to justify its use. Flexible stocking produces relatively high average net sales, but income varies greatly from year to year. Net sales are greatest in poor forage years when animal numbers are reduced, and are lowest in good years when extra animals must be purchased.

- Constant stocking at the average stocking level is impractical, if not impossible, because it results in overstocking about half the time. Overstocking becomes increasingly severe if one dry year follows another, with mounting feed bills, declining range condition, and lowered animal productivity.

- Limited flexible stocking, within the range of 70 to 110 percent of average, is a good system if properly executed. It produced about the same income as constant stocking at 90 percent of average capacity, and with only moderate hazard of overstocking. To maintain animal quality, however, a fixed number of replacement heifers should be retained each year and cows should be culled normally at age 8.

- Grazing damage during drought probably will be less with limited flexible stocking than with constant stocking at 90 percent of the average proper stocking level if the range is grazed yearlong. If a rest rotation system is followed forage plants may come through drought better under constant stocking.

- Constant stocking at 90 percent of average carrying capacity is recommended. This plan resulted in moderate overstocking about 1 year in 3, with severe overstocking only 1 year in 15. The 90 percent level of proper stocking leaves about half of the perennial grass plants ungrazed at the end of an average grazing year.

Stocking Strategies and Net Cattle Sales on Semidesert Range

S. Clark Martin

Introduction

A major problem in making efficient use of forage is that production varies unpredictably from one year to the next. Grass yield may be as low as 60 or as high as 160 percent of the average. How can a southwestern rancher maintain a stable ranching business in the face of such variations in forage yield? How can the fluctuating crop be used so that average income and range condition are both acceptable? What practical compromises can be made between the immediate and long-term needs of the forage plants, the site, the cow, and the rancher?

With planning and effort, the rancher can adjust the distribution, intensity, timing, and frequency of grazing to meet the needs of forage plants. He can also adjust numbers and kinds of livestock carried and sold to meet his need for income. This Paper makes recommendations based on an evaluation of several stocking strategies.

Methods of Study

The objective of this study was to determine how several strategies for coping with year-to-year changes in forage production would affect ranch income. Each strategy was simulated over a 29-year period (July 1, 1941 through June 30, 1970) using records of forage production, animal weights, and prices received for cattle during that period on the Santa Rita Experimental Range, near Tucson, Arizona. Strategies included variations in: the number of bred cows per 100 animal units, age of cow at first calf, cull age for cows, several plans of flexible stocking, and several levels of constant stocking.

Income

The measure of income used to test the various stocking strategies was "net sales," which is defined as the value of animals sold minus the value of weaner calves bought. For most of the comparisons, prices and weights for the classes of animals sold from the range each year were used to compute net sales of livestock for that year. Average net sales for the 29-year period were then calculated from the yearly figures. Additional evaluations were made, using average cattle prices for the 29-year period.

Costs

This study deals only with livestock income and some of the factors that affect it. Ranch costs and expenses for southern Arizona desert ranchers reportedly range from $3,600 to $8,300 per 100 animal units.[2] Because of these extreme differences in ranching expenses, no attempt was made to determine the costs associated with the various stocking plans. Each rancher is his own best authority on costs.

[2] *Dickerman, Alan F., and William E. Martin. 1967. Organization, costs and returns for Arizona cattle ranches. File Rep. 67-6, Dep. Agric. Econ., Univ. Ariz., Tucson.*

The Study Area

The 25,500-acre study area includes eight study pastures and several service pastures or traps. The area ranges in elevation from 3,200 to 4,500 fe[et] above sea level. Annual rainfall is about 12 inches [at] the lowest elevation, and increases with elevation [to] over 16 inches at the highest (fig. 1). Gra[...]

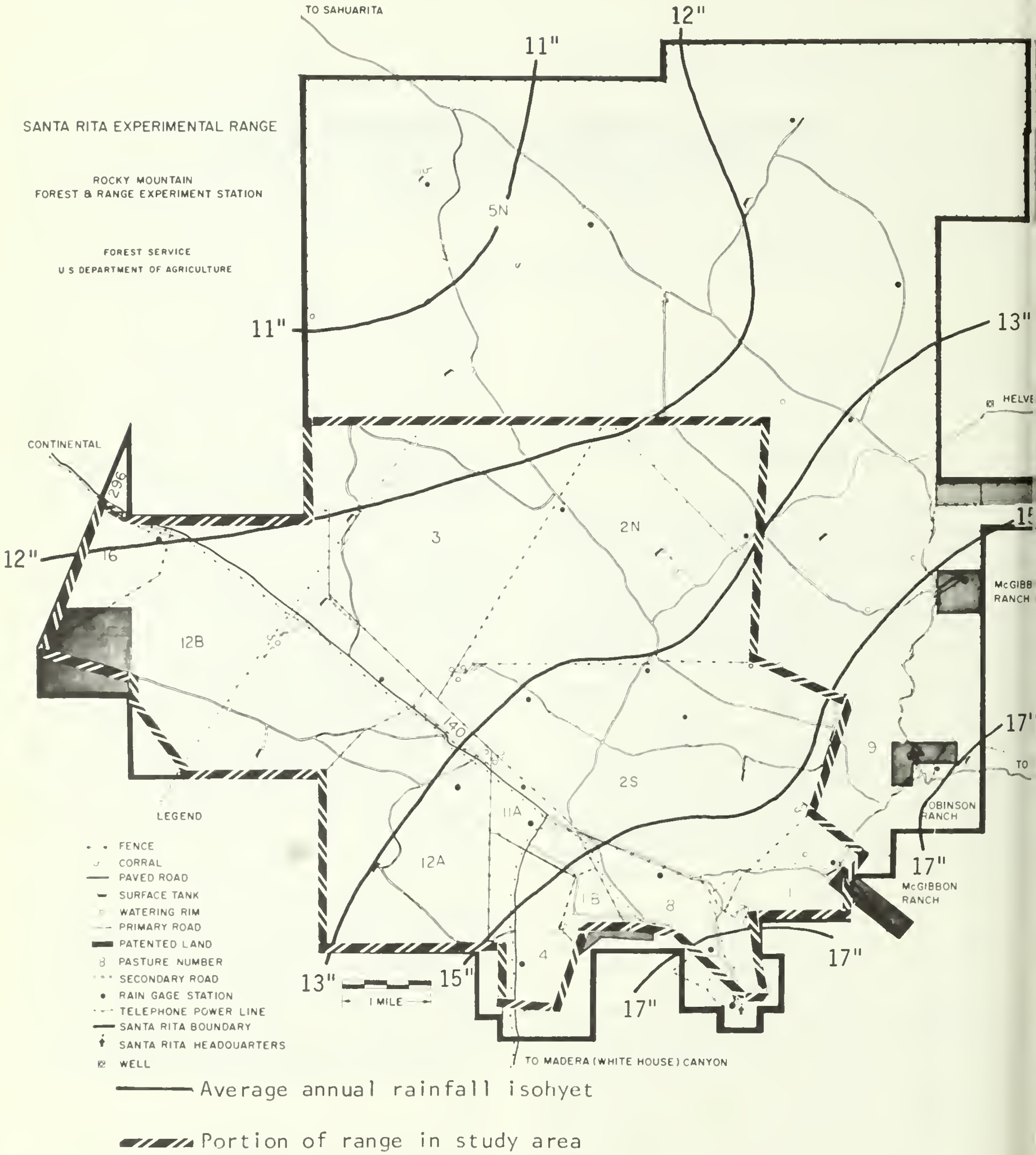

Figure 1.—Map of study area with approximate rainfall isohyets. Major pastures on which stockin[g] is based are 1, 2N, 2S, 3, 4, 8, 12A, and 12B.

production from 1954 to 1967 averaged 82 pounds per acre in the lowest yielding pasture, and 643 pounds per acre in the highest. Total stocking for the eight pastures averaged 283 animal units yearlong, and varied from a low of 220 animal units yearlong in 1965-66 to a high of 400 in 1959-60. An animal unit was considered to be a cow and calf (from date of birth to November 1), or a bull. Calves weaned November 1 were rated as yearlings at 0.6 animal unit. Calculated stocking for 40 percent use of the perennial grass forage for the same period ranged from 159 animal units yearlong in 1965-66 to 368 in 1959-60, and averaged 226.

Stocking Rates

Records of utilization and stocking for the eight pastures were used to compute the estimated proper stocking for the entire range each year from 1941 through 1969. Proper stocking for a pasture was computed as follows:

$$\text{Proper stocking} = \begin{matrix}\text{Average}\\ \text{yearlong}\\ \text{stocking}\end{matrix} \times \frac{40}{\text{Actual use (\%) on perennial grasses}}$$

Proper stocking for the range was the sum of the eight pasture values. Yearly proper stocking levels were expressed as percentages of the average proper stocking for the 29-year period. These relative ratings were rounded to the nearest 10 percent with a maximum value of 140 (fig. 2). These computed yearly stocking levels were used to determine the effect of each stocking strategy on "net sales."

Herd Composition

All calculations were based on a 100-animal-unit herd. Variables tested were: numbers of bred cows, age at first calf, and age to cull cows. The first evaluations were for 40-, 50-, 60-, and 70-cow herds. Additional comparisons for selected strategies were then made for 72-, 78-, and 87-cow herds. Calving was assumed to occur in late winter or early spring (December-March) with heifers bred to calve either at age 2 or age 3. Cows were culled for age around November 1 as they approached their 8th or 10th birthday. Herd composition was computed as of November 1, after fall roundup and sale (table 1). Computations assumed calf crops of 90 percent, no death losses, and no second culling or replacement heifers.

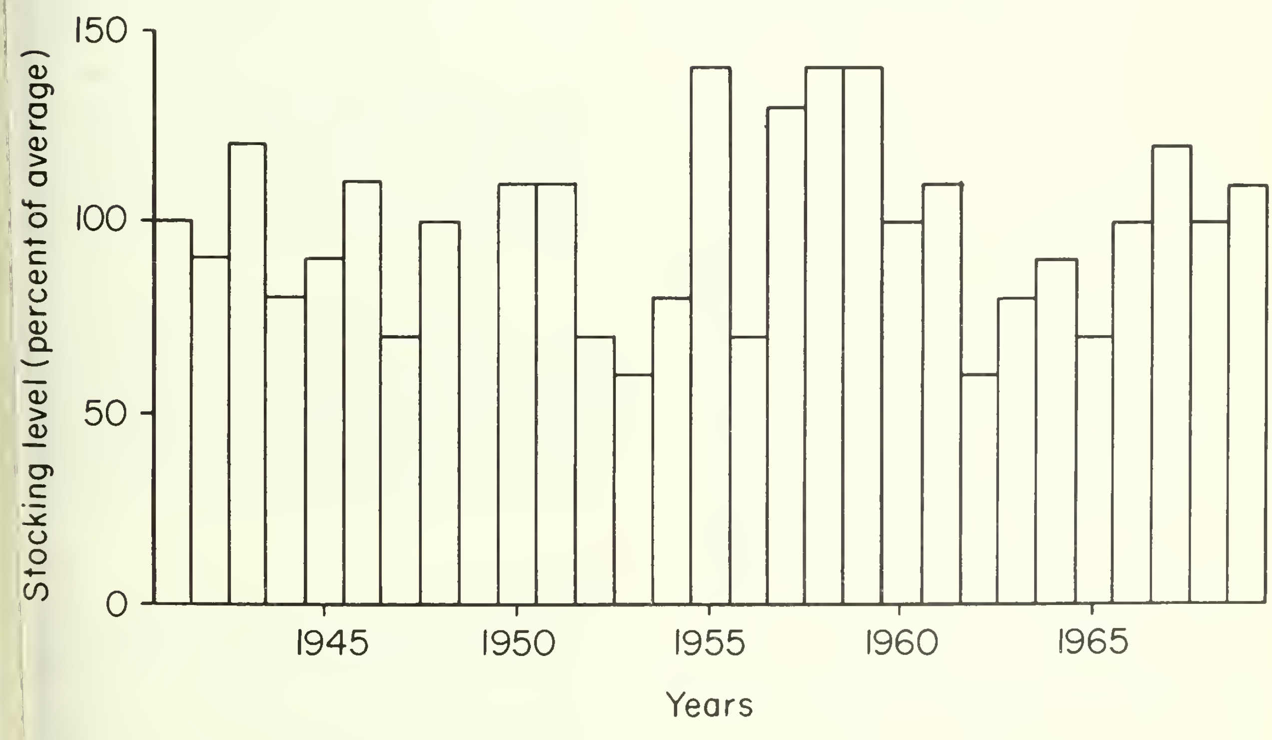

Figure 2.—Stocking level that would have made proper use of the current forage each year during the study, expressed as a percentage of the average stocking level.

Table 1.--Average number of animals of each class per 100 animal units of cattle, with different sizes of breeding herd, calving ages, and culling ages for cows

Stocking plan and animal class	Bred cows per 100 animal units			
	40	50	60	70
CALVE AT AGE 3:				
Cull at age 8 (after 5th calf)--				
Bulls	2	2	3	3
2-year heifers	8	10	12	14
Weaner heifers	8	10	12	14
Holdover weaners	28	35	30	8
Purchased weaners	47	18	0	0
Total number animals	133	125	117	109
Cull at age 10 (after 7th calf)--				
Bulls	2	2	3	3
2-year heifers	6	7	9	10
Weaner heifers	6	7	9	10
Holdover weaners	30	38	38	18
Purchased weaners	51	23	0	0
Total number animals	135	127	119	111
CALVE AT AGE 2:				
Cull at age 8 (after 6th calf)--				
Bulls	2	2	3	3
Weaner heifers	7	8	10	12
Holdover weaners	29	37	44	33
Purchased weaners	61	35	8	0
Total number animals	139	132	125	118
Cull at age 10 (after 8th calf)--				
Bulls	2	2	3	3
Weaner heifers	5	6	8	9
Holdover weaners	31	39	46	36
Purchased weaners	61	35	8	0
Total number animals	139	132	125	118

Stocking Strategies

Three levels of constant stocking were compared with "flexible" and "limited flexible" stocking. The levels of constant stocking were: average, 90 percent of average, and 80 percent of the average proper stocking rate. "Flexible" stocking allowed the number of animal units to fluctuate from 60 to 140 percent of the average proper stocking level, stricl in accordance with the forage crop. "Limit(flexible" stocking restricted the stocking range from 70 to 110 percent of average:

Forage crop	Flexible stocking	Limited flexible stocking
	(percent of average)	
60 or less	60	70
70	70	80
80	80	90
90	90	90
100	100	90
110	110	100
120	120	100
130	130	110
140 or more	140	110

Two plans were tested for culling in years wh forage production was less than the year before. the first plan the priorities were: (1) sell wean calves normally held for sale as yearlings, (2) s replacement weaner heifer calves, (3) sell replac ment heifers (coming 2-year-olds), (4) sell cows fro the breeding herd (oldest cows first). In the secoı plan, old cows were always sold first and replaceme heifers last in order to maintain the replaceme herd.

Priorities for increasing stocking in years wh forage production was greater than the year befo were: (1) if the number of bred cows under 8 years age is less than the number needed to meet t stocking plan for an average year, hold cows th would normally be culled for age;[3] (2) hold calv normally sold as weaners; (3) buy weaner calves.

Effects of Strategies on Net Sales

For herds with 40 to 70 cows, average annual r sales per 100 animal units ranged from $4,621 $6,988 (table 2). The two factors that influenc average net sales most were calving age and numb of cows per 100 animal units.

Calving Age

Average net sales for herds calving at age exceeded those of herds calving at age 3 by fro

[3]The maximum number of bred cows held was t number required for an average year and the option holding cows beyond normal culling age was not co sidered to be available if cows normally were culled age 10.

Table 2.--Average annual net sales per 100 animal units under selected stocking strategies

Stocking plan and animal class	Bred cows per 100 animal units			
	40	50	60	70
CALVE AT AGE 3:				
Cull at age 8--				
Flexible	$5282	$5460	$5804	$5869
Limited flexible	5096	5329	5564	5887
Constant at average	5559	5792	6007	6240
Constant at 90%	5076	5309	5552	--
Constant at 80%	4621	4854	--	--
Cull at age 10--				
Flexible	5468	5725	5743	5850
Limited flexible	5270	5576	5735	5797
Constant at average	5716	6054	6243	6490
Constant at 90%	5234	5572	5789	6006
Constant at 80%	4775	5090	5328	--
CALVE AT AGE 2:				
Cull at age 8--				
Flexible	5705	6058	6327	6599
Limited flexible	5512	5864	6156	6489
Constant at average	5975	6327	6601	6953
Constant at 90%	5489	5839	6146	6496
Constant at 80%	5038	5394	5663	--
Cull at age 10--				
Flexible	5691	6103	6381	6615
Limited flexible	5503	5924	6208	6516
Constant at average	5966	6387	6687	6988
Constant at 90%	5483	5906	6200	6531
Constant at 80%	5028	5451	5716	6076

$223 to $765. The advantage of calving at age 2 was greatest for the 70-cow herds, for which net sales were $500 to $700 greater than for herds calving at age 3. Thus, the advantage of earlier calving increased as the number of bred cows per 100 animal units increased from 40 to 70 cows.

Number of Cows

Net sales also increased consistently as the size of cow herd increased (table 2). Within the range from 40 to 70 cows, increases varied from as little as $12.75 per cow to as much as $34.94. Increases in net sales per unit of cow increase were greater for herds calving at age 2 than for those calving at age 3. Net sales for 70-cow herds averaged as much as $1,000 greater than for 40-cow herds.

Age to Cull

Cull age had no consistent effect on average net sales if cows were bred to calve at age 2. Culling at age 10 increased net sales slightly if cows were bred to calve at age 3, and the advantage was consistently greater for 40- to 50-cow herds than for herds of 60 to 70 cows. These results include no adjustments for changes in productivity of cows with age.

Culling Plan

Simulated net sales were about the same for the two culling plans used in flexible stocking. In practice, however, there would be a real advantage in maintaining the breeding herd if cow numbers were high. If emphasis was on maintaining the cow herd, and if cows were bred to calve at age 2 and were culled at age 8, the number of replacement heifers required each year for a 42-cow herd was always seven. The top seven heifer calves therefore could be selected each year to go into the breeding herd. For a 72-cow herd with a normal replacement of 12 heifers, however, there were years when no heifers were kept, and in others the entire crop of heifer calves was needed for replacement, leaving no opportunity to cull. This problem was avoided if a fixed number of replacement heifers was kept each year, and reductions in time of drought were made by selling the older cows.

Constant Stocking

Net sales under constant stocking were reduced about $470 for each 10 percent reduction in the level of stocking. And, for a given stocking level, changes in calf prices accounted for up to 96 percent of the year-to-year change in net sales. The effect of forage production on net sales was negligible (fig. 3). In real life this is not strictly true, of course, because calf weights and calf crops are affected by forage conditions.

The highest simulated average net sales resulted from constant stocking at the average level of proper stocking. This strategy is not realistic, however, because there were too many years when the range was overstocked. High feed bills and other emergency costs in the poor years can easily outweigh the apparent advantage in net sales.

Since constant stocking at average capacity often results in high feed bills and range deterioration, constant stocking at 90 percent of average capacity is almost certain to be more profitable in the long run. But, how do you know when you are stocked at 90 percent of average capacity? Utilization is one clue. In the average year, about half of the perennial grass plants should be ungrazed at the end of the grazing season. The percentage of ungrazed plants may vary from as low as 10 percent in dry years to 70 to 75 percent in years of high production, but the average over a period of years should be close to 50.

Flexible Stocking

Net sales under all flexible stocking plans were affected only slightly by changes in cattle prices, but were related strongly and negatively to changes from the previous year in forage production. High net sales came when livestock numbers were reduced because forage was scarce. Conversely, net sales were low when the forage crop improved.

Net sales under flexible stocking (60 to 140 percent of average) were second only to constant stocking at the average proper level. Yearly changes in income were extreme, however, with high income when a poor forage year followed a high production year, and low or negative net sales if a good year followed a poor one (fig. 4). Changes in forage conditions accounted for 70 percent of the year-to-year change in net sales, and changes in cattle prices only for 14 percent. Net sales under flexible stocking were low than for constant stocking mainly due to the cost buying stocker calves in years of high fora production. Flexible stocking, like constant stocki at average capacity, can result in high feed bills other expensive emergency measures when a po year follows an extremely good one.

Limited flexible stocking, in which stocki ranged from 70 to 110 percent of the average prop stocking level, produced average net sales $50 $200 less than for flexible stocking—about the sa as for constant stocking at 90 percent of avera capacity. This system eliminated the need to b stocker calves, and net sales were always positive.

Flexible stocking, by forcing the rancher to s extra animals in poor forage years, and buy cattle i good years, may cause him to sell on a depress cattle market and to buy on one that is inflated. O results show, however, that the average impact this marketing disadvantage was not great. F example, if current prices were applied to each yea sales and purchases, average net sales under flexib stocking (a 72-cow herd with cows bred to calve age 2 and culled at age 8) were $6,659. For the sa strategy and herd composition, average cattle pri

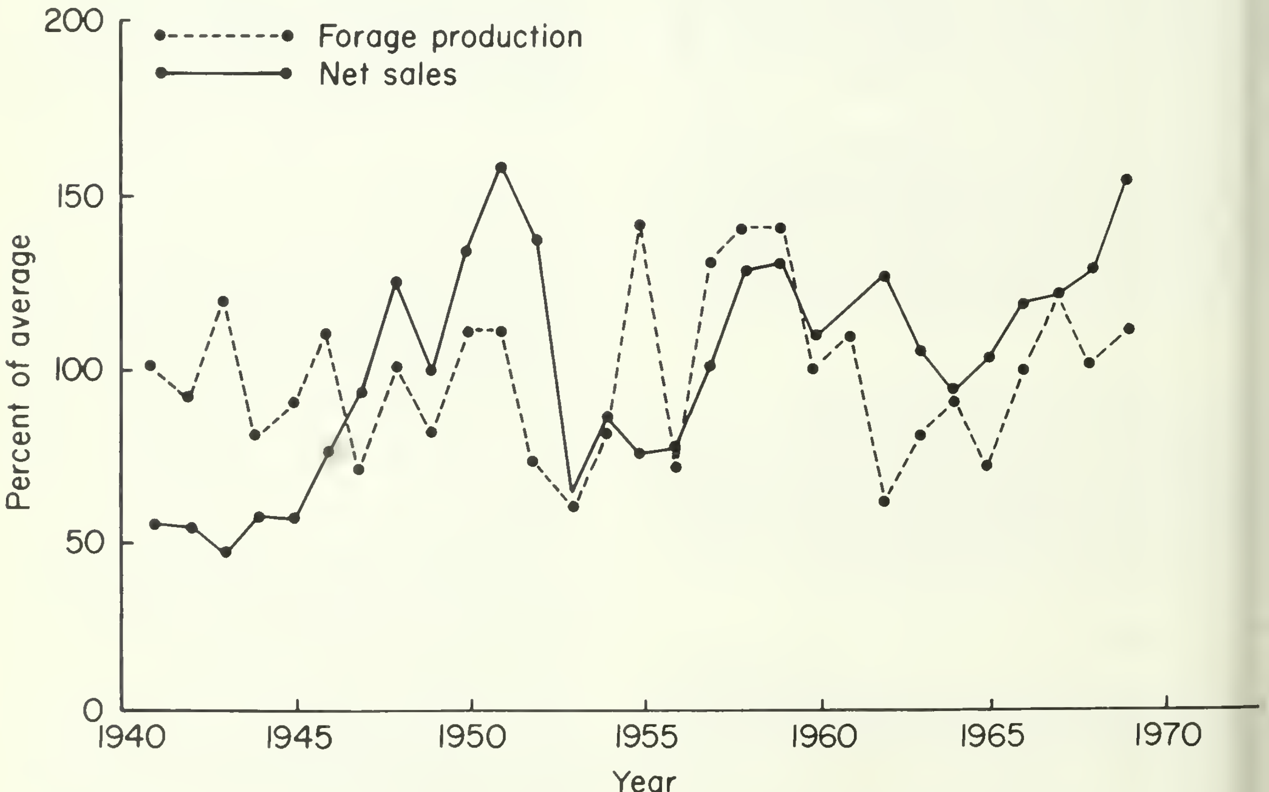

Figure 3.—Relation between relative values for forage production, and net sales under consta stocking at 90 percent of average proper stocking.

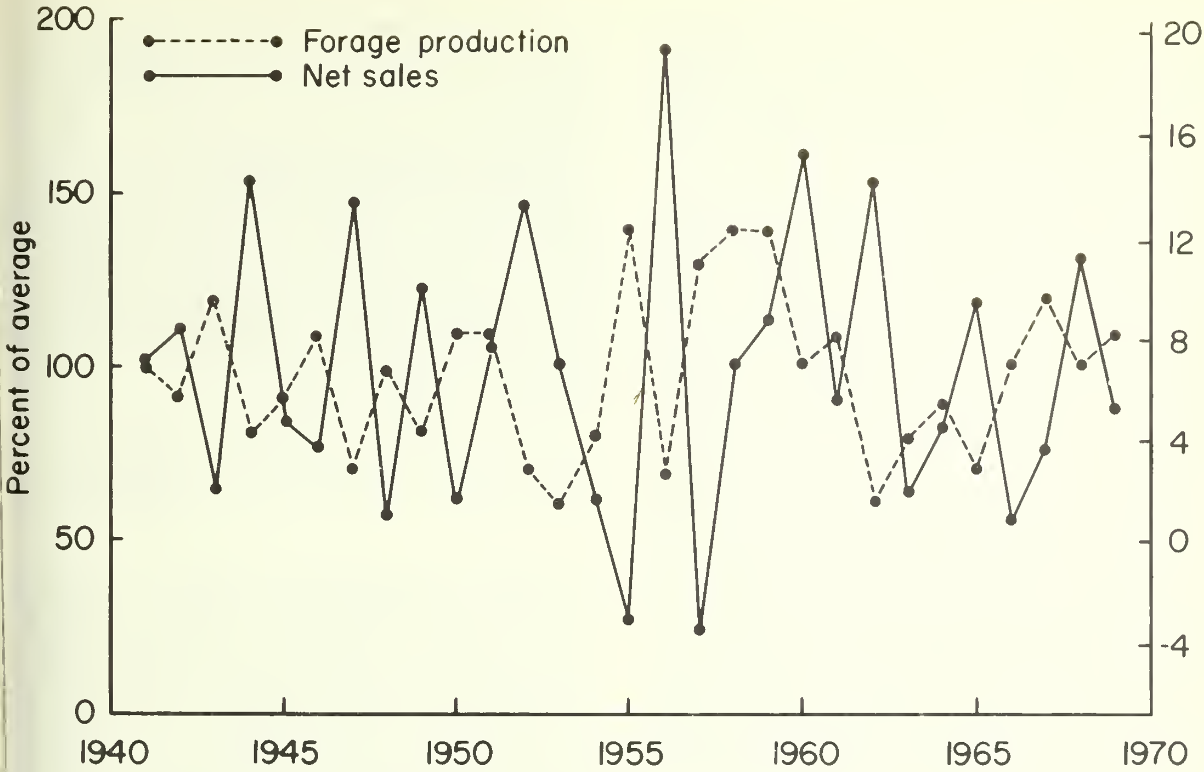

Figure 4.—Relation between forage production and value of net sales under flexible stocking at constant livestock prices. Data are for a 72-cow herd bred to calve at age 2 and culled at age 8, using average prices for the 29-year period.

for the 29-year period would have generated $6,750 in net sales. Thus, the average annual loss per 100 animal units due to selling or buying at current prices was only $91.

Risk of Overstocking

Net sales should not be the only consideration in deciding on a plan of stocking. The hazards and high costs of overstocking in the dry years must also be considered. The apparent risks of overstocking for several of the stocking plans are indicated by the number of years during the 29-year study period when actual stocking would have exceeded the forage supply by given percentages (table 3).

Constant stocking at average capacity and flexible stocking would result in overstocking almost half the time, with 1 year in 5 or 6 being high by over 40 percent. Such overstocking would occur during the summer growing season in dry years when the perennial grasses are most susceptible to damage from repeated close grazing. The costs of such frequent overstocking in damage to the range and high feed bills during drought rule out these systems for both economic and conservation reasons. Main-

Table 3.--Numbers of years in the study period when stocking during the summer growing season under different stocking plans would have exceeded production by given percentage

Stocking plan and range in stocking (Animal units)	Stocking exceeded forage production by--					
	0	1-20%	21-40%	41-60%	61-80%	81+%
	- - - *Number of years* - - -					
Flexible (60-140 AU)	18	3	3	3	0	2
Limited flexible (70-110 AU)	20	2	3	3	1	0
Constant (Average capacity) 100 AU-100)	16	3	4	4	2	0
Constant (90% of average) 90 AU-90)	19	4	4	2	0	0
Constant (80% of average) 80 AU-80)	23	4	2	0	0	0

taining average stocking is particularly harmful when two or more dry years occur together, because the degrees of overstocking increases each year as forage production declines. The impact of flexible stocking is worst when a high production year is followed by a summer of extreme drought.

The hazards of overstocking with constant stocking at 90 percent of average capacity and with limited flexible stocking were about equal in some respects, but there were differences. Both would result in overstocking during the summer growing season about 1 year in 3 with an excess of more than 40 percent about 1 year in 15 for constant stocking and 2 years in 15 for the flexible plan. Both systems would meet the needs of forage and livestock in most years, although some feeding might be necessary in the poorest years. Limited flexible stocking resulted in 2 consecutive years of overstocking only once, 1952 and 1953. Constant stocking at 90 percent of average proper stocking resulted in 3 consecutive years of overstocking once (1952-53-54) and in 2 consecutive years once (1962-63). The degree of overstocking in a 1-year drought or during the first year of a prolonged drought was almost always higher for the limited flexible plan than for constant stocking. But if the drought lasted more than 1 year, overgrazing during subsequent drought years was lower under the limited flexible plan.

Grazing damage during drought also depends on the grazing system. In a prolonged drought, with constant stocking the degree of overgrazing increases each year under yearlong grazing. Appropriate rest-rotation grazing systems normally prevent heavy use of the same area in 2 years in a row. Under flexible stocking, however, overgrazing in the first drought year can be more severe under rotation grazing than under yearlong grazing because the rate of stocking during the summer growing season is much greater.

Cows or Yearlings

Do breeding cows or yearlings make more efficient use of the forage crop? The answer hinges primarily on the relative differences in prices of calves and yearlings, on the relative amount of forage consumed by each class, and on the percentage of calf crops. During the 29-year study period the average sale prices of cattle were: cull cows $107.76, calves $91.88, and yearlings $120.33. For maximum calf production, a breeding herd composed of 87 cows, 4 bulls, and 15 replacement weaner heifers is assumed, with average sales of 63 calves and 14.5 cull cows per 100 units with constant stocking, 90 percent calf crop, and no death losses. If cows calve first at age 2 and are culled at age 8, expected net sales per 100 animal units of stocking then would be:

63 calves at $91.88	=	$5,788.44
14.5 cows at $107.76	=	1,562.52
		$7,350.96

or $73.51 per animal unit grazed.

How do these values compare with income p animal unit of yearlings? A herd composed of cows, 3 bulls, and 11 replacement weaner heif plus 46 carryover weaner calves also constitutes 1 animal units, with all calves held over a full year a sold as long yearlings or finally as cull cows. T income from such a herd with cows calving at ag and culled at age 8 would be:

46 yearlings at $120.33	=	$5,535.18
10.5 cull cows at $107.76	=	1,131.48
		$6,666.66

or $66.67 per animal unit grazed. Thus, rais yearlings would return about $7 less per animal u of grazing than would calves marketed in the fall.

If yearlings are bought, the return per animal u of yearlings is the difference between the calf a yearling price adjusted for forage consumption. Th turns out to be $47.72. Net sales for cows and calv and for raised yearlings decline with the calf cr (table 4). Livestock prices during the study were su that cows and calves always provided a higher retu than yearlings. Only if calf crops dropped to percent would return from purchased yearlin approach that of cows and calves.

Table 4.--Effect of calf crop on net sales fro cow-calf and cow-yearling operations

Calf crop (%)	Value of net sales per animal unit stocking		
	Calf-cull cows	Raised yearlings	Purchased yearlings
90	$73.51	$66.66	$47.42
80	66.15	58.24	47.42
70	57.89	51.02	47.42
60	47.78	46.21	47.42
50	42.47	36.58	47.42

The relative economic advantage of cows ar calves over yearlings depends mainly on differenc in weight and price per pound between calves ar yearlings. We calculated the price that must b received for yearlings of different weights in order bring as much money as would be obtained by sellir calves in the fall. We assumed that 1.67 carryov yearlings were the equivalent of a cow and calf, th net sales from cull cows would be worth 25 percent the value of calves or yearlings sold, and added percent interest to the value of the calf. W considered yearling weights ranging from 350 to 950 pounds, and calf prices of 25 to 65 cents per pound.

The calculations show that if calves and yearlings sell for the same price per pound, yearlings must weight about 550 pounds to bring in as much money as cows and calves (table 5). Yearlings weighing 500 pounds or less must sell at a premium price to be equivalent in value. On the other hand, the break-even price for 650-pound yearlings was from 4 to 10 cents less per pound than for calves. What these figures mean for southern Arizona is that, if calves are held over until the fall of their second year, and if they weigh at least 650 pounds, they stand a good chance of returning net sales superior to those of cows and calves. On the other hand, if calves are held only until late May, they probably will have gained less than 150 pounds and usually will produce less income than if they had been sold in the fall.

Table 5.--Break-even price for yearlings, compared to that for 400-pound calves sold in the fall

Weight of yearling (pounds)	Comparative price per pound for calves sold in fall				
	$0.25	$0.35	$0.45	$0.55	$0.65
	Break-even price for yearlings				
350	$0.40	$0.56	$0.71	$0.87	$1.03
450	.31	.43	.56	.68	.80
550	.25	.35	.45	.56	.66
650	.21	.30	.38	.47	.56
750	.18	.26	.33	.41	.48
850	.16	.23	.29	.36	.42
950	.15	.20	.26	.32	.38

Discussion

The results of this study do not fully support such opular beliefs as: (1) cow herds should not exceed 0 percent of the total stocking, (2) cow-yearling perations produce more income than cow-calf perations, (3) heifers should be bred to calve first at ge 3, and (4) stocking must be flexible. Rather, the esults indicate that (1) the breeding herd should be aximized by calving at age 2 and carrying a inimum number of replacement heifers, and (2) ocking should be relatively constant, but at a level omewhat below the average "proper" stocking level.

Our results show no advantage in keeping the cow erd to 60 percent of total stocking. Regardless of ther conditions, net sales increased as the size of the reeding herd increased. It was apparent, however, that high cow numbers could seriously upset the breeding program if culling practices under flexible stocking emphasized maintaining the cow herd. The reason is that, in years of high production following a drought, the entire heifer crop must be held for replacement and none can be culled. This problem can be overcome by holding a fixed number of replacement heifers each year and culling older cows in drought. Average differences in net sales between the two culling practices were negligible. And, for both systems, average net sales increased as the percentage of breeding cows increased. This suggests that a reduced breeding herd can be recommended only if it is more profitable to market yearlings than calves.

At average prices during the study, cow-calf units would produce more income per animal unit of stocking than cow-yearlings units, so long as the calf crop was 60 percent or better. And, at equal prices per pound, yearlings would have to weigh 550 pounds to produce as much income as 400-pound calves. In southern Arizona, yearlings held over a full year and sold in the fall might easily weigh enough to justify keeping them, but if they are held only until the following May they probably will not. This introduces another consideration. If yearling numbers are increased in the fall in a year of high forage production, they should be sold, or at least removed from the range, the following May or June to avoid possible severe overgrazing during the summer growing season.

The relative merits of marketing range animals as calves or yearlings also depend on economic conditions. Abundant, cheap feed grains make light weight cattle a good buy for the feeders and favor cow-calf production. Expensive feed shifts the advantage toward the cow-yearling production. Cattle prices also have an impact. Sustained periods of high calf prices tend to increase cow numbers as well as the number of animals marketed. Recent developments suggest that a general shift from cow-calf to cow-yearling operation may be in order. High feed prices in 1974 and 1975 and lower prices for slaughter beef caused calf prices to drop sharply, slowed the flow of animals to market and resulted in high cattle numbers. A shift to cow-yearling operation could reduce the number of animals marketed by about 27 percent. This could relieve the apparent oversupply of beef as well as reduce cattle inventories. Cow-yearling production would greatly reduce the amount of grain fed to beef cattle because animals would enter the feed lot 200 to 400 pounds heavier and because about 27 percent few animals would be fed.

Calving at age 2 consistently resulted in higher net sales than did calving at age 3. The reason, of course, is that the younger calving provides more bred cows per 100 animal units. Successful calving at age 2 may require special effort, however. Breeding heifers to bulls of a small-boned breed may reduce calving problems. Also, first-calf heifers should always be pregnancy tested. Any heifer not with calf should be sold. Her place in the herd can be filled by holding a good pregnant cow that would otherwise be culled for age. This points up the value of culling at age 8 rather than at 10. Many of these 8-year-old cows can be held an additional year or two if they are needed to replace younger cows that are culled because they are not with calf or for other reasons.

One appeal of flexible stocking is that it allows more complete use of the forage in high production years. This is commonly believed to increase ranch income, thereby offsetting low income and high expense in years of low production. The results of this study show, however, that net sales per 100 animal units obtained by increasing stocking to 120, 130, or 140 percent of average in the best years were only $100 to $200 greater than for constant stocking at the 90 percent level or for limited flexible stocking. In practice, this small monetary advantage would probably be offset by the apparent disadvantages of the flexible system. These include the sheer difficulty of estimating forage crops and adjusting animals accordingly, possible serious damage to the range in years of low forage production when stocking is high due to high production the year before, the administrative costs of buying ex animals to stock the range in good years, t possibility of introducing parasites or disease w cattle from off the range, and the natural reluctar to cull as heavily as necessary for the good of t range in years when forage production is low.

An easier plan to administer is constant stocki at a conservative rate, say 90 percent of avera carrying capacity. Under this system, a fixed numb of replacement heifers are held each year and t number of calves and older cows sold each year relatively constant. The rancher who follows constant stocking plan still needs to make su however, that he is not overestimating the avera capacity of his range. Constant stocking at percent of average capacity will have a mu different longtime effect on the range than w stocking at average. It is almost certain that stocki at 90 percent of average will be more profitable the long run, because production of the moderat grazed range will be maintained or improved, wh that of heavily grazed range will almost sur decline. Constant stocking at 90 percent of avera proper stocking, with some stocking reductions prolonged severe drought, appears to offer stabil of operation, relatively high income, and moderate low risk of damage to the range or financial cri during drought.

Martin S. Clark.
1975. Stocking strategies and net cattle sales on semidesert range. USDA For. Serv. Res. Pap. RM-146, 10 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521

The impact of variable forage yields on income from semidesert range was simulated over a 29-year period for several stocking strategies. Stocking factors evaluated were cull age for cows, age of cows at first calf, number of cows per 100 animal units total stocking, several levels of constant stocking, and two plans of flexible stocking. Results indicate that the cow herd should be maximized, that cows should be bred to calve at age 2 and culled at age 8, and that constant stocking at 90 percent of average proper stocking produces relatively high income as well as relatively low risk of overstocking.

Keywords: Range management, semidesert ranges, ranch income.

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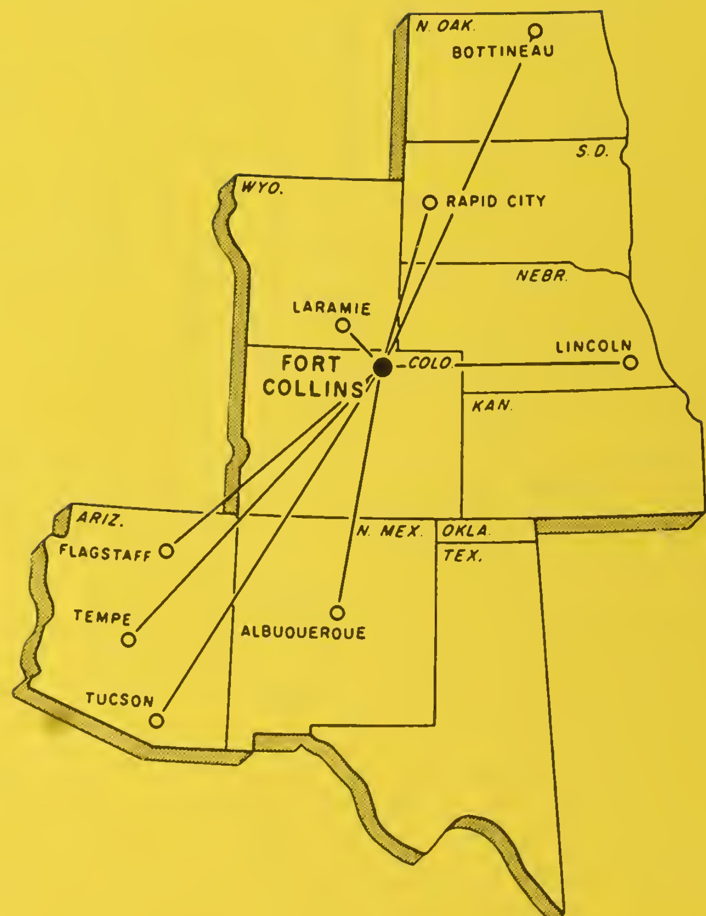

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Rocky Mountain Forest and
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Forest Service
U.S. Department of Agriculture
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Logging Damage to Advance Regeneration on an Arizona Mixed Conifer Watershed

June 1975

Gerald J. Gottfried and John R. Jones

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Abstract

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1975. Logging damage to advance regeneration on an Arizona mixed conifer watershed. USDA For. Serv. Res. Pap. RM-147, 20 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521

Old-growth southwestern mixed conifer stands commonly have considerable advance regeneration, but one-cut overstory removal, with subsequent slash piling, typically has destroyed most of it. Furthermore, except where aspen suckers abundantly, subsequent regeneration is usually very slow. This study examines damage to advance regeneration where special care was taken to avoid damage. With the selection method, 50 percent was destroyed, and in a one-cut overstory removal, 65 percent. The overstory removal area was left seriously understocked. Logging modifications are recommended to further reduce damage.

Keywords: Advance regeneration, logging damage, mixed conifer forests.

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Research Paper RM-147

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Logging Damage to Advance Regeneration on an Arizona Mixed Conifer Watershed

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[1]*Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University; Gottfried is assigned to the Station's Research Work Unit at Tempe, in cooperation with Arizona State University; Jones is assigned to the Station's Research Work Unit at Flagstaff, in cooperation with Northern Arizona University.*

Contents

Logging Damage to Advance Regeneration on an Arizona Mixed Conifer Watershed

Gerald J. Gottfried and John R. Jones

INTRODUCTION

Southwestern mixed conifer stands occupy about 2.5 million acres in Arizona, New Mexico, and southern Colorado. They often have considerable advance regeneration—young trees that have already survived the critical first years and passed the period of very slow early growth. If enough of these small trees survive logging operations, a harvested area is already restocked, and the next rotation is significantly shortened. Where logging removes large timber volumes, however, much of the advance regeneration is typically destroyed.

Saving this advance regeneration is important in the Southwest, where natural regeneration of openings is often slow (Jones 1967) and planting is costly. In this case study we found that, even when special care is taken, conventional logging reduced the abundance and distribution of advance regeneration below acceptable stocking levels.

THE STUDY AREA

The study area is a gaged watershed on the Apache-Sitgreaves National Forest in east-central Arizona, drained by the East Fork of Willow Creek. Elevations range from 8,800 to 9,300 feet. Slopes average 20 percent. Soils are a stony silty clay loam, and do not erode readily. Parent material is basalt.

Average annual precipitation is 29.6 inches. Winters are normally mild, but snow cover commonly persists from November into April. May and June have many windy days and are almost always very dry. In July and August, rain falls on about 50 percent of the days, mostly as daytime thundershowers, some of them heavy. September and October often are dry but have occasional high water-yielding storms.

The heavy soils, abundant snow, and warm days in winter make roads and soils susceptible to damage from trucks and tractors, thus restricting winter logging. Skidding and hauling are occasionally halted in summer and fall to avoid damage to saturated slopes and roads. Extreme fire danger sometimes slows logging in May and June. Trees with decayed butts, and occasional strong winds, sometimes frustrate attempts at directional felling.

The watershed covers 492 acres, 468 of which were virgin forest prior to the study. The other 24 acres are a narrow meadow along the creek. All forested areas were stocked with at least 25 square feet of basal area in trees 7 inches in diameter breast high (d.b.h.) and larger, in 1970. Average timber volume was 23,800 board-feet per acre. Many trees, especially Douglas-fir, were more than 30 inches d.b.h. The species, in descending order of volume, were Douglas-fir, Engelmann spruce, ponderosa pine, aspen, white fir, southwestern white pine, blue spruce, and corkbark fir.[2] Composition and structure were variable. All of the species, with the exception of blue spruce, occurred widely over the watershed. Some species were particularly abundant in certain areas: 27 acres were dominated by aspen with a partial understory of conifers; 8 acres were dominated by Engelmann spruce.

There were some single-storied patches, but even these had some advance regeneration. Most of the stands had two or more stories. Patches and thickets of saplings were common. Much of the forest was a small-patch mosaic of different structures.

Our evaluation of logging damage to advance regeneration is part of a larger study on Willow Creek. The overall objective is to test the effects of a combination of cutting methods, based on stand conditions, on the timber, water, and wildlife resources. Two different treatments were applied: the selection method and overstory removal (fig. 1). On the 114-acre area where the selection method was

[2]Common and scientific names of species mentioned are listed on page 20.

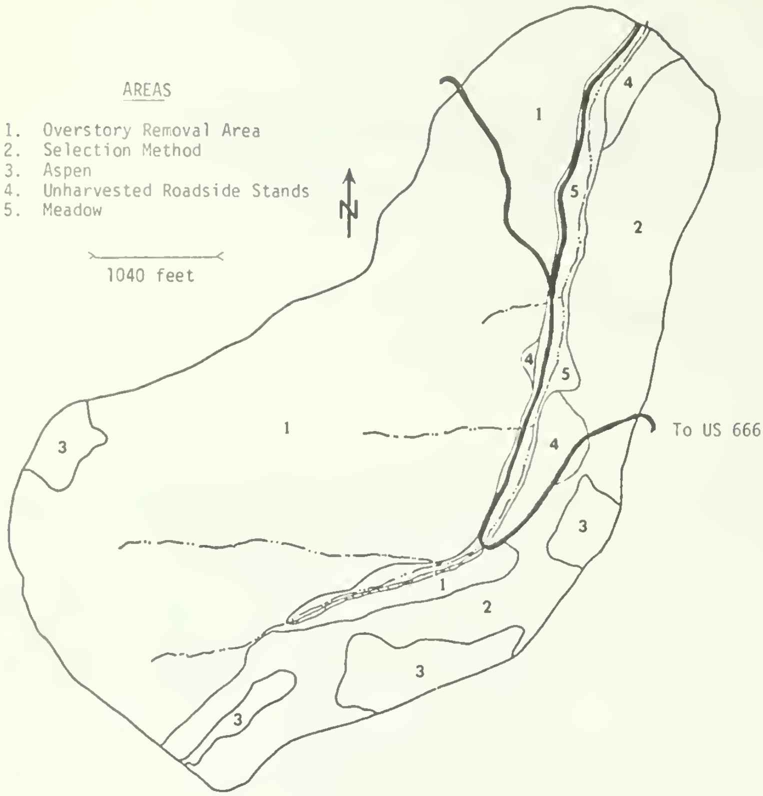

Figure 1.—

The Willow Creek East Fork watershed is located 25 miles south of Alpine, Arizona.

used, cutting was light to moderate, removing individual trees and small groups, with an emphasis on salvaging defective veterans.

Marking on the 302-acre overstory removal area was based on a 10-inch diameter limit. Some trees larger than 10 inches were left, especially near roads to reduce visual impact. Occasional large defective veterans were left, primarily for use by birds. Where pole-sized trees were numerous, some as small as 6 inches d.b.h. were marked for pulpwood. In addition, 8 acres of single-storied Engelmann spruce were clearcut. Aspen was not cut, because there was little market for it. Seventeen acres of conifers along the meadow were uncut.

Table 1 summarizes the changes in overstory conditions for both treatment areas. Stocking after treatment on the overstory removal area was highly variable. Some parts were nearly bare, while some aspen patches were undisturbed.

Logging Control

Before logging, the timber sale area was examined jointly by the Black River District Ranger and staff assistants, representatives of Southwest Forest Industries (the timber purchaser), and of Holliday Logging Company (the logging operator). Also present were the Forest Supervisor and staff assistants, representatives of the Regional Forester, and personnel of the Rocky Mountain Forest and Range Experiment Station. The purposes and problems of the operation were discussed thoroughly, with emphasis on the need for special care to avoid damage to the advance regeneration.

Table 1.--Overstory conditions for areas treated by selection method and by overstory removal (based on a 25 basal-area-factor cruise of trees 7 inches d.b.h. and larger)

Treatment	Area treated	Per-acre conditions		
		Trees	Basal area	Gross volume[1]
	Acres	*No.*	*Ft*^{2}	*Bd.ft.*
SELECTION METHOD:	114			
Before logging		230.40	197.30	23,617
After logging		152.38	135.14	16,483
OVERSTORY REMOVAL:	302			
Before logging		146.18	178.81	26,564
After logging		43.71	29.24	3,017
		Percent reduction		
SELECTION METHOD		34	32	30
OVERSTORY REMOVAL		70	84	89

[1]Scribner Decimal C.

Supervision and contractor cooperation were good. The sawtimber and pulpwood operations were separate, though overlapping in time. A sale administrator was assigned to each operation to provide close supervision. Both sale administrators had a good working relationship with the logging operator and his crews. Whenever they were in the vicinity, Experiment Station personnel visited the area and examined operations along with the operator and sale administrators. Southwest Forest Industry foresters were often on the area. It was clear that sawyers were making an effort to avoid dropping trees in concentrations of advance regeneration, or where skidding damage would be severe. Sometimes, however, the two were mutually exclusive, and the sawyer had to choose between either substantial felling damage or substantial skidding damage.

The sawtimber was ground skidded by D6 and D7 crawler tractors. Small rubber-tired skidders were used to remove much of the pulpwood. Hot logging greatly reduced the area denuded for decking logs.

Slash Treatment

Slash piling and burning has often virtually eliminated the advance regeneration which survived logging. At Willow Creek, slash was lopped and left in place over most of the area to avoid such damage. Slash was skidded and piled on the 8 acres of spruce clearcutting, however, to avoid a possible buildup of spruce beetles. In addition, a 3-chain-wide (198-feet) fuel break was constructed by the Forest Service around the watershed perimeter. Slash within 1 chain (66 feet) of the main road also was piled. Only dead fuel was piled in the fuel break. Bulldozers were kept out of concentrations of advance regeneration during construction. If slash lay where machine piling would do appreciable damage, it was simply lopped in place or, where abundant, lopped and hand piled. Piles were scheduled for burning in 1974.

STUDY METHODS

Advance regeneration was compared before and after logging. To reduce error, the same sample strips were used for both examinations.

Marked timber survey points had previously been established on 12 lines according to a multiple-random start design. Transects through the survey points were used as the basis for sampling advance regeneration. Each of the 12 transects was the center line of a narrow sample strip. A 30-inch steel stake was driven at each survey point, usually to within 3 or 4 inches of the ground surface. Each stake was referenced to one or more (usually two) witness trees, which were tagged below stump height.

Advance regeneration was divided into five classes so we could ascertain the relationship between size and susceptibility to damage:

Established small seedlings	3.0-11.9 inches tall
Large seedlings	1.0-4.5 feet tall
Small saplings	0.1-1.9 inches d.b.h.
Large saplings	2.0-3.9 inches d.b.h.
Small poles	4.0-6.9 inches d.b.h.

Small seedlings were sampled on circular 4-milacre plots. The plot centers were located 15 feet magnetic south of the stakes, roughly at right angles to the transects, to avoid damaging sample seedlings while we conducted other activities. There were 37 plots in the selection area and 117 in the overstory removal area. Total small seedlings were not counted; they were recorded by species as zero, one, two, or more than two per plot.

Large seedlings and small saplings were counted along all 12 transects. Strips were 6.6 feet wide, with a total sample area of 3.33 acres in the overstory removal area and 0.96 acre in the selection area. Large saplings and small poles were counted along six alternate transects on strips 16.5 feet wide, with a total area of 4.05 acres in the overstory removal area and 1.20 acres in the selection area.

Advance regeneration was rated as growing stock if it would reasonably produce a merchantable product at some time. Trees not considered growing stock were primarily saplings and seedlings with severe dwarf mistletoe or with dead tops; the latter were usually severely suppressed.

During the postlogging examination only, growing stock (except for small seedlings) was further classed as good or fair. Good growing stock was that which the examiner judged to be at least fairly vigorous, free of dwarf mistletoe, and of good form. Fair growing stock had some defect but had the potential to maintain itself in the stand and eventually produce at least pulpwood. Good growing stock is more meaningful from the viewpoint of timber production. For cover and forest scenery after logging, however, total growing stock is important.

Forty-three photos were taken from transect stakes both before and after logging. The camera was aimed along or at estimated angles from the transects. The views were selected before logging to show the spectrum of stand conditions. An edge or corner of each view was referenced before logging to some distinctive feature, such as the base of a large tree, so that the same view could be rephotographed after logging. In a few instances the after photo only approximates the view of the original because the reference feature was lost.

RESULTS

Overstory

Changes in the number of trees, basal area, and volume were more severe in the overstory removal area (fig. 2) than in the selection area (table 1). After logging, 95 percent of the timber inventory points in the selection area were stocked with one or more trees 7 inches d.b.h. or larger as defined by a 25 basal area factor gage. In contrast, 53 percent of the inventory points were stocked in the overstory removal area, only 35 percent by conifers.

Advance Regeneration

Before logging, the two treatment areas were similarly stocked with advance regeneration (table 2). Logging damage was considerably greater on the overstory removal area than on the selection area.

Photo Comparisons

The data can be better appreciated after examining the "before and after" photographs (figs. 3-15). The photos labeled *A* were taken before logging; those labeled *B* were taken after logging. The situations illustrated are described in the captions. Results of the selection method did not vary greatly; figures 3-6 were sufficient to show most of the range of before-and-after contrasts. Figures 7-13 show the results of overstory removal. Figures 14 and 15 show the results of logging in the aspen patches.

Table 2.--Total advance regeneration per acre,[1] by treatment, before and after logging

Treatment and size class	Before logging	After logging	Lost	Survivors rated 'good'
	Stems/acre		*Percent*	
SELECTION METHOD:				
Large seedlings	404.17	187.50	54	54
Small saplings	96.88	51.04	47	61
Large saplings	61.67	35.83	42	54
Small poles	71.67	42.50	41	55
Total	634.39	316.87	50	55
OVERSTORY REMOVAL:				
Large seedlings	446.25	148.65	67	43
Small saplings	110.81	37.24	66	37
Large saplings	69.63	25.68	63	45
Small poles	79.26	35.80	55	48
Total	705.95	247.37	65	43

[1]Conifers and aspen; excludes small seedlings.

Figure 2.—A broad view of the overstory removal area.

A. BEFORE

Figure 3.—Selection method. Exterior view, relatively little disturbance.

B. AFTER

A. BEFORE

Figure 4.—Selection method. Interior view, relatively little disturbance.

B. AFTER

A. BEFORE

Figure 5.—Selection method. Area moderately disturbed.

B. AFTER

A. BEFORE

Figure 6.—Selection method. Area considerably disturbed.

B. AFTER

A. BEFORE

Figure 7.—Overstory removal. Some areas had relatively few unmerchantable trees. Overstory removal and accompanying disturbance constitute clearcutting. (The midground trees were purposely left along the meadow edge.)

B. AFTER

A. BEFORE

Figure 8.—Overstory removal. Considerable areas with advance regeneration had heavy volumes of large, old trees whose removal largely destroyed the advance regeneration. The result was essentially a clearcutting.

B. AFTER

A. BEFORE

Figure 9.—Overstory removal. Some areas had abundant regeneration and substantial but not heavy merchantable volumes, as in the foreground and midground. Logging damage commonly left such patches partially stocked. (The background ridge is in the selection area.)

B. AFTER

A. BEFORE

Figure 10.—Overstory removal. In some instances where advance regeneration was fairly abundant, logging damage seemed excessive.

B. AFTER

A. BEFORE

Figure 11.—Log landing. Little or no advance regeneration survives on or around log landings. Landings usually occupy more ground where cutting is heavy, as in overstory removal. Hot logging on this sale minimized landing area. (The background ridge is in the selection area.)

B. AFTER

A. BEFORE

Figure 12.—Overstory removal. Numerou patches had low merchantable volume an abundant advance regeneration. Carefu routing of skidding traffic left most of thes moderately to well stocked.

B. AFTER

A. BEFORE

Figure 13.—Overstory removal. Some areas were essentially two-storied with a sawtimber overstory and many subordinate small poles. Removal of the overstory resulted in heavy blowdown of residual poles.

B. AFTER

A. BEFORE

Figure 14.—Aspen patch. Numerous patches within the overstory removal area were dominated by aspen. Removal of associated conifers did not constitute overstory removal, nor was the advance regeneration seriously damaged. Exterior view.

B. AFTER

A. BEFORE

igure 15.—Interior view of a patch dominated by aspen.

B. AFTER

Data Comparisons

Trees per Acre

Comparative density data, before and after logging, are given for both treatment areas in table 2. Logging activities on the overstory removal area, destroyed 65 percent of the advance regeneration (if small seedlings are ignored). Only 43 percent of the survivors were rated good. Losses were also heavy on the selection area—50 percent—despite much lighter timber removal. Of the survivors, 55 percent were rated good.

In both treatment areas, the data show a consistent trend of decreasing losses with increasing size from large seedlings to small poles. Larger regeneration is easier for fallers and tractor operators to see, and both workers in deciding where to drop a tree or drive a tractor, are more likely to spare a pole or large sapling than a seedling.

We do not know the exact percentages of small seedlings lost because our inventory method did not give full counts on some plots. Full counts were more common in the posttreatment inventory. On the selection area, the postlogging tally of 257 trees per acre was 60 percent less than the prelogging count, and on the overstory removal area, the postlogging tally of 122 trees per acre was 80 percent less. Actual losses were greater than these percentages.

Stocking Level Distribution

The **distribution** of advance regeneration within the stand is as important as the **number** of trees. It is conceivable that we could denude half the area, but still only lose a moderate number of trees.

Because the original sampling design did not allow for evaluation of stocking level distribution we made a supplemental survey in 1974. Four-milacre plots were offset at about 1-chain intervals along the inventory lines. There were 116 plots in the selection area and 350 plots in the overstory removal area. Trees of all sizes that were present in 1971 were tallied, as were new aspen sprouts. Approximately 4 percent of the overstory-removal plots contained prelogging aspen.

The results are indicated below. Two levels of stocking are shown because of the uncertainty of what constitutes optimum stocking in Arizona mixed conifer stands.

	Selection area	Oversto remova area
Percent stocked with at least:		
1 conifer	47	36
2 conifers	32	19
Percent stocked with at least:		
1 aspen	28	40
2 aspens	20	32
Percent stocked only with aspen	14	23
Percent stocked with at least 1 tree		
in 1972	47	37
in 1974	60	59
Percent stocked with at least 2 trees		
in 1972	32	21
in 1974	47	48

DISCUSSION

Overstory Removal

Heavy logging damage to advance regenerati combined with removal of most of the overstory, the overstory removal area understocked. Furth more, many residual poles and suddenly expo immature sawtimber trees blew down, mostly a the postlogging survey. Their loss, not reflected the regeneration data and only partly in the phot graphs, leaves the area still more poorly stock Salvaging the blowdowns will cause additional ging damage.

Establishment of new seedlings is usually slow exposed sites, especially in the absence of abund seed. Even under highly favorable conditions takes a decade or more for most newly germina mixed conifer seedlings to reach breast height (Jo 1971). Therefore, the poor stocking of adva regeneration in general, and especially the los numerous saplings and poles which were beyond t slow-growing seedling stage, will seriously d production of coniferous timber on the overs removal area.

Since the survey, aspen suckering on the overs removal area has been widespread, fairly abund and of acceptable vigor. This has greatly impro overall stocking, which now approaches adequate most of the overstory removal area. Overs removal has, in this case, converted a fo dominated by old conifers to a young forest dominatly of aspen suckers but with a modest representation of conifers. Some of these conifers, primarily those which are already saplings and poles, will share the future canopy with the fast-growing young aspens and provide a future seed source. Most of the smaller advance conifer regeneration will be outgrown and return to understory status.

While the market for aspen timber has been very limited in the Southwest, aspen has become salable as pulpwood here since this operation. It is likely that aspen fiber will be fully marketable within a few decades. Thus the value of timber produced by the predominantly aspen forest may match in value that which would have been produced had the overstory removal area been treated instead by the selection method or a three- or four-cut shelterwood that maintained coniferous dominance. The simplicities of aspen regeneration should be attractive to forest managers.

The consequences of this one-cut overstory removal and the accompanying type conversion influence values other than timber production. Conversion to young aspen forest has advantages for deer and elk management.[3] Also, a fair amount of aspen forest in locales widely dominated by conifers seems esthetically desirable, especially when the aspen stands include scattered coniferous trees and groves. It will be decades, however, before the overstory removal area will be as attractive to most people as the adjacent selection forest.

The treatments should increase water yields from the watershed. Based on the experiments on Workman Creek, Arizona,[4] most of this increase would come from the overstory removal area. Young aspen stands may bring water yields back down to prelogging levels much sooner than if the area had regenerated gradually with only slow-growing coniferous seedlings. Limited study suggests, however, that yields will probably remain above prelogging levels for more than 3 years, despite vigorous growth by the young aspen (Johnston et al., 1969). Continued gaging of streamflows from this and the adjacent uncut watershed will provide information on the duration of increased water yields.

[3] *Patton, David R., and John R. Jones. 1975. Management of aspen for wildlife in the Southwest. (Unpublished manuscript on file with Project 1702, Forest Hydrology Laboratory, Rocky Mountain Forest and Range Experiment Station, Tempe, Arizona).*

[4] *Rich, Lowell R., and Gerald J. Gottfried. 1975. Water yields resulting from treatment on the Workman Creek experimental watersheds of Central Arizona. (Unpublished manuscript on file with Project 1612, Forest Hydrology Laboratory, Rocky Mountain Forest and Range Experiment Station, Tempe, Arizona).*

Selection Method

The selection forest remains satisfactorily stocked with a combination of residual overstory trees and advance regeneration. Much advance regeneration was destroyed, however, especially seedlings and small saplings, despite efforts by the loggers to avoid damage.

The removals and disturbance would have been much the same had this been the first of three shelterwood cuts in the same stand. In most virgin mixed conifer forests in the Southwest, the first cut must be light to moderate in either system, to develop windfirmness in the residual stand. In the shelterwood system, however, the entire overstory would be removed in installments covering a period of perhaps 20 years, and the repeated loss of so much regeneration might be more serious.

RECOMMENDATIONS TO REDUCE DAMAGE

Logging damage can be reduced by three changes in logging procedures:

1. **Marking and clearing skid trails.**—Skid trails were made as needed by the skidding tractors. Windfalls, fallen snags, and other unmerchantable down material, commonly in long lengths, were pushed out of the way or detoured. Detours slowed the work, disturbed excessive area, and damaged more regeneration. Pushing the down material out of the way with the tractor blade also did considerable damage to advance regeneration. Much of that damage could be avoided by marking skid trails and having a swamper saw out sections of the down material to help clear the trail. Bulldozing these short sections aside would do much less damage. Trees along marked skid trails can be felled at angles to minimize skidding damage.

2. **Careful winching.**—More winching would be necessary if tractors were restricted to marked and pre-cleared trails. Logs being winched to a tractor sometimes catch on down material and drag it sideways, destroying and damaging regeneration. A swamper or the choker setter, using a light chain saw, could sever or saw out sections of material that lay in the way, making winching easier and reducing damage to regeneration.

3. **Varying log lengths.**—Logs sometimes fall in situations where they are difficult to remove, especially by winching, if they are of large diameter and a standard 32 feet long. Tractors must sometimes circle around through regeneration to push such heavy logs into positions from which they may be pulled. This commonly requires pushing or rolling

the log sideways, regardless of damage to seedlings and saplings. If sawyers are trained to watch for these situations, they could cut shorter logs when necessary. It is sometimes necessary to fall a tree at an unfavorable angle to the skid trail, for example, to avoid lodging, or felling a treetop into regeneration. Logs being winched or otherwise pulled onto the trail are then dragged through an arc sideways, often destroying saplings and seedlings and damaging poles and larger trees. If sawyers are trained to recognize these situations, they could cut shorter logs to reduce the arc of destruction.

Putting these suggestions into effect would involve changes in sale preparation and administration, and possibly modification of standard contracts. They probably would be considerably more effective if brief training sessions were held for sawyers, skidders, swampers, and choker setters. It might even be specified that men without such training could not work on timber sales where such methods are required.

CONCLUSIONS

One-cut removal of a mixed conifer overstory destroyed about two-thirds of the advance regeneration and left the area seriously understocked, despite substantial efforts to avoid damage. This harvesting system should not be used where advanced regeneration is to provide the subsequent stand. Even with care and improved logging techniques, adequate stocking of advance coniferous regeneration seems unlikely to survive one-cut overstory removal in stands with large merchantable volumes. The result approaches clearcutting. One-cut overstory removal can only be recommended where clearcutting is acceptable—perhaps to increase water yields, or improve forage for deer and elk.

The selection method, and the first removals under a multiple-cut shelterwood system, do less damage, but considerable advance regeneration is lost nonetheless. Minor changes in harvesting methods could reduce this damage, and make timber production more fully compatible with other forest management goals.

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COMMON AND SCIENTIFIC NAMES OF PLANTS MENTIONED

Engelmann spruce	*Picea engelmannii* Parry
Blue spruce	*Picea pungens* Engelm.
Rocky Mountain Douglas-fir	*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco
White fir	*Abies concolor* (Gord. and Glend.) Lindl.
Corkbark fir	*Abies lasiocarpa* var. *arizonica* (Merriam) Lemm.
Ponderosa pine	*Pinus ponderosa* Laws.
Southwestern white pine	*Pinus strobiformis* Engelm.
Quaking aspen	*Populus tremuloides* Michx.

Gottfried, Gerald J., and John R. Jones.
1975. Logging damage to advance regeneration on an Arizona mixed conifer watershed. USDA For. Serv. Res. Pap. RM-147, 20 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521

Old-growth southwestern mixed conifer stands commonly have considerable advance regeneration, but one-cut overstory removal, with subsequent slash piling, typically has destroyed most of it. Furthermore, except where aspen suckers abundantly, subsequent regeneration is usually very slow. This study examines damage to advance regeneration where special care was taken to avoid damage. With the selection method, 50 percent was destroyed, and in a one-cut overstory removal, 65 percent. The overstory removal area was left seriously understocked. Logging modifications are recommended to further reduce damage.

Keywords: Advance regeneration, logging damage, mixed conifer forests.

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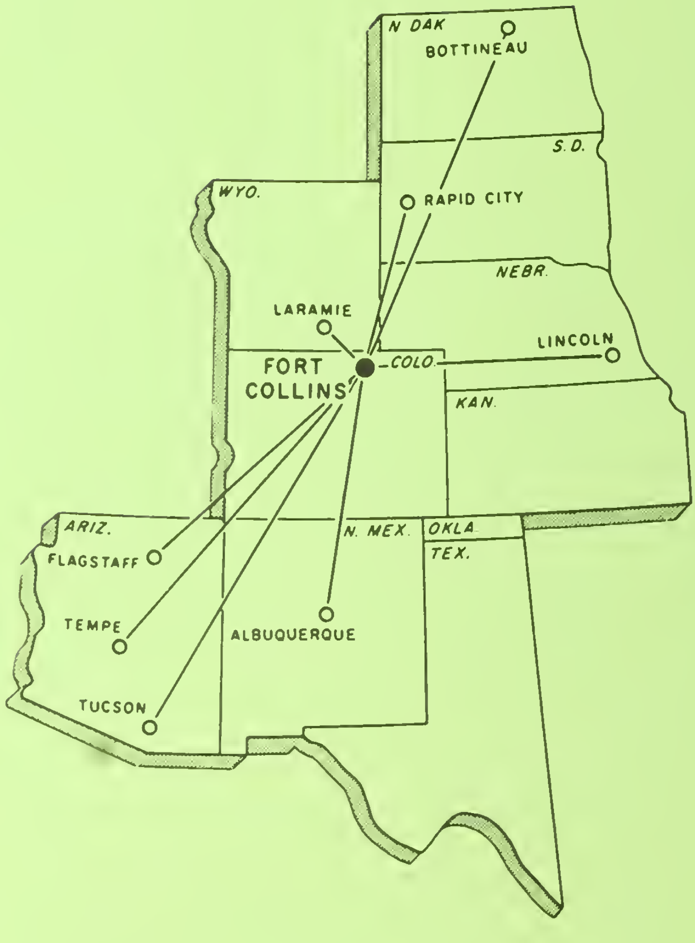
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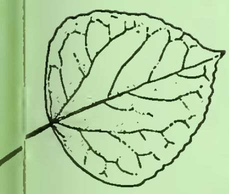

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A Southwestern Mixed Conifer Plantation—
Case History and Observations

John R. Jones

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Abstract

Jones, John R.
1975. A southwestern mixed conifer plantation—case history and observations. USDA For. Serv. Res. Pap. RM-148, 8 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521

Ponderosa pine, Douglas-fir, and two lots of blue spruce were planted on clearcuttings in east-central Arizona at about 9,200 ft elevation. The Douglas-fir and one lot of blue spruce were markedly inferior planting stock. After five growing seasons, survival and condition of the inferior planting stock were very poor. Many ponderosa pines were girdled during a meadow mouse outbreak, but on south slopes most of the survivors were vigorous. Survival and growth of blue spruce from good planting stock were good on north-facing slopes, but considerably poorer on south slopes. Management implications are discussed.

Keywords: *Pinus ponderosa*, *Picea pungens*, *Microtus*, planting.

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July 1975

A Southwestern Mixed Conifer Plantation— Case History and Observations

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[1]*Central headquarters maintained at Fort Collins, in cooperation with Colorado State University; research reported here was conducted at the Station's Research Work Unit at Flagstaff, in cooperation with Northern Arizona University.*

Contents

A Southwestern Mixed Conifer Plantation—

Case History and Observations

John R. Jones

Very little forest planting was done on Southwestern mixed conifer sites prior to 1970. For years the selection method had been the basis of harvesting mixed conifer forests, and natural regeneration was relied upon. The infrequent destructive fires in mixed conifers commonly were followed by extensive aspen[2] suckering, or, on some habitats, by profuse growth of Gambel oak.

In the ponderosa pine climax zone, ponderosa pine had been planted on a rather small scale for years, with some notable successes but a preponderance of failures. It also had been planted occasionally on mixed conifer burns with their more favorable moisture regimes, but survival did not seem any better.

Many causes have been suggested for failures: the severe spring dry seasons; competition from grasses; frost heaving; predation by pocket gophers and meadow mice; browsing by cattle, sheep, deer, and elk; and handling and planting practices that are inadequate for Southwestern conditions (Jones 1967, 1974).

Interest in clearcutting in the Southwest to obtain increased water yields grew out of watershed research in North Carolina, Colorado, and the Sierra Ancha in Arizona. In 1958-59, seven blocks of mixed conifer forest were clearcut on the Burro Creek Watershed, Apache National Forest, Arizona, to examine silvicultural side effects of clearcutting to increase water yield. Two blocks were planted with ponderosa pine. First-year survival was 27 percent. The seedlings which survived were virtually eliminated over the next several years through browsing by the numerous deer and elk attracted to the clearcuttings (Jones 1967). Browsing also eliminated aspen suckers. Of the scattered pines which survived browsing, most were killed by debarking during the winter of 1966-67, when meadow mouse populations became very high.

Research foresters had enjoyed an encouraging degree of success in small-scale experimental plantings of ponderosa pine. They felt that the numerous natural factors mentioned above, although the immediate causes of failures, could commonly be overcome if the necessary knowledge were put together and used. This attitude was shared by the Branch of Silviculture in the Southwestern Regional Office of the USDA Forest Service and by numerous foresters in the field.

To test and extend our knowledge for the mixed conifer zone, an experiment was planned and installed by Robert S. Embry.[3] It was designed to compare performances of four species on north- and south-facing slopes, with and without protection from browsing by game and cattle. This Paper reports the results of that experiment.

Area and Methods

The study was installed at 9,200-9,300 feet elevation on small mixed conifer clearcuttings along the Blue Lookout Road, Apache National Forest, Arizona. The locale averages about 33 inches of precipitation per year, with about 30 percent of it as July and August rains. Three sites were selected on north-facing and three on south-facing slopes. Their soils were similar—gravelly silt loams and gravelly silty clay loams derived from basalt. Slopes varied from 12 to 22 percent. At the time of planting, the sites were largely bare of competing vegetation. At each site, three contiguous subplots were laid out. One subplot, selected at random, was fenced to exclude cattle, deer, and elk; another to exclude cattle only; and a third was left unfenced. Each subplot was subdivided into four quarters, to each of which a different species was assigned at random: Douglas-fir, ponderosa pine, blue spruce, and Engelmann spruce.

At this point, the purpose and design of the study were compromised in two ways:

1. Although it was not apparent at the time of planting, as the "Engelmann" spruce seedlings grew and took on more definitive characteristics, it became clear that they were actually blue spruce seedlings grown in the nursery from mis-identified seed. Therefore we do not have

[2]*Scientific names of plants and animals mentioned are listed at the end of this report.*

[3]*Formerly Associate Silviculturist at the Station's Research Work Unit at Flagstaff; now Hydrologist, Idaho Panhandle National Forests, St. Maries, Idaho.*

Engelmann spruce in the study at all. Instead, we have a comparison of two very different lots of blue spruce planting stock. That shipped as Engelmann spruce will subsequently be referred to as normal-stock blue spruce and the other as poor-stock blue spruce.

2. The quality of planting stock differed markedly by species, which confounds most species comparisons. The ponderosa pine, like the normal-stock blue spruce, was good. The Douglas-fir stock, 4 years in the seedbeds, had tall, spindly tops and long, sparsely branched root systems, but was the only Douglas-fir available from Southwestern sources. The poor-stock blue spruce were mostly only 2 to 3 inches tall, with densely branched root systems only 3 to 4 inches long.

Species selection reflected several considerations. All are significant mixed conifer species. Ponderosa pine and blue spruce seem well adapted to the full sunlight found on clearcuttings. The suitability of Engelmann spruce and Rocky Mountain Douglas-fir for regenerating clearcuttings was questionable (Jones 1974); this study was to provide a test. Observations also had suggested that the spruces were much less attractive to browsing game and cattle (Jones 1974) and less subject to girdling by mice. Ponderosa pine definitely seemed more resistant to drought, but it also seemed quite possible that, with competing grasses initially absent, spruce and Douglas-fir nursery stock would be able to survive dry seasons on south-slope clearcuttings.

A planting program did not yet exist on the Apache National Forest, so the planting stock used was from other Southwestern seed sources. Choices were very limited. Shipping invoices described the planting stock and seed sources as follows:

2-0 ponderosa pine, Sitgreaves National Forest, Arizona.
4-0 Douglas-fir, Carson National Forest, New Mexico.
3-0 blue spruce, Carson National Forest, New Mexico.
3-0 Engelmann spruce, Carson National Forest, New Mexico.

The first three lots were raised at the Lucky Peak Nursery, Boise, Idaho, and the fourth at the Mt. Sopris Nursery, Basalt, Colorado.

The sites were planted in the spring of 1970—the south slopes in mid-April when the seedlings arrived, and the north slopes at the end of April when the snow melted from them. An exception was the "Engelmann" spruce planting stock, which was not received unt early May.

The seedlings were planted in slits mac with planting bars. The method was standard a that time, but is no longer recommended (Jone 1974, Ronco 1972, Schubert et al. 1969, 1970).

After the study plots had been planted, e cess seedlings were planted in a small catt exclosure where orchardgrass had been esta lished earlier beside the logging road. Ther were 40 normal-stock blue spruce, 40 Dougla fir, 38 ponderosa pine, and 32 poor-stock blu spruce in this accessory plot. These extra tree were planted in the thick orchardgrass witho site preparation and watered weekly until th summer rains began in July. They were n formally part of the study.

During the first growing season, 1970, th seedlings were examined every 7 to 10 days. appropriate intervals during the spring an summer of 1970, soil moisture was measured depths of 0-4 and 4-8 inches on each study plo In 1971 seedlings were checked three times, 1972 twice, and in 1973 once. A closing examin tion was made in September 1974, when th height of each survivor was measured.

During the 1970 and 1971 examinatio each live tree was rated as healthy or unhealth Beginning in 1972, live seedlings were class as:

Good—healthy-looking seedlings growing we
Hopeful—seedlings with a notable lack of vig or, if vigorous with some other serious i pairment, but considered to have a substa tial chance to survive and grow.
Doubtful—seedlings judged unlikely to surviv

Criteria included: amount and condition foliage; length of leader, both as an absolute a with respect to previous size; size of new bu and physical damage such as gnawing, brov ing, and breakage. Competitive situation, su as being overtopped by dense raspberry, w not a criterion; only characteristics of the see ling itself were used to rate condition.

Results

Except where otherwise specified, data a from the study proper, and do not include da from the accessory plot.

Soil Moisture

The dry season immediately followi planting was normal. Soil water potential neath the bare-plot surfaces did not reach bars until late June, however, and then only some plots. At no time did it approach the permanent wilting point.[4] Rains beginning early in July kept the soil near field capacity until sampling was discontinued in September.

Survival and Growth of Different Stocks

After five growing seasons, normal-stock blue spruce had survived best and had most trees rated good, followed by ponderosa pine, poor-stock blue spruce, and Douglas-fir (table 1). Heights tabulated are averages for trees rated good. The tallest of all was a very exceptional ponderosa pine which reached 66 inches.

Table 1.--Survival and growth of seedlings for five growing seasons on formal study plot and on an accessory plot

Plot data	Survival	Rated 'Good'	Height
	- *Percent* -		*Inches*
STUDY PLOT:			
Spruce, normal-stock	67	37	23.3
Ponderosa pine	26	19	26.5
Spruce, poor-stock	23	10	19.1
Douglas-fir	19	8	22.0
ACCESSORY PLOT:			
Spruce, normal-stock	93	55	14.8
Ponderosa pine	26	18	18.7
Spruce, poor-stock	6	0	--
Douglas-fir	5	0	--

On the accessory plot, planted in grass and watered through the first dry season, 5-year survival for ponderosa pine was almost exactly the same as in the study proper (table 1). Surprisingly, survival of the normal-stock blue spruce was much better on this plot than in the study proper. Almost all the Douglas-fir and the poor-stock blue spruce died the first year.

Initial growth on the accessory plot was relatively poor; the trees hardly grew at all until the fourth growing season, when a number of them showed considerably improved vigor. At the end of the fifth growing season, heights were relatively uniform; no tree was taller than 21 inches.

Causes of Death

Little can be said about the immediate causes of death of Douglas-fir and poor-stock blue spruce, but the basic cause seems to have been their initial poor quality. Almost all showed poor vigor the first year, and most remained in poor condition until they died. Most of the survivors show little tendency toward recovery.

Ponderosa pine.—Rodents killed 34 percent of all the ponderosa pines planted in the study proper; 204 were girdled by meadow mice while pocket gophers girdled or cut the roots of 15. Eleven other pines were missing, and rodents are a plausible explanation. Virtually all the pocket gopher damage was in 1972 on two of the 18 plots. A large majority of the meadow mouse damage came during the winter of 1973-74, when populations were very high throughout the White Mountains. Many pines were stripped of bark from the ground to the terminal shoot, and smaller pines commonly were cut off. A number of the larger pine seedlings had only a narrow girdle of bark removed. Many surviving pines had been partly girdled, but in most such cases the subsequent (1974) growth seemed normal. A few had been girdled or even completely debarked above the lowest branch, leaving a live but small and deformed seedling.

A few plots had little rodent damage. The accessory plot had no trees killed by rodents, and only one damaged.

Other identified factors killed fewer than 4 percent. They include trampling (15 seedlings), burial by soil, rocks, or cow manure (five seedlings), and browsing (one seedling). In a very dense patch of raspberry the death of four seedlings was ascribed to competition.

No cause could be identified for 220 deaths (34 percent of the pines planted). Of these, 195 died during the first 2½ years and were very largely trees which showed poor vigor from the beginning; 63 pines died the first summer. Mortality was not associated more with one slope direction than with the other.

Blue spruce.—In contrast with ponderosa pine, only 3 percent of the normal-stock spruce, 20 trees, were killed by rodents. Other identified causes were trampling (six trees, less than 1 percent), competition (two trees), cow manure and a falling snag (one tree each). The other 183 that died (28 percent of those planted) succumbed to unidentified causes. Because 115 died during or just after the exceptional 1974 drought, 98 of them on southerly slopes, drought is clearly implied. These included numerous seedlings taller than 20 inches that previously had been rated good. Many of the blue spruce survivors classed as only hopeful or doubtful in 1974 had dropped most or all of their pre-1974

[4] *Permanent wilting point is generally taken as -15 bars unless otherwise defined. Seedlings do not necessarily die when the soil water potential reaches or exceeds -15 bars.*

needles during the drought; nearly all of these were on southerly slopes.

Effects of Fencing

Survival and condition class differences between fencing treatments were trivial and statistically insignificant. This is consistent with the scarcity of deaths assignable to cattle or game.

Seedling height differences between fencing treatments also are trivial, which is consistent with the infrequency of browsing or serious trampling damage on the unfenced plots.

Effects of Slope Direction

Pine survival was substantially greater on southerly slopes (33 percent) than on northerly slopes (20 percent, fig. 1), but the difference was statistically insignificant because of the large error variance. Of all pines planted on southerly slopes, 27 percent were rated good at the end of 1974; on northerly slopes the percentage was only 10. This difference was statistically significant ($P<0.05$).

In contrast, survival of normal-stock spruce was much better on northerly slopes than on southerly: 80 percent compared to 53 percent, while those rated good were 59 and 16 percent, respectively, of all planted. These differences were highly significant ($P<0.01$). The differences on different aspects were even greater for Douglas-fir and poor-stock blue spruce.

Effect of slope direction on height was not analyzed statistically. For trees rated good the differences were trivial on the different slope aspects. For all surviving trees, height differences simply reflect differences in the proportions of trees of good vigor.

Discussion

One lesson learned from this study is already well known in regions with established major planting programs: successful planting is only the first step toward a satisfactory new forest. The plantations must then be monitored for subsequent hazards, the relative importance of which varies from region to region and, to some extent, from habitat to habitat within a region. This study, as well as recent research in the ponderosa pine climax zone and operational experience, points to the particular importance of monitoring rodent populations and the conditions which influence outbreak populations. Development of severe shrub competition can also become a problem on some sites. Although not a problem in this study, damage from browsing, trampling, and perhaps insects may require attention.

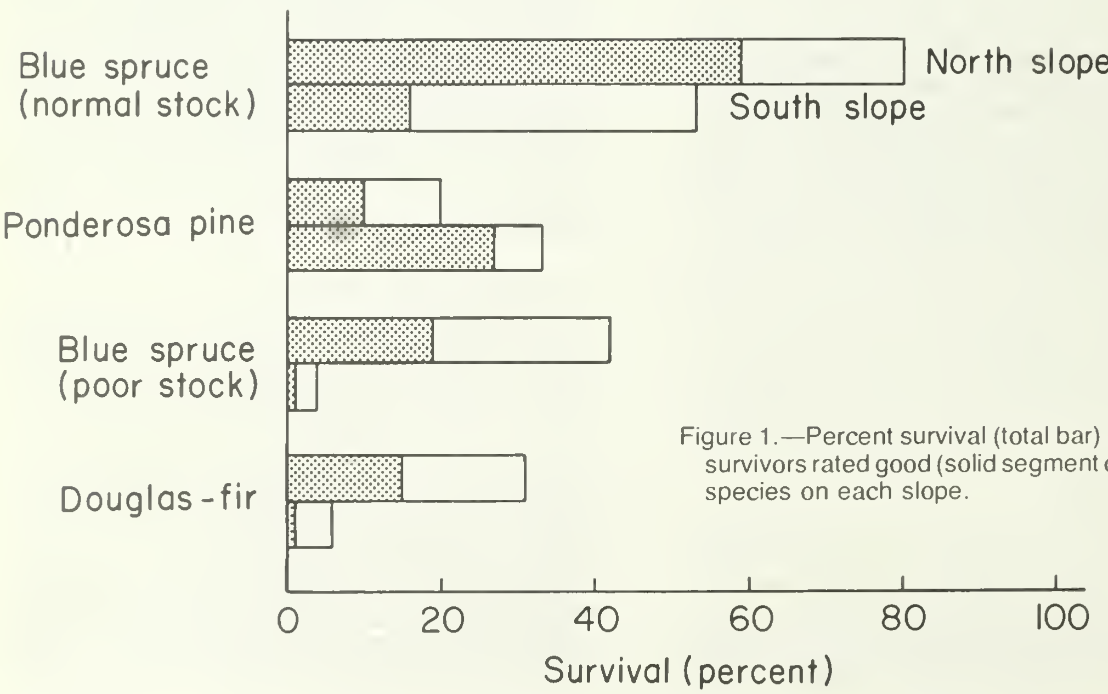

Figure 1.—Percent survival (total bar) and percent of survivors rated good (solid segment of bar) for each species on each slope.

Another lesson has been the importance of slope direction and its relation to species selection. Near winter's end, the snowpack on even a moderate north-facing slope is considerably deeper than on a similar south-facing slope, as indicated in figures 2 and 3 by the amount of 8-foot elk fence exposed. Commonly, snowmelt exposes seedlings to the sun and air 3 to 4 weeks earlier on open south slopes. This exposure often occurs after the beginning of the spring drought, which is characterized by mostly clear skies and persistent winds, with midday relative humidities frequently about 10 percent.

At mixed conifer elevations, soil moisture stresses under bare-soil surfaces are probably seldom severe below the upper 2 inches or so, even on south slopes. Where grass is well established, however, soil moisture stresses in June become severe on southerly slopes and level ground to a depth of at least 16 inches (Embry 1971).

In natural regeneration with root systems as large as those of normal planting stock, tissue moisture stresses are unlikely to become high during the dry season if competition is not serious (Embry 1971; Jones 1971, 1972). In newly planted seedlings, however, lethal moisture stresses may develop during the dry season even where considerable soil moisture is available, presumably because the transplanted root system is not yet functioning adequately to cope with severe atmospheric moisture stresses.[5]

Substantial amounts of grass, weeds, bracken, shrubs, or aspen developed on most plots after planting, but until the abnormally severe drought of the spring and early summer of 1974, almost all the normal-stock spruce still were alive and growing well. Yet spruce on south slopes suffered heavy mortality in 1974, and many survivors lost much of their foliage, presumably due to drought intensified by competition. This was not simply attrition of the weaklings—many of the spruce on southerly slopes that died in 1974 had been large and vigorous the previous autumn.

On the other hand, fewer ponderosa pines died on the warm southerly slopes, and the proportion of trees rated good there was much higher than on northerly slopes. The logical factors seem to be the persistent snow cover, cool microclimates, and cool soils on high-elevation northerly slopes. The elevation of the seed source, 1,800 feet lower than the planting site, may have been an important contributing factor. Performance on the north slope might have been substantially better, had seedlings from a high-elevation source been available.

Figure 2.—Three- to four-foot snowpack on 17-percent slope facing S5°E. March 2, 1973.

Figure 3.—Five- to six- foot snowpack on 22-percent slope facing N5°E. March 2, 1973.

Although an afterthought, and not formally part of the study, the watered plot in thick orchardgrass proved interesting. Orchardgrass reduces soil moisture to critical levels during the dry season—it was the major grass on Embry's (1971) benchmark soil-moisture study—and has been associated with plantation failures in the past. On this plot a disproportionate number of pines died the first year despite watering, and while 5-year survival almost exactly equaled the study average for pine, none of the deaths on the accessory plot were attributable to rodents. Almost all of the normal-stock spruce, on the other hand, survived

[5]*Unpublished research on ponderosa pine and Engelmann spruce. Rocky Mt. For. and Range Exp. Stn. Provided by W.J. Rietveld, Flagstaff, Arizona, and Frank Ronco, Fort Collins, Colorado, respectively.*

through the five summers, and there was no indication of drought injury during 1974. The ambiguities, absence of an unwatered treatment in orchardgrass, and the lack of replication make interpretation difficult. Heavy first-year mortality suggests that orchardgrass has important effects on ponderosa pine beyond reduction of soil moisture. Excellent survival of blue spruce with first-year watering suggests that high soil-moisture stresses are much less critical after the first year.

Unfortunately, watering is totally impractical on an operational scale. Site preparation is practical but expensive. Cheapest, of course, is to not seed grass at all, and reforest promptly before competition necessitates site preparation. Even where important soil losses are a genuine threat, seeding a quick-starting rainy season annual such as black mustard is an alternative that should be much more compatible with reforestation. The mustards provide excellent living soil protection the first summer and dead mulch the second (Lavin and Springfield 1955, p. 38).

Severe woody competition was uncommon on the study plots. Ponderosa pine was badly suppressed by levels of shrub competition that did not seriously retard blue spruce growth. A dense raspberry patch (fig.4), which was not there at the time of planting, has seriously suppressed the few Douglas-firs surviving beneath it. Dense raspberry with an overstory of locust saplings also developed on a north-slope normal-stock spruce plot (fig. 5). While 26 of the 36 spruce in this thicket were still alive at the end of the study, only two were rated good. Where competition was primarily from weedy forbs, seedlings were in much better condition (fig. 6).

Use of the habitat type classification being developed by the Southwestern Region of the USDA Forest Service should assist preplanting evaluation of probable shrub competition.

Competition from aspen suckers had not yet retarded the growth of either spruce or pine. Aspen regeneration was not heavy on any of the plots, however, amounting at the most to individuals and small clumps that had not formed a

Figure 4.—Dense raspberry on a Douglas-fir plot.

Figure 5.—Dense raspberry and locust on a blue spruce plot.

closed canopy. On some clearcuttings, including some unplanted parts of those in this study, suckering has been heavy. The resulting dense stands of aspen saplings would provide critical competition for ponderosa pine seedlings, and would no doubt retard the growth of other conifers significantly.

Figure 6.—Vigorous spruce on northerly slope. Stalks of competing forbs were removed to show the spruce more clearly.

Rodents generally have been considered an important problem in ponderosa pine plantations in the Southwest (Schubert 1974). Also, observations following the major meadow mouse outbreak in the winter of 1966-67 indicated that meadow mice prefer Douglas-fir to Engelmann spruce. This study found meadow mice strongly favoring ponderosa pine over blue spruce, and suggested the same order of preference by pocket gophers.

In the White Mountains the last two major meadow mouse outbreaks were 7 years apart. Damage was severe to natural regeneration as well as to plantations. In the intervening years mouse damage was significant only in places. It is not known how typical that 7-year interval is.

The 66-inch-tall pine in figure 7 completely was surrounded by smaller pines killed by mice. The larger tree tentatively had been gnawed at several points, but at no point did the attacks penetrate the inner bark. It is interesting to consider the possibility that, when they become taller than 50 or 60 inches, ponderosa pines become unattractive to meadow mice. In this study, however, several pines taller than 40 inches partly or entirely were girdled.

Grass seeding on these clearcuts was limited almost entirely to roads and roadsides, and use by cattle was concentrated largely on the seeded areas. Rather light general use of the clearcuts by cattle did only scattered minor damage.

The high deer and elk populations of the late 1950's and early 1960's seriously damaged regeneration of most coniferous species, but not the spruces, in numerous Arizona locales (Heidmann 1963; Jones 1967, 1974; Schubert 1974). The existing relatively light populations did no apparent damage on this study area, however.

Management Conclusions

- Plantations should be systematically examined to monitor rodent populations, competition, and other potentially damaging agents.

Figure 7.—Vigorous 66-inch pine surrounded by pines killed by meadow mice.

- Poor-quality planting stock should not be shipped. If received it should not be planted.
- On southerly slopes, vigorous blue spruce seedlings taller than 20 inches may still be killed in years of severe drought.
- Until more specific guidelines are available, a conservative working guide might be: (a) do not plant ponderosa pine on northerly slopes 500 feet higher than the seed source, and (b) do not plant ponderosa pine on northerly slopes at all above about 8,500 feet unless the seed source is from an elevation at least as high.
- Ponderosa pine seems preferable to blue spruce for planting in the open on southerly slopes, provided that: (a) rodent populations and competition from shrubs or aspen are controlled where necessary, and (b) heavy use of the area by cattle, deer, or elk is not expected.

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Common and Scientific Names of Plants and Animals Mentioned

Aspen (quaking)	*Populus tremuloides* Michx.
Black mustard	*Brassica nigra* (L.) Koch
Blue spruce	*Picea pungens* Engelm.
Bracken	*Pteridium aquilinum* (L.) Kuhn
Deer (mule)	*Odocoileus hemionus hemionus* Rafinesque
Douglas-fir (Rocky Mountain)	*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco
Elk	*Cervus canadensis nelsoni* Bailey
Engelmann spruce	*Picea engelmannii* Parry
Gambel oak	*Quercus gambellii* Nutt.
Locust (New Mexico)	*Robinia neo-mexicana* A. Gray
Meadow mouse	*Microtus* spp.
Orchardgrass	*Dactylis glomerata* L.
Pocket gopher (Botta's)	*Thomomys bottae* Eydoux & Gervais
Ponderosa pine	*Pinus ponderosa* Laws.
Raspberry	*Rubus strigosus* Michx.

Jones, John R.
1975. A southwestern mixed conifer plantation—case history and observations. USDA For. Serv. Res. Pap. RM-148, 8 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521

Ponderosa pine, Douglas-fir, and two lots of blue spruce were planted on clearcuttings in east-central Arizona at about 9,200 ft elevation. The Douglas-fir and one lot of blue spruce were markedly inferior planting stock. After five growing seasons, survival and condition of the inferior planting stock were very poor. Many ponderosa pines were girdled during a meadow mouse outbreak, but on south slopes most of the survivors were vigorous. Survival and growth of blue spruce from good planting stock were good on north-facing slopes, but considerably poorer on south slopes. Management implications are discussed.

Keywords: *Pinus ponderosa*, *Picea pungens*, *Microtus*, planting.

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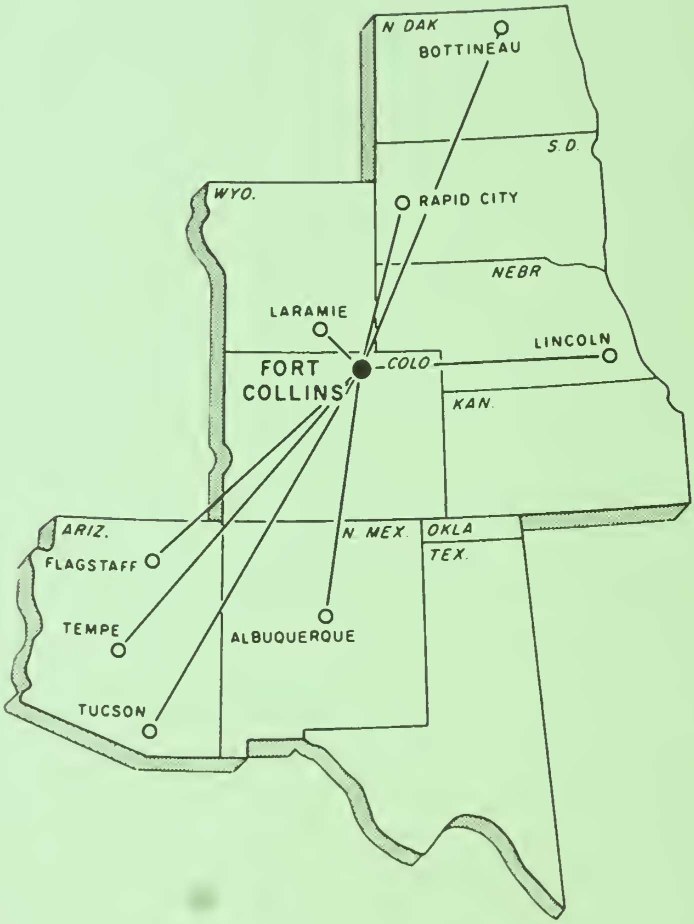

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Rocky Mountain Forest and
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Forest Service
U.S. Department of Agriculture
Fort Collins, Colorado 80521

July 1975

Vegetation Responses to Grazing, Rainfall, Site Condition, and Mesquite Control on Semidesert Range

Dwight R. Cable and
S. Clark Martin

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Abstract

Cable, Dwight R., and S. Clark Martin.
1975. Vegetation responses to grazing, rainfall, site condition, and mesquite control on semidesert range. USDA For. Serv. Res. Pap. RM-149, 24 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

Changes in herbage production, basal intercept, and grazing use of perennial grasses, herbage production of annual grasses, and crown intercept of shrubs and trees were related to changes in rainfall, presence or absence of velvet mesquite, and to differences in soil, topography, and salting. Over a 10-yr period, mesquite control increased perennial grass production 52 percent. Perennial grass production was highly dependent on both last summer's and this summer's rainfall, indicating that 2 yrs are required for recovery from a 1-yr drought. Too heavy use greatly restricted production in wet years that followed dry years. Because of the strong relationship between rainfall and grass production, stocking rates could be estimated as accurately from rainfall as from grass production.

Keywords: Semidesert range, mesquite control, grass production, rainfall effects, grazing effects, site conditions.

Although this report discusses research involving pesticides, such research does not imply that the pesticide has been registered or recommended for the use studied. Registration is necessary before any pesticide can be recommended. If not handled or applied properly, pesticides can be injurious to humans, domestic animals, desirable plants, fish, and wildlife. Always read and follow the directions on the pesticide container.

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USDA Forest Service
Research Paper RM-149

July 1975

Vegetation Responses to Grazing, Rainfall, Site Condition, and Mesquite Control on Semidesert Range

Dwight R. Cable and S. Clark Martin,
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[1] *Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University; authors are located at the Station's Research Work Unit at Tucson, in cooperation with the University of Arizona.*

Contents

RESEARCH HIGHLIGHTS

Herbage production, basal intercept, and grazing use by cattle of perennial grasses were measured annually from 1957 to 1966 at 20 locations in each of four pastures at the upper edge of the semidesert grass-shrub type on the Santa Rita Experimental Range. Mesquite trees were killed on two of the pastures prior to the start of the study. Herbage production of annual grasses and crown intercept of shrubs and trees were also measured annually. Changes in these variables were related to changes in rainfall, presence or absence of velvet mesquite, and to differences in soil, topography, and salting. The major findings of this study, summarized in the following paragraphs deal largely with the ecological relations among the vegetation, climate, and grazing treatments. Some have strong management implications.

1. Effect of mesquite control on perennial grass production. Perennial grass production for the 10-year study period averaged between 352 and 524 lb/acre on the four pastures. At the time the mesquite was controlled (1954-57), perennial grass production was in equilibrium with the invasion stand of mesquite. The influence of mesquite on perennial grass production became apparent as the grass stand responded over time to the release from mesquite competition. The grass stand had readjusted to the additional moisture available as the result of mesquite control by about 1963. By that time, perennial grass production on the mesquite-killed (M-K) pastures had increased 168 lb/acre (52 percent) relative to that on the mesquite-alive (M-A) pastures.

2. Effects of summer rainfall on perennial grass production. Perennial grass production changed greatly from year to year due to changing precipitation. The precipitation components having the greatest effect on year-to-year changes were: (1) rainfall for August of the current summer, and (2) the interaction (product) of rainfall for the current August times rainfall for June-September of the previous summer. The most influential component was the interaction product, which accounted for from 63.5 to 91.0 percent of the year-to-year variation in total perennial grass production. This means that the grass-producing effectiveness of a given amount of rainfall during a given summer depends on the amount of rainfall received the previous summer.

3. Practical implications of rainfall effects. The above results have strong management implications. Summer rainfall gives the range manager some advance indication of what to expect in the way of grass production, and rainfall is much easier to measure than is grass production. The fact that rainfall in two successive summers is involved in the current summer's perennial grass production means that low rainfall in one summer not only reduces production during the current summer but reduces the prospects for the next summer as well. Management decisions should be made with the thought in mind that it takes at least 2 years to recover from a 1-year drought.

4. Effects of degree of use on perennial grass production. Different levels of use during the 10-year study period significantly affected perennial grass production. The specific effect of heavy use (10-year mean use between 52 and 59 percent) was to greatly restrict gains in production in wet years following a dry year. Gains were highest on transects with the lowest mean use (21 to 28 percent) and decreased with each successively higher use level. Two or three favorable years were required for recovery of heavily used transects following a single dry year. One major species, Arizona cottontop, reacted differently from the other species, in that successively higher levels of use stimulated rather than lowered production in wet years. Cottontop is able to tolerate levels of use that are quite damaging to most other species.

5. Results of alternate-year summer deferment. Alternate-year summer deferment did not improve perennial grass production. This does not mean that these ranges may not benefit from periodic rest. Rather, the rest given by this schedule simply did not adequately satisfy the physiological needs of the grasses. Other studies on the Santa Rita also show that alternate-year summer rest does not provide enough recovery time between grazing periods.

6. Influence of slope on perennial grass species. Most perennial grasses exhibited slope preferences. Of the 14 most productive species, six preferred slopes less than 10 percent, four preferred slopes over 30 percent, and four showed no particular preference. Of the five major producers, Arizona cottontop showed a strong preference for flatter slopes, tall threeawns a weak preference for flatter slopes, side-oats grama a weak preference for steeper slopes, and black and slender gramas little or no preference.

7. Soil-species association for perennial grasses. Two soil types predominated on the more moderate slopes on the study pastures: Whitehouse with clayey subsoils, and Comora with gravelly subsoils. The steeper slopes were characterized by shallow, rocky Coronado soils. Tall threeawns and slender grama grew almost equally well on all three soils, but with a slight tendency to decreasing preference from Comora to Whitehouse to Coronado. Arizona cottontop was well adapted to the Comora and Whitehouse soils, but poorly to the Coronado. Side-oats grama was particularly well adapted on the Coronado soils, moderately on Comora and Whitehouse. Black grama showed no particular preference, but grew almost equally well on all soils.

8. Effects of rainfall on annual grass production. Annual grass production fluctuated markedly from year to year. Changes in June-through-August rainfall of the current year accounted for from 78 to 91 percent of year-to-year changes. The general levels around which these fluctuations occurred differed from place to place, however, depending largely on the amounts of perennial grasses and mesquite present at the particular site. Perennial species, with their established root systems, have a strong competitive advantage over annuals in the extraction of available soil moisture. The annual grasses thrive only when more moisture is available than the perennial species can use.

9. Competition between annual and perennial grasses. Annual grass production was highest, relative to perennial grass production, on the most favorable sites; as environmental conditions became less favorable, competition between perennial and annual grasses increased and annual grass production decreased relative to perennial grass. On optimum sites for grass growth and with no mesquite competition, annual grass production varied from zero where perennial grass production was 940 lb/acre to about 500 lb/acre where perennial grass production was 275 lb/acre (increasing 75 lb/acre for each decrease of 100 lb/acre in perennial grass production).

10. Mesquite and annual grass production. Yields of annual grass were three times as great on mesquite-killed as on mesquite-alive range. However, effects of mesquite on annual grass production were so interwoven with other site factors (soil, slope, other competing vegetation) that annual grass production was essentially zero at some locations at all levels of mesquite density. Maximum annual grass production was limited by the degree of mesquite cover, however, where mesquite crown cover exceeded 10 or 12 percent. Annual grass production decreased about 50 lb/acre for each 10 percent increase in mesquite crown cover, and reached zero at about 40 percent mesquite crown cover. Ten-year mean annual grass production was 149 and 208 lb/acre on the two M-K pastures and 26 and 87 lb/acre on the two M-A pastures.

11. Changes in mesquite cover. Mesquite showed little recovery on the M-K pastures during the 10-year study period. Crown cover averaged less than 0.5 percent on both pastures at the end of the period. On the two M-A pastures, crown cover increased from 11.04 to 13.31 percent on one pasture and from 7.17 to 12.67 percent on the other.

12. Relation of utilization to stocking. Ten-year mean perennial grass utilization for the four pastures ranged from about 30 to 50 percent. Use of perennial grass herbage on individual transects averaged between 19 and 72 percent. Forage use was influenced by the amount of forage available per animal and by animal preference for different grass species. Relative use of any given crop of forage varies, of course, with rate of stocking. In this study, however, stocking rates were adjusted each fall to utilize about 40 percent of the perennial grass available for grazing, and measured differences in use from year to year were not significantly related to animal numbers.

13. Species preferences of cattle. Cattle preferences for individual species varied widely. For 18 species of record, average use ranged from 6 to 62 percent. Levels of use were more or less independent of the abundance or productiveness of the various species. However, the amounts of each species available, of course, limited actual consumption. Typically, the preferred species were grazed first and most heavily; use of less preferred species increased as the overall level of use increased.

14. Apparent cattle diet composition. Production and utilization records for individual species provided a basis for approximating the cattle diet:

Major species	Mean percent use	Percent of production	Percent of diet
Slender grama	31	19.2	17.5
Arizona cottontop	57	13.6	22.4
Side-oats grama	29	13.0	11.2
Tall threeawns	38	12.6	14.2
Black grama	12	11.8	7.1

Of the five major producers, cottontop contributed much more to the diet than its proportion of total production. Black grama contributed much less than its production would indicate. The other three contributed to the diet roughly in proportion to their productivity.

15. Importance of less palatable species. On a properly managed range, much of the herbage of the least-preferred species will be ungrazed at the end of the grazing year (especially following a wet summer of high production). This unused dry herbage, even though of relatively low nutrient content, constitutes a reserve of forage that may be used later.

16. Influence of slope and distance to water. Cattle prefer to graze close to water on flat land. As distance from water increases and slopes become steeper, use typically declines. However, other factors such as local surface relief features or unusual concentrations of vegetation can completely override slope and distance effects, particularly where slopes are less than 10 percent and distances from water less than 1 mile. Under maximum effects of slope and distance, percent use decreased about 5 percent for each increase of 10 percent in slope, and decreased 3 to 3.5 percent for each increase of 0.1 mile from water. Under such conditions, either slope or distance can account for as much as 50 percent of the variability in use within a pasture. Light grazing of steep slopes in this study was only partly the result of lazy cows. The steeper slopes generally were occupied by less palatable species. Moreover, the steep slopes probably were not grazed until the forage was mature and well past its peak palatability.

17. Effect of salt on utilization. The placement of salt grounds can markedly alter utilization patterns and promote more even utilization of the perennial grass crop. Establishment of a new salt ground 1.5 miles from water midway in the study increased use within 0.5 mile of the new salt ground. Use averaged about 9 percent before establishment of the new salt ground and 25 percent afterward. Meanwhile, use in the remainder of the pasture increased from 38 percent to 41 percent.

18. Estimating stocking rates. Stocking rates were determined annually from a formula involving available annual and perennial grass, and past stocking adjusted to 40 percent use. However, because of the strong relationship between perennial grass production and rainfall (interaction product—item 2 of Research Highlights), estimating equations developed from records of rainfall, stocking, and use give stocking rate estimates that appear even better than those based on grass production, stocking, and use.

19. Economic evaluation of mesquite control. Estimates indicate that increased stocking made possible by increased grass production would recover mesquite control costs within about 6 years. Increased productivitiy can be expected to continue for 15 to 20 years after mesquite has been controlled.

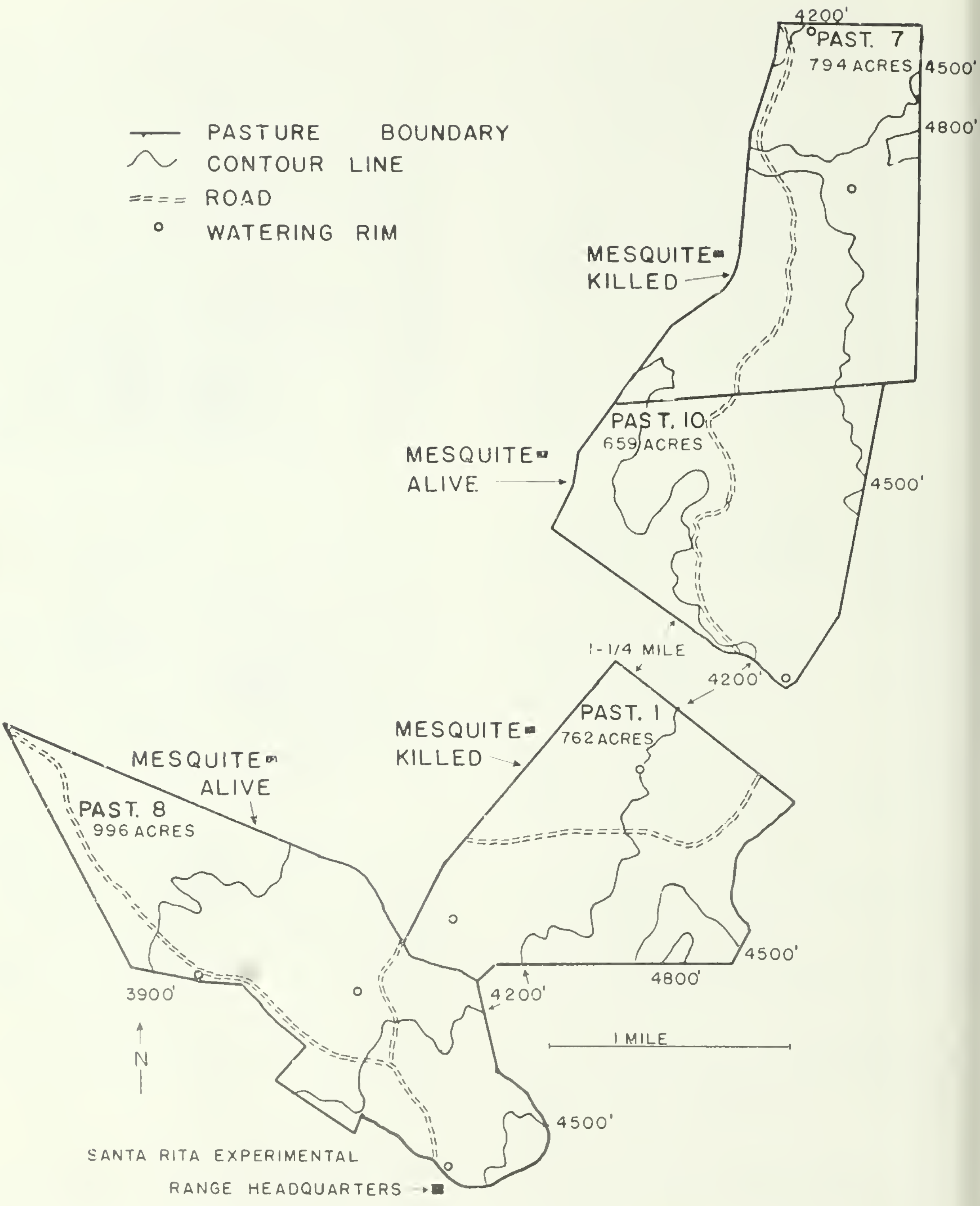


Figure 1.—Arrangement of pastures used in the study.

Vegetation Responses to Grazing, Rainfall, Site Condition, and Mesquite Control on Semidesert Range

Dwight R. Cable and S. Clark Martin

INTRODUCTION

Management of Southwestern rangelands must serve various purposes, among which are the raising of livestock, the production of wildlife, provision of open-space recreation opportunities for city dwellers, and the protection of the soil. These uses of rangelands all require (1) the maintenance of a vegetation cover on the land, (2) an understanding of the particular types of vegetation best adapted to particular uses, and (3) an understanding of the effects of particular uses on the vegetation.

This Paper discusses changes in vegetation during a 10-year period (1957 to 1966) on semidesert rangelands on the Santa Rita Experimental Range near Tucson, Arizona, as affected by climatic factors, cattle grazing, and the control of velvet mesquite.[2] Some preliminary results were discussed in an earlier paper (Cable and Martin 1964).

THE STUDY PASTURES

The four pastures used in this study were located on a narrow band of foothills along the base of the Santa Rita Mountains between elevations of 3,700 and 4,800 feet (fig. 1). Soils varied widely, from relatively deep coarse sandy loams on the flatter slopes (some with clayey subsoils), to shallow stony soils on the steeper slopes. Major soil series were Whitehouse, Comora, Coronado, and Tumacacori.

Average annual (October to September) precipitation varied among the four pastures from 14.7 to 18.6 inches from 1954 to 1966. Daily maximum temperatures during the summer were usually in the nineties, although a few days of 100+°F occurred most summers. Summer minimums generally were in the sixties. In winter, maximums in the high fifties or low sixties were typical, with minimums in the high thirties, although lows in the twenties, or occasionally below, were sometimes recorded.

Vegetation Cover

In the early years of this century the vegetation cover on these pastures was characterized as grassland, as evidenced by photographs and reports of early workers. In the ensuing 40 years, velvet mesquite rapidly invaded, with continued more gradual increases until 1954-57 when the mesquite in two of the pastures was killed. Prior to the start of this study, mesquite densities averaged from about 80 to 180 per acre, although one 0.5-acre plot contained 775 mesquites per acre. Perennial grass understory in 1957 varied from essentially none under the few very dense stands of mesquite to fair to good over most of the acreage (fig.2). Vegetation characteristics of the study pastures in 1957 were as follows:

Figure 2.—Representative area in pasture 10, supporting ocotillo and velvet mesquite, with the Santa Rita Mountains in the background. The grasses are mainly black grama and Arizona cottontop.

[2] *Nomenclature follows Kearney and Peebles (1951). Common and botanical names of plants mentioned are listed at the end of this paper.*

	Mesquite-killed	Mesquite-alive
Perennial grass basal intercept (percent)	0.82	1.09
Perennial grass herbage production (lb/acre)	221	299
Annual grass production (lb/acre)	179	38
Shrub crown intercept (percent)	9.58	12.16
Mesquite crown intercept (percent)	0.19	3.76
Mesquite density (trees/acre)	9	128

The major perennial grasses, in order of decreasing abundance, were: slender grama, side-oats grama, tall threeawns, Arizona cottontop, black grama, and sprucetop grama. Predominant annual grasses were sixweeks threeawn and needle grama. The most abundant shrubs, other than mesquite, were false-mesquite, velvetpod mimosa, and catclaw acacia.

Grazing History

The four pastures had been grazed yearlong by cow-calf herds since 1915. From 1915 to 1925 the stocking rates averaged from 32 to 34 head per section. Declining productivity showed, however, that such rates were too high, and numbers were reduced more or less progressively until around 1940. During the 16-year period, 1941-56, immediately before this study began, stocking rates averaged 16, 13, 14, and 15 animal units per section in pastures 1, 7, 8, and 10, respectively. Utilization of perennial grasses during this period averaged 60, 58, 59, and 47 percent in the four pastures.

METHODS

Mesquite Control

Mesquites in pastures 1 and 7 were killed between 1954 and 1957 by spraying the stem bases with diesel oil (Reynolds and Tschirley 1957). A followup treatment in 1960 killed new plants and the few plants missed in the original treatment. Costs for each treatment averaged about 5 cents per tree, although labor cost was proportionately higher for the followup treatment. The original treatment cost was split equally between labor and diesel oil. The followup treatment cost was divided 80 percent for labor and 20 percent for oil. More diesel oil was required in the original treatment (1.5 pints/tree) than in the followup treatment (0.75 pint) because most of the mesquites treated in the followup were small.

Grazing Management

Two changes in management were instituted in the fall of 1957 at the start of the study period: (1) the utilization objective was lowered to 40 percent, and (2) summer deferment (July to September) in alternate years was started. Deferment of summer grazing was started in one mesquite-killed (M-K) and one mesquite-alive (M-A) pasture in 1958 and in the other pastures in 1959.

Stocking rates necessary to obtain 40 percent use of perennial grasses were estimated separately for each pasture in October each year, based on measurements of annual and perennial grass produced during the previous summer. Multiple regression equations, to determine these stocking rates, were based on past records of annual and perennial grass yields, actual stocking, and utilization of perennial grasses. They were of the form:

$$S=b_1A+b_2P+a$$

where

S=estimated stocking for 40 percent utilization

A=current-year air-dry annual grass yield (lb/acre)

P=current-year air-dry perennial grass yield (lb/acre)

b_1, b_2, and a=constants derived from the regression computations involving prior production, stocking, and utilization data.

The procedure used in developing this equation was similar to that presented by Reid et al. (1963). A separate equation was developed for each pasture and recomputed annually to include data for the year immediately past.

Vegetation Measurements

Vegetation records were obtained at 20 randomly selected locations in each pasture. At each sampling location, a 100-foot line transect was established along which intercepts of vegetation were measured annually in late summer (except in 1960), by the method of Canfield (1942). A forage production transect, established adjacent to each intercept transect, was used for yearly early-fall measurement of annual and perennial grass production by the double-sampling technique of Wilm et al. (1944). At each transect, estimates were made on five permanent 9.6- by 1-ft plots, and on one temporary plot from which herbage was clipped and weighed. Utilization of perennial grasses was measured by the ungrazed-plant method (Roach 1950) in June each year on a 100- by 200-ft plot centered over the intercept transect. Crown diameters of all mesquites on the 100- by 200-ft plots were measured in 1957 and 1967, at the start and end of the study.

Other Records

Precipitation data were obtained from one standard rain gage in each of three pastures and two gages in the fourth pasture. Storm totals were obtained at two gages, and were interpolated from nearby recording gages for the other three gages. Soils information was available from two detailed surveys (Youngs et al. 1936).[3]

RESULTS AND DISCUSSION

Information pertaining to individual physical and biological attributes are presented first, either for the period of record (1954-66) or for the study period (1957-66), and then their interrelationships are discussed.

Analysis of Precipitation Records

The effectiveness of precipitation in producing grass herbage varies greatly with season of the year, and to a lesser extent with other factors such as size, spacing, and intensity of storms. Because of the two distinct rainy periods characteristic of southern Arizona, and the fact that growth of all our grass and shrub species depends on one or both of these rainy periods, annual precipitation for the four study pastures has been divided into four periods: the two rainy periods (June-September, and December-April) and the two intervening drier periods (October-November, and May). June is normally a very dry month too, but in about 1 year in 6 or 7, the first major storm of the summer rainy season occurs during the last 10 days of June; this rainfall is important in the production of herbage for that summer.

During the 13-year period from 1953-54 to 1965-66, annual precipitation for the four pastures averaged 17.07 inches (table 1). About 62 percent of the annual precipitation fell during June-September, about 10 percent in October-November, about 27 percent December-April, and less than 1 percent in May.

Table 1.--Four-pasture average of seasonal precipitation, by grass year (October 1 - September 30) for period of record (1954-66) and study period (1957-66)

Grass year	Oct.-Nov.	Dec.-Apr.	May	June-Sept.	Total
			Inches		
1953-54	0.21	4.13	0.69	11.31	16.34
1954-55	.55	3.16	0	16.25	19.96
1955-56	.47	3.53	0	5.12	9.12
1956-57	.49	4.51	.28	8.70	13.98
1957-58	2.71	6.09	.02	15.07	23.89
1958-59	2.45	1.20	0	12.17	15.82
1959-60	2.67	5.86	0	6.10	14.63
1960-61	1.67	3.41	0	12.94	18.02
1961-62	3.69	5.97	0	5.42	15.08
1962-63	.76	5.01	.04	8.64	14.45
1963-64	4.01	2.75	.03	14.65	21.44
1964-65	2.13	3.81	.15	8.97	15.06
1965-66	.98	11.48	.04	11.64	24.14
Mean	1.75	4.68	.10	10.54	17.07
			Percent		
	10.25	27.42	.59	61.74	100.00

Rainfall in September is a part of summer rainfall; however, only that rainfall received during the June-August period is intimately associated with perennial grass production. Al-

[3] *Clemmons, Stan, and L.D. Wheeler. 1970. Soils report, Santa Rita Experimental Range, Coronado National Forest. n.p. (Typed report by the Southwestern Region, USDA Forest Service, Albuquerque, N.M.; copy on file at Rocky Mountain Station's Research Work Unit, Tucson, Arizona.)*

though June-August precipitation varies widely from year to year (up to four times as much in one year as the next), a significant downward trend is evident in June-August rainfall during the period of record (fig. 3), averaging 0.38 inch decrease per year for the four pastures.

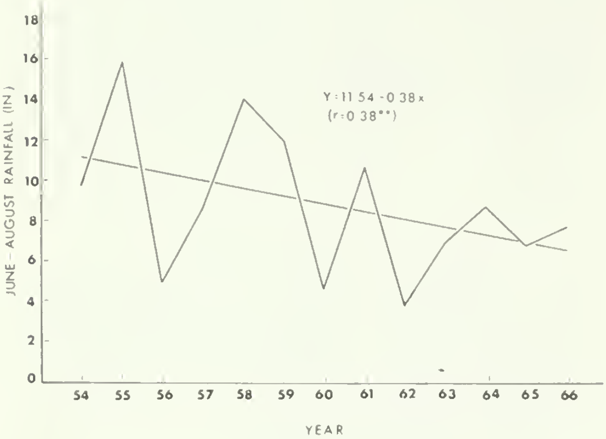


Figure 3.—Trends in June-August rainfall, showing average yearly rainfall for the four pastures and average trend.

Perennial Grass Production

Average perennial grass production for the 13-year period of record (1954 to 1966) varied from 314 lb/acre in pasture 7 to 465 lb/acre in pasture 1 (table 2). For the 10-year study period (1957-66), production varied from 352 to 524 lb/acre. Production in the highest year of the 10-year period was three to five times as high as in the lowest year.

Three-year moving averages of perennial grass production, computed for the 1957-66 study period for the two pairs of pastures (pastures 1 and 7—mesquite-killed; pastures 8 and 10—mesquite-alive), show that production on the M-K pastures increased 52.3 percent relative to that on the M-A pastures between 1957-59 and 1964-66 (fig. 4). Production on the M-K pastures held more or less steady, despite a 24 percent decrease in summer (June-August) rainfall, while production in the M-A pastures decreased somewhat more than did summer rainfall.

Effect of Deferment

Alternate-year summer deferment had no apparent beneficial effect on perennial grass production. This conclusion is based on a comparison of production on the two M-A pastures with that of a similar mesquite-infested pasture that not only was grazed yearlong, but was grazed more heavily during summer than winter in alternate years. Changes in perennial grass

Table 2.--Perennial grass production, with representative standard errors, for period of record (1954-66) and study period)1957-66)

Year	Pasture 1	Pasture 7	Pasture 8	Pasture 10
	Lb/acre			
1954	217	193	251	199
1955	389	300	242	417
1956	197	69	144	140
1957	282 ± 42	160 ± 19	241 ± 33	357 ± 27
1958	605	368	645	631
1959	773	568	742	857
1960	357	183	197	358
1961	744	575	480	559
1962	368 ± 28	116 ± 10	289 ± 42	169 ± 16
1963	475	288	353	223
1964	484	233	364	227
1965	584 ± 57	551 ± 39	393 ± 33	486 ± 32
1966	573	483	453	483
Mean:				
13-yr*	465	314	369	393
1957-66*	524 ± 13	352 ± 14	416 ± 11	435 ± 9

*Differences between pasture means significant at P = <0.05.

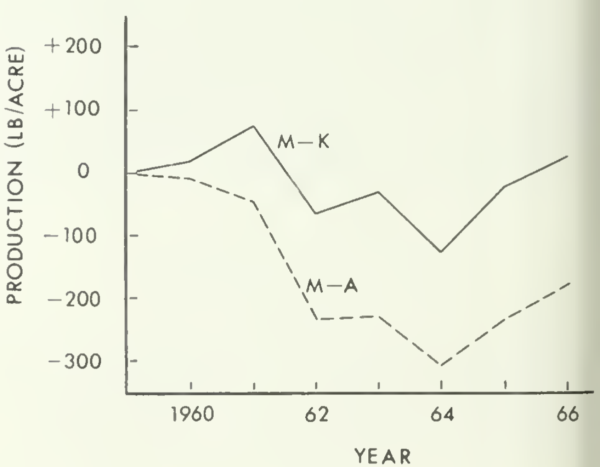


Figure 4.—Cumulative change in perennial grass production on mesquite-killed (M-K) and mesquite-alive (M-A) pastures (3-year moving averages ending on the indicated year).

production between the first 3 years and the last 3 years in this pasture were similar to those on the M-A pastures: 25.2 percent less production in the last 3 years, compared to 30.7 percent less on the M-A pastures. No similar comparison can be made for the M-K pastures because of the lack of an M-K pasture grazed yearlong.

The fact that summer deferment in alternate years did not improve perennial grass production on the M-A pastures does not mean that these ranges do not need, or will not benefit from, periodic rest. It does mean that resting at this season and frequency did not result in significant benefits. Other data collected on the Santa Rita indicate that other resting schedules do result in improved perennial grass density and production (Martin 1973). It is also possible that perennial grass production on the M-A pastures is at near-optimum levels for mesquite-infested ranges.

Composition of Perennial Grass Herbage

Of the 31 perennial grass species observed, from 15 to 22 were recorded in each pasture. Three to five species each contributed over 10 percent of the herbage and together produced 50 to 80 percent of the total. Four to eight other species contributed between 2 and 10 percent each, and the remaining 8 to 10 species contributed less than 2 percent each. Considering all four pastures, the dominant species were: slender grama, side-oats grama, tall threeawns, Arizona cottontop, and black grama. These five species, on the average, produced from 64 to 75 percent of the perennial grass herbage.

Relative amounts of herbage produced by species that contributed more than 1 percent of the total either for the first or last 3 years of the study period are shown in figure 5. For the five major species, standard errors for the means (fig. 5) are mostly between 20 and 50 percent of the means. Standard errors of the less common species in some cases exceed the means.

In general, the composition of pastures 1 and 7 was similar, with the same three major perennial grasses (slender grama, side-oats grama, and tall threeawns). In pasture 8, side-oats grama and Arizona cottontop were the most productive species in the 1957-59 and 1964-66 periods, respectively. In pasture 10,

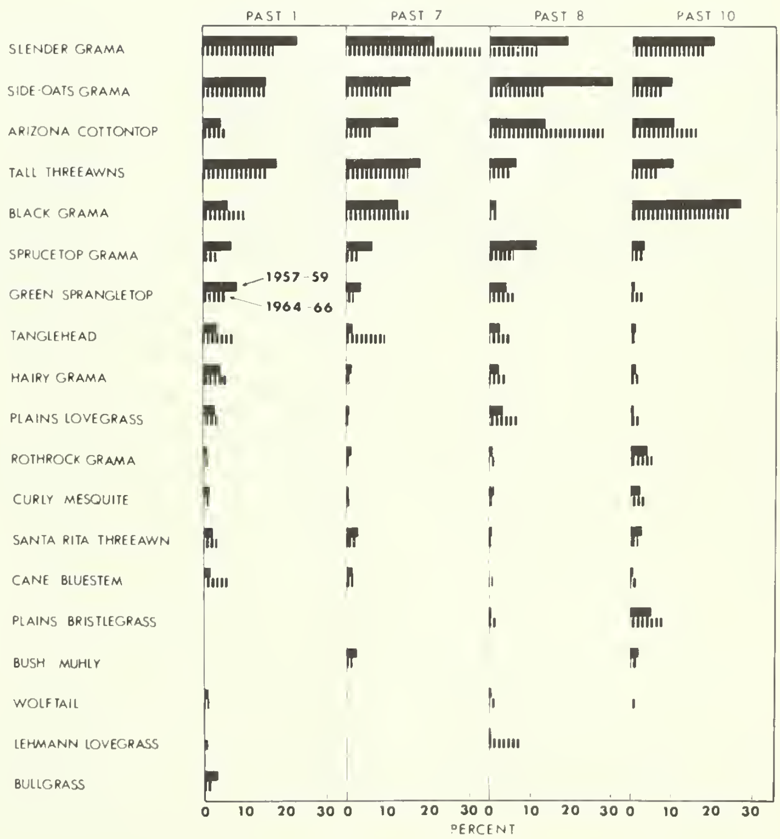


Figure 5.— Percentages of perennial grass herbage produced by individual species during the first 3 (1957-59) and the last 3 (1964-66) years of the study.

black grama was the most productive species throughout the study period. In each pasture, the most productive species in 1957-59 were nearly always the most productive in 1964-66, and in about the same order.

A few large changes in relative production were recorded. Among the major species, production of sprucetop grama decreased nearly 60 percent between the first and last 3-year periods. Among the minor species, tanglehead nearly tripled its production, and Lehmann lovegrass (an introduced species) increased from a four-pasture average of less than 1 lb/acre to over 7 lb/acre. The large relative increase in lovegrass was due mainly to an increase from 1.6 lb/acre in 1957-59 to 28.6 lb/acre in 1964/66 in pasture 8, as the grass spread from seeded areas onto adjacent native range.

Perennial Grass Basal Intercept

Basal intercept of perennial grasses is a measure of basal ground cover. For the 10-year study period, perennial grass basal intercept averaged from 1.50 to 2.02 percent for the four pastures. Intercept fluctuated less from year to year than did production, and measured 2.5 to 3.5 times as much in the highest year as in the lowest.

Basal intercept increased less than did production. Three-year moving averages show that intercept increased 40.2 percent on the M-K pastures relative to that on the M-A pastures between 1957-59 and 1964-66 (fig. 6).

Contributions by individual species to perennial grass basal intercept were somewhat different from their relative contributions to herbage production. As with production (fig. 5), however, the same five species were dominant (fig. 7), comprising from 62 percent to 70 percent of total perennial grass intercept.

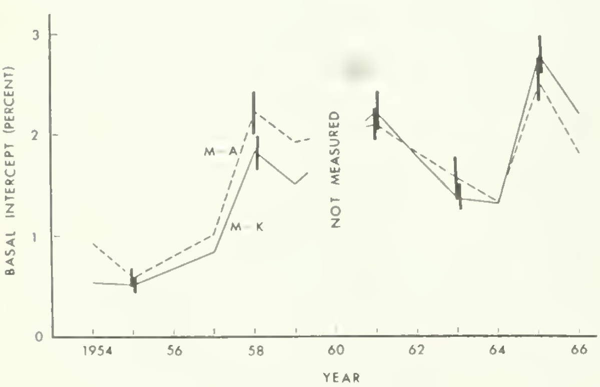


Figure 6.—Basal intercepts of perennial grasses for mesquite-killed (M-K) and mesquite-alive (M-A) pastures for the period of record ± one standard error for selected years.

Low-growing species produced less herbage per unit of basal intercept than the taller growing species. Table 3 shows average production (lb/acre) and average productivity per unit of basal intercept for the 17 most common species.

Table 3.--Average production and average productivity per unit of basal intercept for the 17 most common species on the four study pastures

Species	Average production	Productivity index[1]
	- - *Lb/acre* - -	
Curly-mesquite	5.7	0.93
Sprucetop grama	22.0	1.10
Santa Rita threeawn	8.5	1.66
Hairy grama	10.8	1.67
Slender grama[2]	85.7	1.92
Side-oats grama[2]	58.9	2.25
Black grama[2]	52.4	2.62
Rothrock grama	7.2	2.95
Tall threeawns[2]	55.7	3.26
Arizona cottontop[2]	63.0	3.72
Plains lovegrass	9.3	4.03
Lehmann lovegrass	3.4	4.45
Bush muhly	4.0	5.27
Green sprangletop	21.2	6.95
Tanglehead	16.1	8.24
Plains bristlegrass	7.2	8.27
Cane bluestem	8.9	8.60

[1]Weight of herbage per acre per 0.01 percent of basal intercept.
[2]Major species.

Thus curly-mesquite, Santa Rita threeawn, and the lower growing gramas produced the smallest amounts of herbage per unit of basal intercept, and the tall grasses—cane bluestem, plains bristlegrass, and tanglehead—produced the most. The five major species were intermediate in productivity. Standard errors of the productivity indexes varied from about 10 percent of the mean for high-producing species to 20-25 percent for low-yielding species.

Year-to-year variability (in terms of coefficient of variation, CV) averaged lower for the major species than for the minor species for both production and intercept. The important implication is that herbage yields of

Figure 7.—Average percent of total perennial grass intercept contributed by each species during the first and last 3 years (1957-59 and 1964-66) of the study.

the major species are more dependable than those of the minor species:

	Coefficient of variation Production	Coefficient of variation Intercept
	(Percent)	
Five major species	51	38
Seven minor species	64	75

Utilization of Perennial Grasses

Utilization of perennial grass herbage for the 1954-66 period of record on the four pastures varied from 29 percent to 65 percent; and was higher in dry years than in wet years (fig. 8). During the 3 years before the start of the study (1954-56) utilization in the four pastures averaged 55 percent; for the 10-year study period, use averaged between 35 percent and 44 percent, reasonably close to the desired 40 percent.

Utilization of individual species varied widely (fig. 9), and was related more strongly to preference by cattle than to relative availability on the range. Plains bristlegrass and Lehmann lovegrass, two of the three most heavily utilized species were minor producers, but one of the three least utilized species, black grama, was a major producer.

Up to this point we have considered the relative importance of perennial grass species only in terms of herbage production (lb/acre)

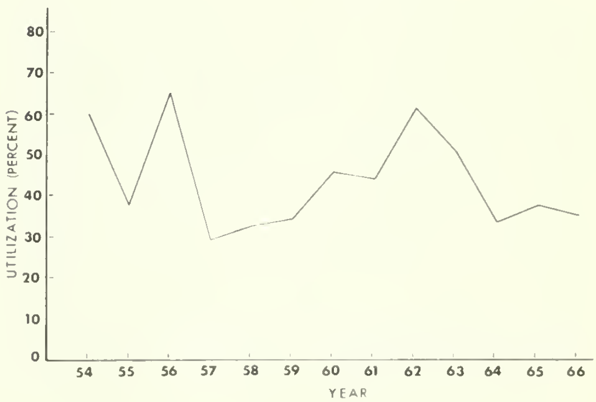


Figure 8.—Average utilization of perennial grass herbage (four-pasture average).

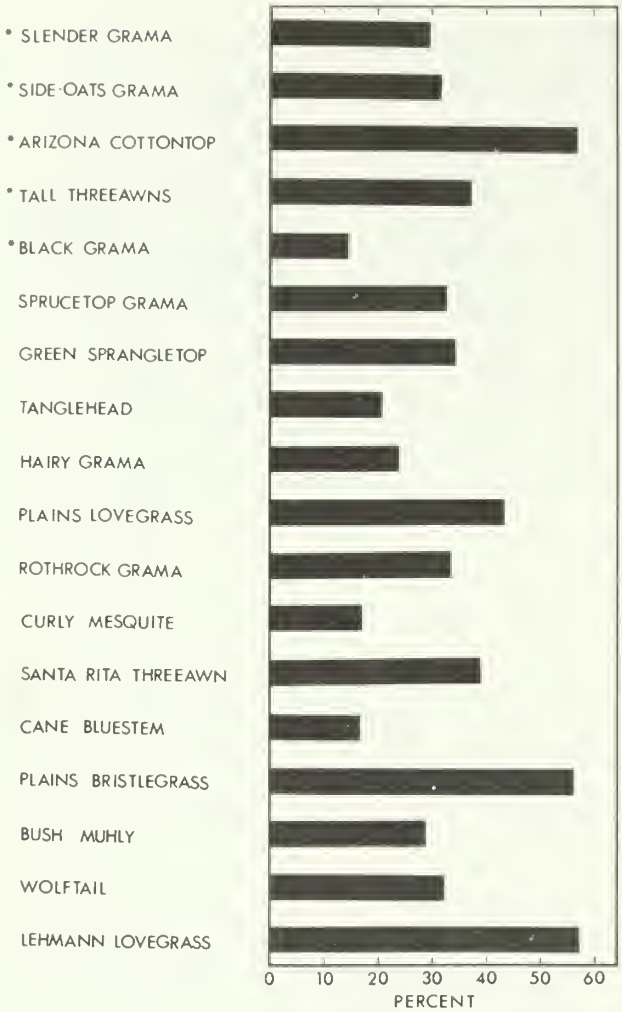


Figure 9.—Utilization of perennial grasses, first 3 and last 3 years averaged (five most productive species indicated by *).

and utilization (percent). Neither of these, alone, measures species importance as sources of forage. Pounds of grass consumed, however (a product of production times utilization), provides a useful basis for rating species.

On this basis, Arizona cottontop ranked first as a forage producer. It accounted for 22.4 percent of perennial grass consumed on the four pastures during the 10-year period (fig. 10). Slender grama ranked second; contributed 17.5 percent of the amount consumed. There was no correlation between production and consumption for the five major species.

For species of intermediate preference, consumption was in proportion to abundance, but for species near the high and low ends of the preference scale, consumption was disproportionately above and below abundance, respectively. Three of the major species—slender grama, side-oats grama, and tall threeawn—contributed to forage consumption about in the same proportion as their contribution to production, and are considered to be of intermediate palatability. Arizona cottontop contributed much more to forage consumption than to production. Black grama's contribution to herbage grazed, however, was relatively small. Cottontop made up between 20 and 25 percent of the total herbage grazed, while comprising only 13 to 14 percent of the total herbage produced, indicating that this species was definitely preferred. Black grama, on the other hand, produced about 12 percent of the herbage but accounted for only 7 percent of the herbage grazed. Other species that were preferred include Santa Rita threeawn and plains bristlegrass. Other less preferred species include tanglehead, curly-mesquite, and cane bluestem.

Production of Annual Grasses

Annual grass production varied from essentially none in 1962, the driest year, to 425 lb/acre on the M-K pastures in 1959 (fig. 11). Annual grass production fluctuated much more than perennial grass production, reflecting the greater dependence of annual grass on short-term growing conditions. The management implication is that annual grasses are an undependable source of forage, particularly in the drier years when forage is most needed.

Three major factors affected annual grass production: (1) rainfall, (2) mesquite competition, and (3) perennial grass competition. Annual grass production was closely correlated ($P<0.05$) with June-through-August rainfall, and even more closely with June-August rainfall for storms of 0.25 inch or more. Data for 9 of the 10 study years indicate that from 54 to 89 percent of the year-to-year variation in annual grass production was associated with changes in June-August rainfall.

Mesquite strongly affects annual grass production, although annual grass production varies widely from place to place over a relatively wide range of mesquite cover. Annual grass production can be essentially zero at any level of mesquite cover, but maximum annual grass production is limited by the amount of mesquite present, particularly where mesquite crown cover exceeds 10 or 12 percent. This inhibitory effect of mesquite is apparent in the regressions of annual grass production vs. June-August rainfall. Annual grass production increases least, per inch of increasing rainfall, where

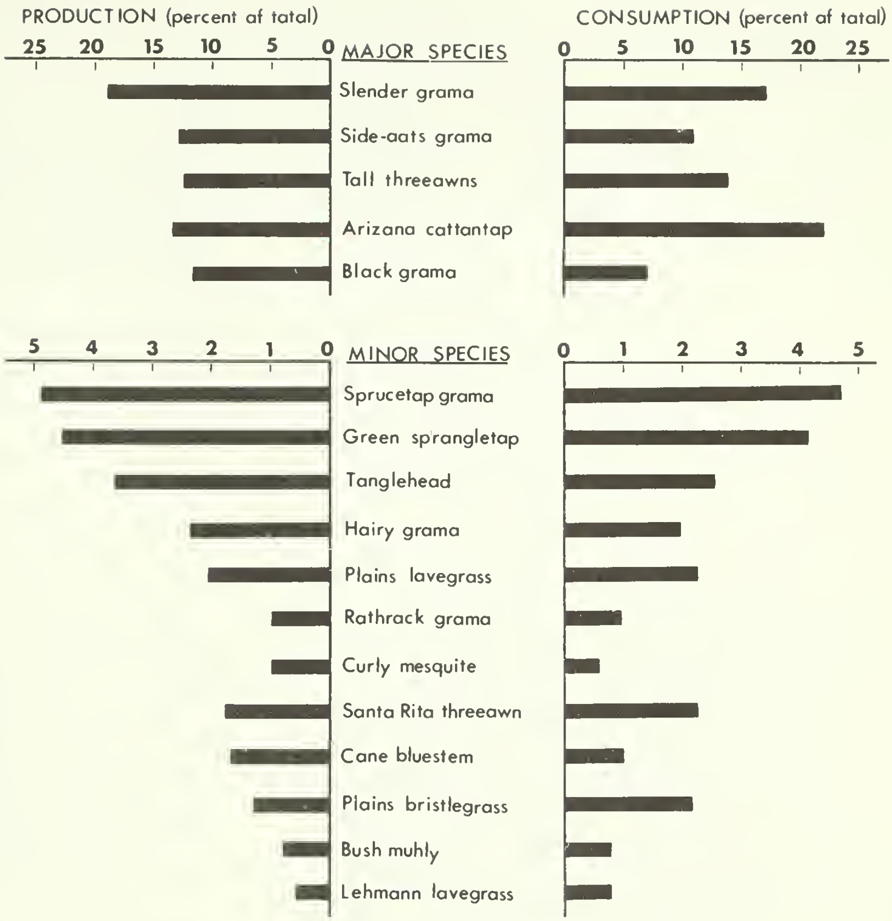


Figure 10.—Relative production compared to relative consumption of herbage for individual perennial grass species.

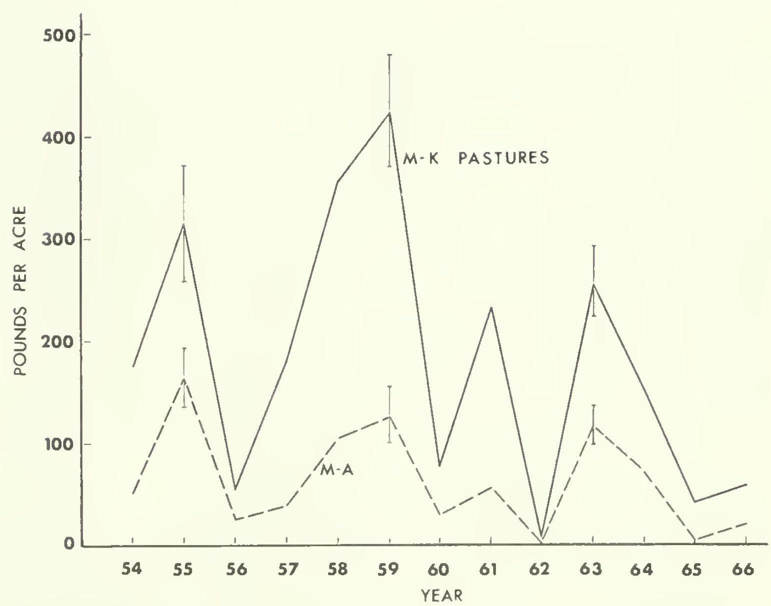


Figure 11.—Yearly production of annual grasses in mesquite-killed (M-K) and mesquite-alive (M-A) pastures, with standard errors for selected years.

mesquite crown cover is most dense (pastures 8 and 10) and most where mesquite cover is least dense (pastures 1 and 7):

Pasture	Mesquite cover	Increase per inch of precipitation
	(Percent)	*(lb/acre)*
1	0.46	29.2
7	.80	42.4
8	12.18	6.5
10	9.92	14.0

The influence of perennial grasses on annual grass production is difficult to isolate. Year-to-year changes in annual grass production tend to follow the same ups and downs as those for perennial grass production on any given transect, because they both are strongly affected by year-to-year changes in summer rainfall. Over a period of years, however, average annual grass production is negatively related to average perennial grass production, reflecting the strong competitive effect of perennial grasses on annual grasses.

This competitive effect can be illustrated by 8 of the 20 transects in pasture 1 (M-K). These transects are scattered over about 320 acres, but all are on smooth, gentle slopes of less than 10 percent, and all are on Comora sandy loam soil. They represent near-optimum conditions for grass production. Ten-year mean annual grass production varied between 75 and 506 lb/acre among transects, while mean perennial grass production varied between 292 and 336 lb/acre. In a strong negative linear relationship, 88 percent of the variation in annual grass production among the transects was accounted for by differences in perennial grass production. An increase in perennial grass production of 100 lb/acre resulted in a decrease of 75 lb/acre in annual grass production, with annual grass production reaching zero when perennial grass production was 940 lb/acre.

Changes in annual grass production were different in pasture 7, during the first half of the study period, than in the other three pastures. This difference is apparent in the ratios of annual grass production to perennial grass production (fig. 12). In general, on the four pastures, annual grass production varied from less than 10 percent as much as perennial grass production in dry years to nearly as much in some wet years. But in pasture 7, the ratio was 1.6 in 1957 and dropped sharply to less than 0.1 in 1962. Associated changes in perennial grass production show that perennial grass production increased 16 percent from the first to the last 3 years of the study period in pasture 7 while in the other three pastures production decreased as much as 35 percent (see table 2). These data suggest that, during the early years of the study, pasture 7 was recovering from a much more depleted condition than were pastures 1, 8, and 10. As perennial grass production increased, with recovery from the depleted condition, annual grass production decreased. Pasture 1 exhibited this same pattern to a somewhat lesser degree.

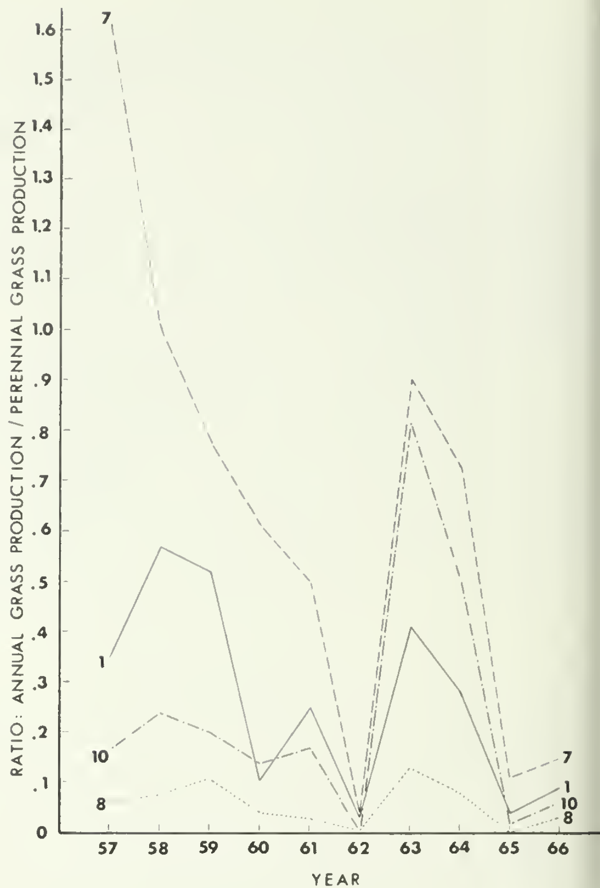


Figure 12.—Ratios of annnal grass production to perennial grass production in the four study pastures.

The particular combinations of environmental conditions that affected soil moisture relations, and thus annual and perennial grass production, varied widely among transect locations. In general, as environmental conditions became less favorable for grass growth (steeper slopes, shallower or rockier soils, more shrub competition, etc.) the competitive advantage of perennial over annual grasses increased, and relative annual grass production decreased.

Tree and Shrub Cover

Mesquite

Mesquite crown cover was measured by two means: (1) intercept of crowns on twenty 100-ft line transects in each pasture, measured annually, and (2) crown cover of all trees on twenty 100-ft by 200-ft plots in each pasture, measured in 1957 and 1966.

The intercept data indicate little change in mesquite crown cover during the study period. In the two M-K pastures (1 and 7), crown cover did not exceed 0.55 percent during the first 9 years of the study period; in the 10th year, however, it averaged 1.59 percent and 1.43 percent, respectively. In the two M-A pastures (8 and 10) mesquite intercept averaged 7.30 percent and 3.14 percent, respectively, for the 10-year period, and showed no real increasing trend.

Crown-cover measurements based on crown diameters of all mesquites on the 100- by 200-ft plots revealed a somewhat different picture. In 1957, mesquite crown cover in pasture 10 was one-third less than in pasture 8, but by 1966 differences were relatively small (table 4).

The crown-cover measurements probably portray changes in mesquite crown cover more accurately than do the intercept measurements because they constitute a much larger sample.

Other Shrubs

Most of the tree-shrub cover was contributed by species other than mesquite. Between 15 and 19 "other" shrubby species were recorded on the line transects in each pasture. Of these, four contributed 76 to 87 percent of the total of other-shrub intercept. False-mesquite ranked first among all shrubs, making up from 23 to 41 percent of total shrub intercept (including mesquite). Velvetpod mimosa ranked second among other shrubs, and was one of the four dominants in three pastures. Six other species were dominants in one or more of the four pastures.

Mesquite comprised 32 and 38 percent of total tree-shrub crown intercept on mesquite-alive pastures, but less than 2 percent on the mesquite-killed pastures (table 4).

Total tree-shrub crown cover was relatively high in 1959, 1964, and 1966, and low in 1961 and 1965 (fig. 13). In contrast to the relative stability of mesquite crown cover, intercepts of other shrubs varied more widely with year-to-year changes in growing conditions (table 4).

Vegetation-Precipitation Relations

Perennial grass plants grow and develop in two major phases: (1) enlargement of basal buds preparatory to shoot growth; (2) production of herbage by elongation, branching, and leaf development on the shoots. Each of these phases depends on precipitation at different periods of the year. The enlargement of basal buds depends primarily on late-summer rainfall. The enlarged buds then sprout the following spring or summer. Production of perennial grass foliage, therefore, depends partly on current summer rainfall and partly on that received during the previous summer.

Perennial Grass Production

Simple correlations between perennial grass production and rainfall show that, of the 4

Table 4.--Crown-cover measurements of mesquites, 1957 and 1966, and 10-year means of intercept measurements, on Mesquite-Killed and Mesquite-Alive pastures

Treatment and pasture	Crown cover (with standard errors)		10-year means of intercept		
	1957	1966	Mesquite	Other shrubs	Total
	- - Percent - -		*- - - - ft/100-ft transect - - - -*		
MESQUITE-KILLED:					
Pasture 1	0.53 ± 0.35	0.38 ± 0.11	0.16 ± 0.08	13.91 ± 0.96	14.07 ± 0.96
Pasture 7	1.15 ± .36	.45 ± .10	.05 ± .02	7.18 ± .62	7.23 ± .62
MESQUITE-ALIVE:					
Pasture 8	11.04 ± 2.16	13.31 ± 2.45	7.30 ± .54	11.44 ± .69	18.74 ± .84
Pasture 10	7.17 ± 1.31	12.67 ± 2.03	3.14 ± .45	7.15 ± .35	10.29 ± .58

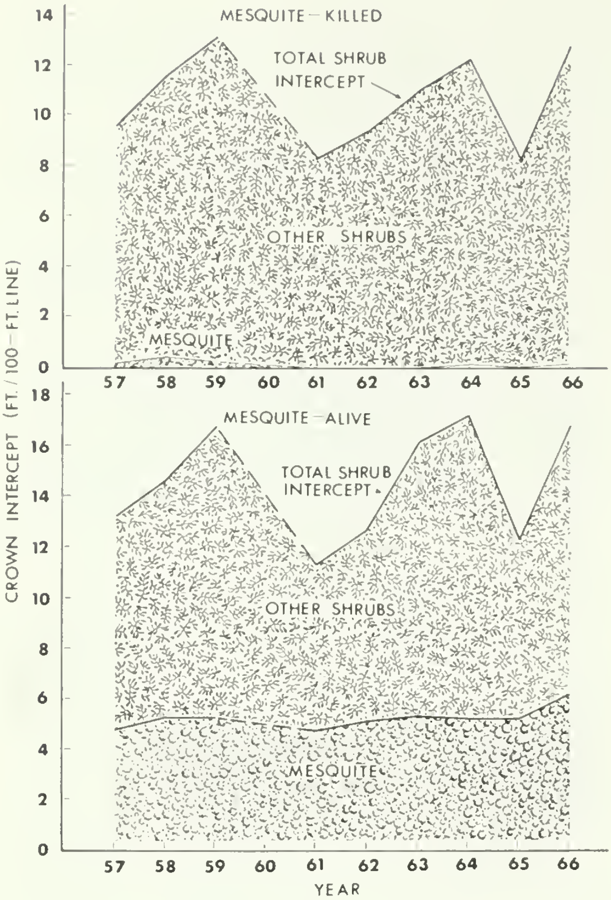


Figure 13.—Comporison of crown intercept of mesquite ond other shrubs in mesquite-killed ond mesquite-olive postures.

summer months, rainfall in August is most highly correlated with grass production for the current summer (r's=0.63 to 0.79 for the four study pastures). Rainfall for the June-August period is next most highly correlated. Correlations between the previous summer's June-September rainfall and current summer's grass production are low (0.22 to 0.28). However, the interaction rainfall term, obtained by multiplying previous June-September rainfall by current August rainfall (PJS x CAug, subject to an imposed maximum of 90.0 for the interaction product), yields much higher correlation coefficients (0.80 to 0.95) than either one alone.

Including all three of these relevant independent variables (CAug, PJS, and CAug x PJS) in a multiple regression equation is no improvement over the interaction rainfall term alone. It is clear that the effectiveness of a given amount of rainfall this summer is strongly affected by the amount of rainfall received last summer.

Regression equations indicate that perennial grass production in pastures 7, 8, and 10 responded in a similar manner to interaction rainfall, increasing from 8.3 to 9.2 lb/acre for each unit of increase in the interaction product (fig. 14). In pasture 1, because grass production was much higher for lower values of the interaction product, the increase in production was much smaller (5.5 lb/acre) for each additional interaction unit.

The influence of many other rainfall components on perennial grass production was also investigated. These components include various expressions of winter precipitation, alone and in combination with summer rainfall, as well as expressions involving size and spacing of storms. No improvement was obtained from these variables.

Low winter precipitation almost never limits perennial grass production the following summer, and high winter precipitation seldom increases summer grass production in the semidesert Southwest. The lack of correlation between winter precipitation and perennial grass production the following summer is due to: (1) the grasses are warm-season grasses, in which most of the development taking place within the grass plant during winter consists of physiological changes rather than the production of herbage, requiring little water, and (2) there is essentially no carryover of available soil moisture from spring to summer.

The five major perennial grass species (and "others" grouped) generally responded to the same precipitation components as the total,

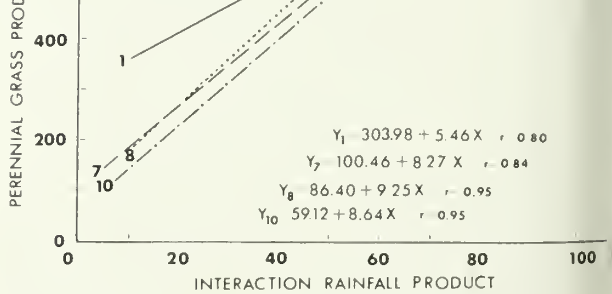


Figure 14.—Relation between perenniol grass production ond interoction roinfoll product (product of lost summer's June-September roinfoll times roinfoll for current August; $\leq$ 90.0).

although most correlation coefficients were somewhat lower.

Perennial Grass Basal Intercept

Changes in basal intercept are the direct result of the enlargement of basal buds. Buds usually enlarge in the early fall after herbage growth has been completed. The number and size of buds that develop during this period depend to some extent on the availability of soil moisture, which in turn depends on precipitation. Correlation coefficients relating September and October precipitation to perennial grass basal intercept measured the following summer are mostly between 0.66 and 0.82. The dependence on September and October rainfall is not strong, primarily because unusual precipitation events that wet the soil deeply at other seasons of the year can modify the typical time sequence of bud development. For example, unusually high winter-spring precipitation will activate additional buds in the spring growing period. And, unusually high rainfall during the summer growing period can also stimulate dormant buds to enlarge and sprout. Still, the size and productivity of the grass "factory" is dependent largely on the number and vigor of buds activated during the fall and winter.

Factors Affecting Utilization of Perennial Grasses

The grazing objective was to utilize 40 percent of the perennial grass available between the time of the forage survey in September and the following June 30. Year-to-year variations in percent use were associated negatively with the amount of perennial grass available per animal and to a lesser extent with the amount of perennial grass produced. These variables explain one-fourth to three-fourths of the year-to-year variation in percent use. Actual use seldom was exactly 40 percent, but the 10-year means were within about 10 percent of that objective.

Before considering utilization further, we should point out that the ungrazed-plant method of measuring utilization distorts the true percent use at the extremes. For example, a transect showing up to 7 percent of the plants grazed is recorded as having 0 percent use. Also, the maximum use that can be computed with the formula, even when 100 percent of the plants have been grazed, is 80 percent.

Percent use varied widely among the 20 transect locations in each pasture, and these differences among transects tended to remain more or less fixed year after year. Three-year averages of use during the first and last 3-year periods varied from 26.3 percent to 43.4 percent, but use on individual transects varied from 0 to 71.4 percent.

The average degree of use of perennial grasses at any given location was affected by several factors, including:

1. Species palatability and composition
2. Distance to water
3. Slope of the ground
4. Rate of stocking of the pasture relative to the amount of forage available.
5. Distance to a salt ground.

Species Palatability and Composition

The most influential factor affecting percent use at a given location was the relative palatability of the forage. Palatability, as used here, refers to the degree of utilization of a particular perennial grass species under conditions of adequate forage and free choice. The palatability values were based on means of the first 3 and last 3 years only. The highest average pasture use was 43 percent. Because scarcity of a given species might not allow true "free choice" by a grazing animal, a transect was included for a given species only if that species contributed 10 percent or more of total perennial grass production.

Palatability ratings varied among the 4 pastures and 20 species from 0 to 73 percent (table 5). For the 15 minor species, 4-pasture palatability ratings varied from 0 percent for bullgrass and spike pappusgrass to 62 percent for plains bristlegrass. Among the five major species, mean palatability varied from 12 percent for black grama to 57 percent for Arizona cottontop.

Differences in palatability among species were most apparent in wet years when abundant forage permitted cattle their freest choice. During drier years, as the more palatable species became fully utilized, use of less palatable species increased. The most palatable species were grazed heavily in both situations. For example, use of Arizona cottontop, the most palatable major species, averaged only 9 percent higher in a dry year (7.5 inches summer rainfall) than in a wet year (12.5 inches summer rainfall). Use of black grama, however, the least palatable major species, averaged 30 percent higher ($r=-0.80^{**}$) in the dry than in the wet year. Thus cattle grazed black grama only slightly when more palatable forage was readily available.

The distortion of free-access preferences by heavy use was evaluated by plotting species

Table 5.--Relative frequency and palatability ratings, by pastures, of perennial grasses ranking among three most productive species at individual transect locations; means of two 3-year periods, 1957-59 and 1964-66 (ratings in parentheses are based on less than four transects in a single 3-year period

Perennial grasses	Frequency	Palatability rating on pastures-- Mesquite-Killed 1	7	Mesquite-Alive 8	10	Mean
	Percent					
MAJOR SPECIES:						
Slender grama	100	28	37	29	30	31
Side-oats grama	69	21	37	23	35	29
Arizona cottontop	60	66	43	64	56	57
Tall threeawns	62	37	38	47	32	38
Black grama	49	10	15	(12)	12	12
MINOR SPECIES:						
Sprucetop grama	26	24	46	30	38	34
Green sprangletop	12	26	(62)	30	51	42
Tanglehead	13	(14)	32	(23)	(28)	24
Hairy grama	15	26	(73)	(16)	(13)	32
Plains lovegrass	13	31		40		36
Rothrock grama	10		(48)	42	37	42
Curly-mesquite	6	(20)	8	(0)	(28)	14
Santa Rita threeawn	11	(61)	51	(30)	(10)	38
Cane bluestem	8	8	(T)		(10)	6
Plains bristlegrass	10			62	61	62
Bush muhly	5		(51)		(44)	48
Arizona muhly	2			(38)		38
Lehmann lovegrass	6	(65)		47		56
Bullgrass	6	0				0
Spike pappusgrass	1				(0)	0

use over transect use for transects on which each species contributed 10 percent or more of total perennial grass production. Species use for the five major species, when transect use was 10 percent, varied from 0 for black grama to 35.6 percent for Arizona cottontop (fig. 15). These use values were strongly correlated with the palatabilities shown in table 5. At 80 percent transect use, however, even the less palatable species were heavily used (68 to 80 percent) and species use values were not significantly correlated with species palatability.

Correlations for the regressions in figure 15 varied from 0.75 to 0.90. All were highly significant. The regressions differed significantly, both among levels and among slopes. The differences in levels are, of course, due to differences in palatability. The differences in slopes are related more to availability than to palatability in that cattle turned increasingly to less palatable species as the more palatable species were grazed off. The practical implication is that the less palatable species cannot be fully used unless overall use is heavy, which should happen only in dry years if at all.

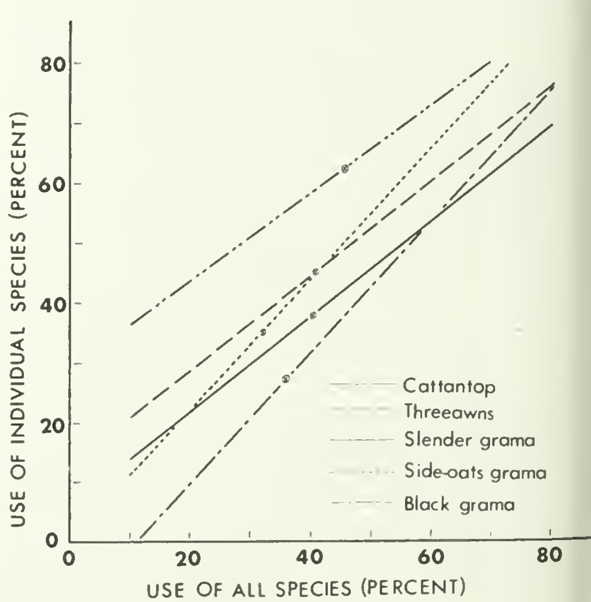


Figure 15.—Average use of individual major species relative to average use for all species.

To evaluate the effect of forage palatability on utilization at each of the 80 transects, a palatability-composition (P-C) index was derived from 3-year averages (1957-59 and 1964-66) of production and use of the three highest yielding perennial grasses on the transect, as follows:

Highest yielding grasses	Percent of production/100	Percent use/100	Product
1st	0.46	0.45	0.2070
2d	.27	.37	.0999
3d	.17	.36	.0612
P-C index			.3681

These palatability-composition indexes varied from 0.0408 to 0.6867. In simple linear regression, they appeared to account for from 61 to 94 percent of the variation in use among transects in a given pasture.

Distance to Water, and Topographic Influences

These variables interact strongly in their effect on forage use. The relationship between distance to water and percent use illustrates the overriding influence of local topographic and vegetation differences. For the four pastures together, the average effect of distance was to decrease use 0.5 percent for each 0.1 mile. Minimum use was about 10 percent for some transects throughout the range of distances, however, and the maximum effect of distance was to decrease use about 3.5 percent for each 0.1 mile from water (fig. 16).

The effect of steepness of slope on herbage use is confounded in part by differences in the preference of certain grass species for slopes of varying steepness. Of the 14 most productive species, 6 were most productive on slopes of 10 percent or less, 4 on slopes over 30 percent, and the other 4 produced about equally on all slopes. Of the species that preferred flatter slopes, four (Santa Rita threeawn, Lehmann lovegrass, plains bristlegrass, and Arizona cottontop) were only rarely found on slopes exceeding 15 percent. The other two (tall threeawns and hairy grama) occurred on slopes over 30 percent, but less frequently.

Of the four species that preferred steep slopes, three (cane bluestem, plains lovegrass, and green sprangletop) showed a strong preference (over 60 percent of their occurrence was on slopes over 30 percent). Side-oats grama was found also on the flattest slopes, but less frequently. Distribution of the four intermediate species (sprucetop, black and slender gramas,

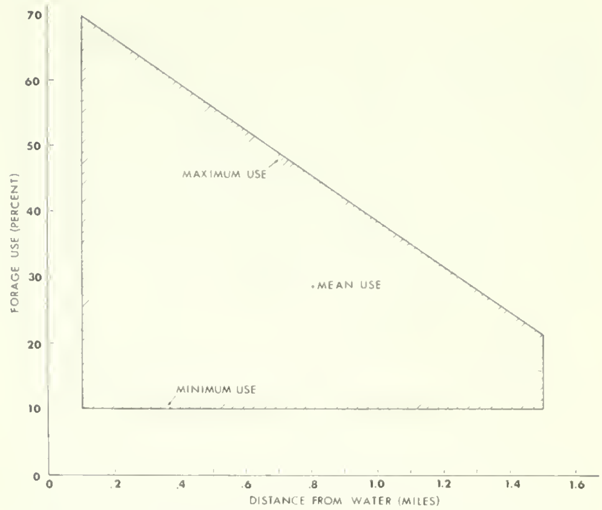


Figure 16.—Relationship between degree of forage use and distance from water.

and tanglehead) was apparently independent of slope.

Distance and slope, together with species palatability and composition, were sufficiently consistent in their effects on utilization to be combined in a multiple regression analysis. On an overall basis, using the 10-year mean percent use for each of the 80 transects as the dependent variable, the effects of palatability and composition, slope of the ground at the transect location, and distance to water are given by the equation:

$$\text{Percent use} = 27.40 + 64.84\ (\text{P-C index}) - 0.17\ (\text{Slope}) - 4.94\ (\text{Distance})$$

(overall F=90.92**).

Distances and slopes were in terms of miles (range: 0.1 to 1.5) and percent (range: 3 to 58), respectively.

According to this equation, mean use increased 6.5 percent for each increase of 0.10 point in the P-C index, decreased 1.7 percent for each 10 percent increase in slope, and decreased 0.5 percent for each increase of 0.1 mile from water. These three variables accounted for 78 percent of the variability in mean use among the 80 transects. On the individual pastures, with less diverse topography and vegetation, they explain from 78 to 93 percent of the variability in mean use among the 20 transects. In most cases, differences in the P-C index were responsible for most of the differences in percent use among transects.

The multiple regression also revealed a highly significant negative correlation between percent slope and the P-C index. This suggests that the more palatable species favor the flatter slopes, and the less palatable species either favor steep slopes, or in some cases are about equally common on all slopes. The significant negative relationship between percent use and slope, previously presented, must therefore be due to a combination of less palatable species on the steeper slopes and a preference by cattle to graze flatter slopes. The fact that the species on the steep slopes are, on the average, less palatable, may be one reason cattle prefer to graze flatter slopes.

Rate of Stocking

For any given forage crop and period of use, increased stocking will increase utilization. In this study, however, stocking was adjusted each year so as to achieve about 40 percent use of the perennial grass herbage. Differences in percent use from year to year tended to be correlated negatively with stocking rates.

Effect of Salt Placement on Utilization Patterns

The establishment of a new salt ground in 1961 in the northwest part of pasture 10, about 1.5 miles from water, provided an opportunity to evaluate the effect of salt on the grazing patterns of cattle. Mean use for the pasture as a whole was 7.5 percent higher in 1965-67 than in 1957-60, but mean use of the transects over 1 mile from water, in the northwest part of the pasture within 0.5 mile of the new salt ground, was 16.5 percent greater (difference significant at $P<0.01$). Meanwhile, the six transects in the northeast part of the pasture, 0.8 to 0.9 mile from water and 0.8 to 1.0 mile from the new salt ground, showed 5.5 percent decrease in use. This new salt ground, therefore, resulted in a significant increase in utilization of nearby areas at the expense of areas farther from salt.

Influence of Degree of Use on Productivity of Perennial Grasses

If the productive capacity of a range is to be maintained, management practices must permit the individual grass plants to remain healthy and vigorous. Since productivity is one of the best measures of range condition, we studied the productivities of the major species, and total productivity on transects used at different levels during the 10-year study. We used a trend analysis of variance of repeated measures, using the 10 years of production records, with the 20 transects in each pasture segregated into 4 groups of 5 transects each, on the basis of 10-year mean use. Mean use for Group 1 averaged from 21 percent to 28 percent among the four pastures, with Groups 2, 3, and 4 varying from 31 to 41 percent, 40 to 48 percent, and 52 to 59 percent, respectively.

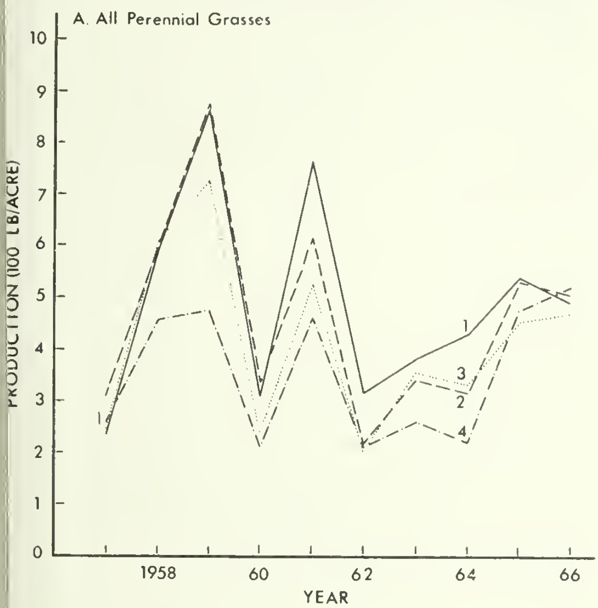
The analysis revealed significant ($P= <0.05$) differences in total perennial grass production among groups, and, more importantly, a highly significant year x group interaction, indicating that production on transects used at different levels did not react the same in different years. This kind of result would ordinarily be assumed to represent changing trends with time among the four groups. In this instance, however, the differences in reaction among groups was not so much a time-trend reaction as a reaction to differences in growing conditions in certain years. Thus, mean production values for the four groups were clustered closely in the first and last years of the study (1957 and 1966 in fig. 17A). In wet years, however, particularly those following very dry years (such as 1957, 1960, and 1962), large differences in production were apparent among use groups. Group 1 transects made the most pronounced gain in production, Groups 2 and 3 intermediate, and Group 4 the least. The logical inference, in terms of the growth and behavior of the grass plants, is that increasing levels of use, and particularly the heavy use in the fourth group, prevented the plants from maintaining optimum vigor. Therefore they were not able to respond fully to high rainfall for at least 2 years following a very dry year. By 1966, following three favorable growing seasons, Group 4 transects had apparently recovered from the 1962 drought. This finding has important management implications in that recovery following drought will be much lower and slower on ranges that are consistently utilized heavily than on moderately used ranges.

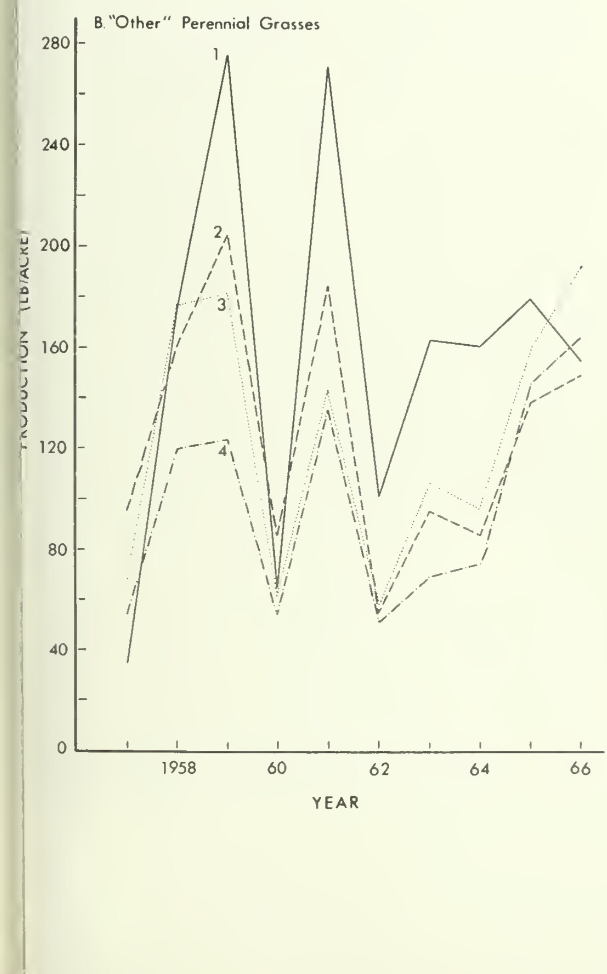
Similar analyses for the five major species and for all other perennial grasses, grouped, indicated that differences among species probably were related to inherent differences in tolerance to heavy use. "Other" perennial grasses, side-oats grama, and black grama exhibited the same fluctuation pattern as for all perennial grasses. Side-oats grama and "other" perennial grasses in particular, exhibited a very pronounced difference in production in the wet years between Use Groups 1 and 4, at the upper and lower extremes, respectively (fig. 17B).

The response of the "other" perennial grasses is of particular importance, in that these species as a group made up 30 percent of the total perennial grass production during the 10-year study—more than any single species

—and because they are especially sensitive to level of use.

Arizona cottontop, on the other hand, showed the largest wet-year gains on Group 4 (heavily used) transects and the lowest gains on Group 1 transects (fig. 17C). We interpret





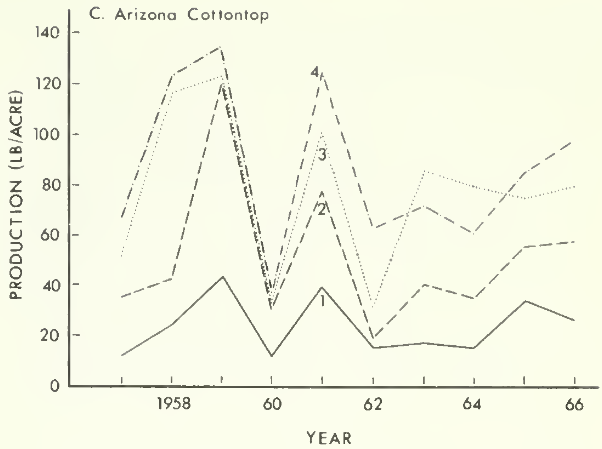


Figure 17.—Perennial grass production on transects used at different levels for the period 1957-66. Mean 10-year use for Groups 1, 2, 3, and 4 were 25, 37, 45, and 56 percent, respectively. A, All perennial grasses; B, "Other" perennial grasses; C, Arizona cottontop.

this response to mean that (1) cottontop can tolerate considerably heavier use than the other species, and (2) cottontop growth is stimulated by grazing. The nature of this growth stimulation undoubtedly is related to the fact that cottontop shoots contain many basal and culm buds (Cable 1971) which sprout easily and quickly when the terminal growing point is removed. With successively lower levels of use, fewer terminal growing points are removed and there is less stimulation to sprouting.

The response of slender grama differed from both of the previous types in that the major increases in wet-year production were on Groups 2 and 3 transects, with less response on transects in Groups 1 and 4.

Stocking Rates

Stocking rates were adjusted annually in the fall in response to changes in perennial grass production. Changes were not in direct proportion, however, because production varied more widely from year to year than cattle numbers could practicably be changed. Ratios of highest to lowest perennial grass production, for example, varied from 3:1 to 5:1 among pastures, while those for stocking varied from 2:1 to 3:1.

Ten-year average stocking on these pastures (for 40 percent use) varied from 22 to 38 head of cattle (15 to 32 head/section yearlong). Stocking rates for individual years were estimated by a regression formula derived from past records of annual and perennial grass production, and stocking adjusted to 40 percent use. These stocking estimates were strongly correlated (r's=0.79 to 0.93) with "backsight" estimates made at the end of each grazing year, of what the stocking rate should have been to obtain exactly 40 percent use. Standard errors of estimate varied between 3.3 and 7.3 head.

The regression formulas met the needs of the study very well, but they would not be useful for the average rancher who does not maintain records of forage production and stocking. The rancher needs an easier method. In an earlier section, a strong correlation between rainfall and perennial grass production was described. Since stocking depends on grass production and grass production depends on rainfall, a logical next step was to relate rainfall directly to stocking. To do this we used the product (Past June-September precipitation) x (Current August precipitation) as the independent variable and actual stocking adjusted to 40 percent utilization ("backsight stocking") as the dependent. These correlations of the "backsight" stocking rates for 40 percent use with the interaction rainfall products showed highly significant ($P = < 0.01$) relationships in all four pastures. From 73 to 94 percent of the year-to-year variation in stocking rates during 1957-66 would have been explained by changes in the rainfall product. Correlations were slightly higher (r's=0.85 to 0.97) and standard errors of estimate were lower (2.8 to 5.7 head) than for the stocking estimates based on grass production.

Thus, on these four pastures with relatively good stands of grass, and with mesquite overstory on two of them, stocking rates to obtain 40 percent use of perennial grass could have been determined as well from rainfall records as from forage estimates. Good records of actual stocking and utilization are necessary in either case, but rainfall is easier and cheaper to measure than is grass production. Successful use of such a relationship for estimating stocking rates also depends on maintaining the range in good vigor so that the grasses can respond quickly to changes in rainfall, especially following drought years.

Influence of Soil Type on Grass Composition and Production

Three soil types predominate on the study pastures: Whitehouse, with clayey subsoils and well developed horizons; Comora, with sands or sandy loams in the subsoil and weak profile development; and Coronado, a shallow, stony, and cobbly soil of the steeper slopes. Tumacacori soils, which are somewhat less coarse than Comora but otherwise similar, have been included with Comora. Surface textures of all soils are open, varying between loam and gravelly sandy loam. Thus the major differentiation among the three soils is in texture and depth of the subsoil. Of the 80 transects, 69 are on these three soils: 31 on Whitehouse, 23 on Comora (and Tumacacori), and 15 on Coronado.[4]

Fourteen of the twenty most common species of perennial grasses grew on all three soils, three grew on two of the three soils, and three species were restricted to a single soil type (table 6). Tall threeawns and slender grama, two of the five major perennial grasses in the study pastures, were also almost equally abundant on the three soils. Arizona cottontop showed strong adaptability to both the Whitehouse and Comora soils (slightly favoring the Comora), but dropped in ranking from third to tenth place on the Coronado soil. Side-oats grama, on the other hand, ranked fifth and fourth, respectively, on Whitehouse and Comora soil, but first on Coronado. Curly-mesquite and plains bristlegrass, which ranked eighth and eleventh, respectively, on Whitehouse soil, were not found on either of the other soils.

Table 6.--Relative productivity rankings of 20 perennial grasses on three soil types

Species	Whitehouse	Comora	Coronado
Tall threeawn	1	1	2
Slender grama	2	2	3
Arizona cottontop	3	3	10
Sprucetop grama	4	8	5
Side-oats grama	5	4	1
Black grama	6	5	9
Hairy grama	7	11	8
Curly-mesquite	8		
Green sprangletop	9	10	4
Spike pappusgrass	10	15	11
Plains bristlegrass	11		
Plains lovegrass	12	16	6
Bush muhly	13	13	
Tanglehead	14	6	14
Cane bluestem	15	14	7
Lehmann lovegrass	16	12	15
Santa Rita threeawn	17	7	
Rothrock grama	18	9	16
Arizona muhly	19		13
Bullgrass			12

[4] *Typed soil survey report dated July 31, 1967, on file at the Rocky Mountain Station's Research Work Unit, Tucson, Arizona.*

Soil type affected production differently for annual and perennial grasses. Perennial grass production (10-year mean) varied within a range of 83 lb/acre, and differences among soils were not significant. Production of annual grasses, on the other hand, differed significantly among the three soil types, and also between M-K and M-A pastures:

Soils	Perennial grasses	Annual grasses
	(lb/acre)	
Whitehouse:		
M-K	412	120
M-A	441	37
Comora:		
M-K	457	277
M-A	495	115
Coronado:		
M-K	487	22
M-A	439	57

Cost-Benefit Evaluation of Mesquite Control

The economics of mesquite control cannot be precisely evaluated because of lack of beef production and other cost data for these pastures. However, an economic evaluation can be approximated on the basis of increased stocking rates resulting from mesquite control.

Stocking rates on the M-K pastures increased 0.15 animal-unit month/acre (AUM/acre) relative to those on the M-A pastures, between 1957-59 and 1964-66. The economic value of this increase can be evaluated on the same basis as an increase in grazing capacity of an existing ranch unit due to improved management practices (O'Connell and Boster 1974). Many of the increased costs associated with such increases in grazing capacity (property taxes, insurance, utilities, etc.) are less per increased AUM than for the previously existing AUM's. O'Connell and Boster estimated a net return, as of 1972, of $5.82 per AUM from such range improvement practices. On this basis, the 0.15 AUM/acre resulting from mesquite control in this study would have a value of $0.87/acre/year.

Actual costs of killing the mesquite in pastures 1 and 7 with diesel oil sprayed on individual stem bases were higher than would be incurred on an operational basis using the most effective herbicides available. Two treatments in successive years with 2,4,5-T, aerially applied, would cost about $5.00 per acre, and provide about 90 percent release from mesquite competition. At this cost for mesquite control, the increased income would recover the cost in about 6 years. Because such control treatments commonly remain effective for 15 to 20 years, the treatments would be economically justified.

Mesquite control also results in other tangible and intangible benefits. Increases in perennial grass cover reduce runoff. Sheet erosion decreases and gullies heal. Opening up the shrub canopy improves visibility and makes handling livestock easier. Tree shade for cattle from other tree species and surviving mesquite would still be available, however. And finally, treated areas, with relatively large expanses of open grassland with interspersed trees, can be more esthetically pleasing.

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COMMON AND SCIENTIFIC NAMES OF PLANTS MENTIONED

Annual Grasses

Needle grama	*Bouteloua aristidoides* (H.B.K.) Griseb.
Sixweeks threeawn	*Aristida adscensionis* L.

Perennial Grasses

Arizona cottontop	*Trichachne californica* (Benth.) Chase
Arizona muhly	*Muhlenbergia arizonica* Scribn.
Black grama	*Bouteloua eriopoda* Torr.
Bullgrass	*Muhlenbergia emersleyi* Vasey
Bush muhly	*Muhlenbergia porteri* Scribn.
Cane bluestem	*Andropogon barbinodis* Lag.
Curly-mesquite	*Hilaria belangeri* (Steud.) Nash
Green sprangletop	*Leptochloa dubia* (H.B.K.) Nees
Hairy grama	*Bouteloua hirsuta* Lag.
Lehmann lovegrass	*Eragrostis lehmanniana* Nees
Plains bristlegrass	*Setaria macrostachya* H.B.K.
Plains lovegrass	*Eragrostis intermedia* Hitchc.
Rothrock grama	*Bouteloua rothrockii* Vasey
Santa Rita threeawn	*Aristida glabrata* (Vasey) Hitchc.
Side-oats grama	*Bouteloua curtipendula* (Michx.) Torr.
Slender grama	*B. filiformis* (Fourn.) Griffiths
Spike pappusgrass	*Enneapogon desvauxii* Beav.
Sprucetop grama	*Bouteloua chondrosioides* (H.B.K.) Benth.
Tall threeawns	*Aristida hamulosa* Henr. and *A. ternipes* Cav.
Tanglehead	*Heteropogon contortus* (L.) Beauv.
Wolftail (Texas timothy)	*Lycurus phleoides* H.B.K.

Trees and Shrubs

Burroweed	*Aplopappus tenuisectus* (Greene) Blake
Catclaw acacia	*Acacia greggii* A. Gray
Engelmann pricklypear	*Opuntia engelmannii* Salm-Dyck
False-mesquite	*Calliandra eriophylla* Benth.
Littleleaf krameria	*Krameria parvifolia* Benth.
Ocotillo	*Fouquieria splendens* Engelm.
Sacahuista	*Nolina microcarpa* S. Wats.
Velvet mesquite	*Prosopis juliflora* var. *velutina* (Woot.) Sarg.
Velvetpod mimosa	*Mimosa dysocarpa* Benth.
Wheeler sotol	*Dasylirion wheeleri* S. Wats.
Wright buckwheat	*Eriogonum wrightii* Torr.

Agriculture—CSU, Ft. Collins

Cable, Dwight R., and S. Clark Martin.
1975. Vegetation responses to grazing, rainfall, site condition, and mesquite control on semidesert range. USDA For. Serv. Res. Pap. RM-149. 24 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

Changes in herbage production, basal intercept, and grazing use of perennial grasses, herbage production of annual grasses, and crown intercept of shrubs and trees were related to changes in rainfall, presence or absence of velvet mesquite, and to differences in soil, topography, and salting. Over a 10-yr period, mesquite control increased perennial grass production 52 percent. Perennial grass production was highly dependent on both last summer's and this summer's rainfall, indicating that 2 yrs are required for recovery from a 1-yr drought. Too heavy use greatly restricted production in wet years that followed dry years. Because of the strong relationship between rainfall and grass production, stocking rates could be estimated as accurately from rainfall as from grass production.

Keywords: Semidesert range, mesquite control, grass production, rainfall effects, grazing effects, site conditions.

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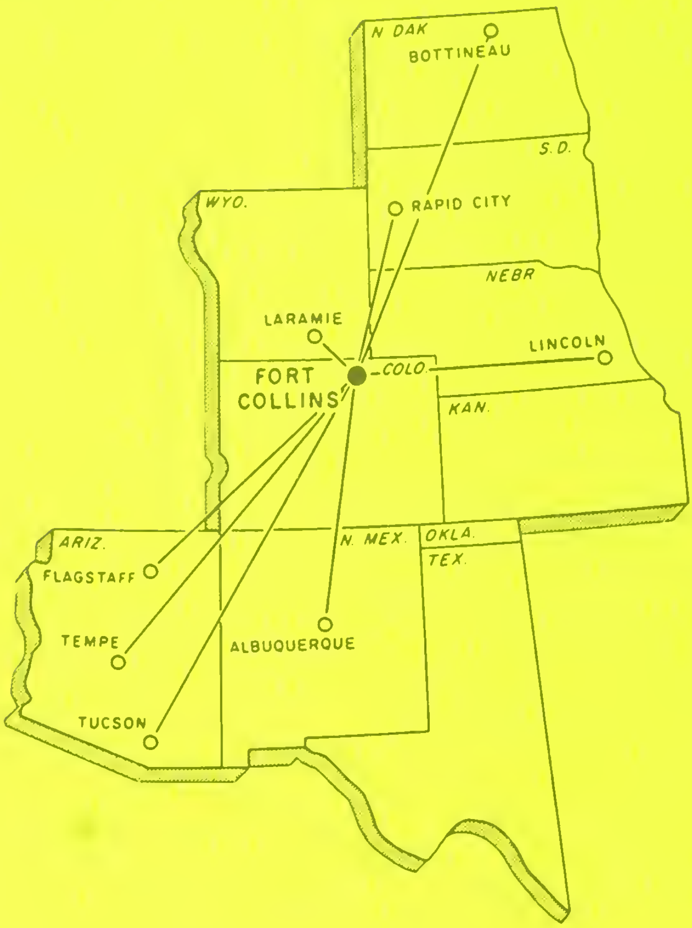
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rd A. Cunningham

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Rocky Mountain Forest and
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Forest Service
U.S. Department of Agriculture
Fort Collins, Colorado 80521

Great Plains Agricultural Council
Publication No. 71

July 1975

Abstract

Cunningham, Richard A.
1975. Provisional tree and shrub seed zones for the Great Plains. USDA For. Serv. Res. Pap. RM-150, 15 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521

The Great Plains Region was subdivided into 86 seed collection zones on the basis of soil, topography, water, and climate. Seed should be collected from the zone to be planted, or, if unavailable, from a zone having similar soil and climate. Future provenance test results will be used to determine any need for adjustments in zone boundaries.

Keywords: Seed zones, Great Plains, forest seed planting.

USDA Forest Service
Research Paper RM-150

July 1975

Provisional Tree and Shrub Seed Zones for the Great Plains

Richard A. Cunningham[1]

Great Plains Agricultural Council
Publication No. 71

[1]*Cunningham is a Forest Geneticist, now with the Rocky Mountain Region of the U.S. Forest Service, Denver, Colorado. He was formerly with the Rocky Mountain Forest and Range Experiment Station's Shelterbelt Laboratory at Bottineau, in cooperation with North Dakota State University - Bottineau Branch and Institute of Forestry. The Station maintains central headquarters in Fort Collins in cooperation with Colorado State University.*

Preface

This publication is sponsored by the Great Plains Agricultural Council. The Council is composed of Directors of the Agricultural Experiment Stations and Cooperative Extension Services of Colorado, Kansas, Montana, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, Texas, and Wyoming, and representatives of 11 agencies of the U.S. Department of Agriculture directly concerned with advancement of agriculture in these States.

This system of seed zoning was developed as one of the initial activities of Technical Committee GP-13, a regional tree improvement project sponsored by the Research Committee of the Great Plains Agricultural Council. The committee consists of 29 members from various State and Federal agencies in the 10 Plains States.

The development of tree seed zoning for the Great Plains was heavily dependent upon the many helpful suggestions of several GP-13 members, and their assistance is gratefully acknowledged.

Publication of this paper was a joint effort of the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, and The Rocky Mountain Region, Denver, Colorado. Copies may be obtained from either of these units of the Forest Service, U.S. Department of Agriculture.

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Contents

Provisional Tree and Shrub Seed Zones for the Great Plains

Introduction

Seed collection zones are subdivisions of land areas established to identify seed sources and to control the movement of seed and planting stock. Seed zones are needed for many species because of the genetic variation associated with their geographic distribution. Zone boundaries may be delineated from experimental data that identify genetic variation, or by analysis of the environmental factors that most likely acted as selective forces in creating such genotypic variation.

Why Seed Collection Zones are Necessary

Geographic variation within several tree and shrub species native to the Great Plains is well documented.

Significant variation in drought tolerance, height growth, and winter injury has been reported for *Fraxinus pennsylvanica* Marsh. by several investigators (Bagley 1970, Collins 1971, Meuli and Shirley 1937). In a provenance test of *Populus deltoides* Bartr. from 25 origins in the southern Great Plains, Posey (1969) detected significant variation among origins in growth rate, fiber length, and drought resistance. Conley et al. (1965) reported geographic variation among *Pinus ponderosa* Laws. seed sources from the northern Great Plains. After nearly 20 years' growth in north-central North Dakota, 10 origins varied considerably in survival, height and diameter growth, branching habit, and foliage density.

In a taxonomic study of *Juniperus* species in the Missouri River Basin, Van Haverbeke (1968) reported considerable intraspecies variation in a number of morphological traits for both *J. scopulorum* Sarg. and *J. virginiana* L., as well as evidence that the two species were hybridizing where their ranges overlapped.

Trees or shrubs grown from local seed are usually best adapted to conditions in that locality (Rudolf 1957). Although introduced races may sometimes be superior to local races, it is best to rely upon a local seed source whenever possible, unless a nonlocal seed source has proved superior in a comparative planting (provenance test).

In an area such as the Great Plains, where natural populations of trees are usually in small, widely scattered groves, it is often necessary to plant nonlocal races, since there are no local races available. For this reason, it is important to know whether the seed for a particular planting originated under conditions comparable to those of the planting site. One way to evaluate seed sources is to establish homogeneous seed collection zones, and identify each lot of seed used to produce planting stock by zone of origin. This procedure will also provide a means for checking field performance in relation to seed origin.

Criteria Used in Delineating Seed Zones

Since information on racial variation among tree and shrub species growing in the Great Plains is quite limited, a seed zoning system must be based primarily on criteria that are only speculative at this stage. After the system has been in use for a number of years, sufficient data should be available from outplantings to permit a reevaluation of the criteria used and the accuracy of the seed zone boundaries.

The USDA Forest Service made the first attempt at tree and shrub seed zoning in the Great Plains in its Prairie States Forestry Project (Engstrom and Stoeckeler 1941). Eleven zones were established in the entire Great Plains, based primarily on latitude. While this system was a step in the right direction, it has not been widely accepted or utilized by seed dealers or nurserymen in the Great Plains. Thus we must look to regions other than the Great Plains for examples of effective seed zoning.

California is divided into six physiographic and climatic regions, 32 subregions, and 85 seed collection zones (Buck et al. 1970). Criteria used in delineating the seed zone boundaries were latitude, elevation, and unusual climatic, topographic, or edaphic conditions that might affect tree growth.

In the Lake States, where topography is less important, Rudolf (1957) developed a series of zones on two temperature factors: (1) summation of normal average daily temperatures per year above 50° F, and (2) mean January temperature. He delineated 10 primary zones for Minnesota, and 8 each for Michigan and Wisconsin.

The forested areas of Arizona and New Mexico were divided into 10 physiographic-climatic regions; each were then subdivided into five to nine seed collection zones about 50 miles wide (Schubert and Pitcher 1973).

Seed collection zones in Ontario, Canada, are based on the site regions developed by Hills (1960). This system divides the Province into 12 regions based primarily on temperature and moisture; the regions are then subdivided into physiographic (landform) groupings differing in moisture, ecoclimate, and nutrients (Holst 1962).

In the Pacific Northwest, the Western Forest Tree Seed Council published maps in 1966 showing seed collection zones based on geographic zones and 500-foot elevation bands.[2]

These examples illustrate that a wide array of factors may be used in delineating seed collection zones. As part of an effort to determine the most reliable combination of environmental variables for delineating seed zones in the Great Plains, we surveyed nurserymen, tree planters, foresters, soil scientists, and geneticists working in the Plains. The criteria they most often suggested as being important for tree and shrub survival and growth were: adaptability to droughty sites, cold hardiness, and tolerance to adverse soil conditions. Primary climate and site factors that determine these criteria were chosen to form the base for the seed zoning system.

The soils of the Great Plains are described in detail in "Land Resource Regions and Major Land Resource Areas of the United States" (Austin 1972). Austin's map (fig. 1) delineating the major land resource regions and areas in the Great Plains was

[2]*Map, as revised 1973, is available from West. For. and Conserv. Assoc., Am. Bank Build., Portland, Oreg.*

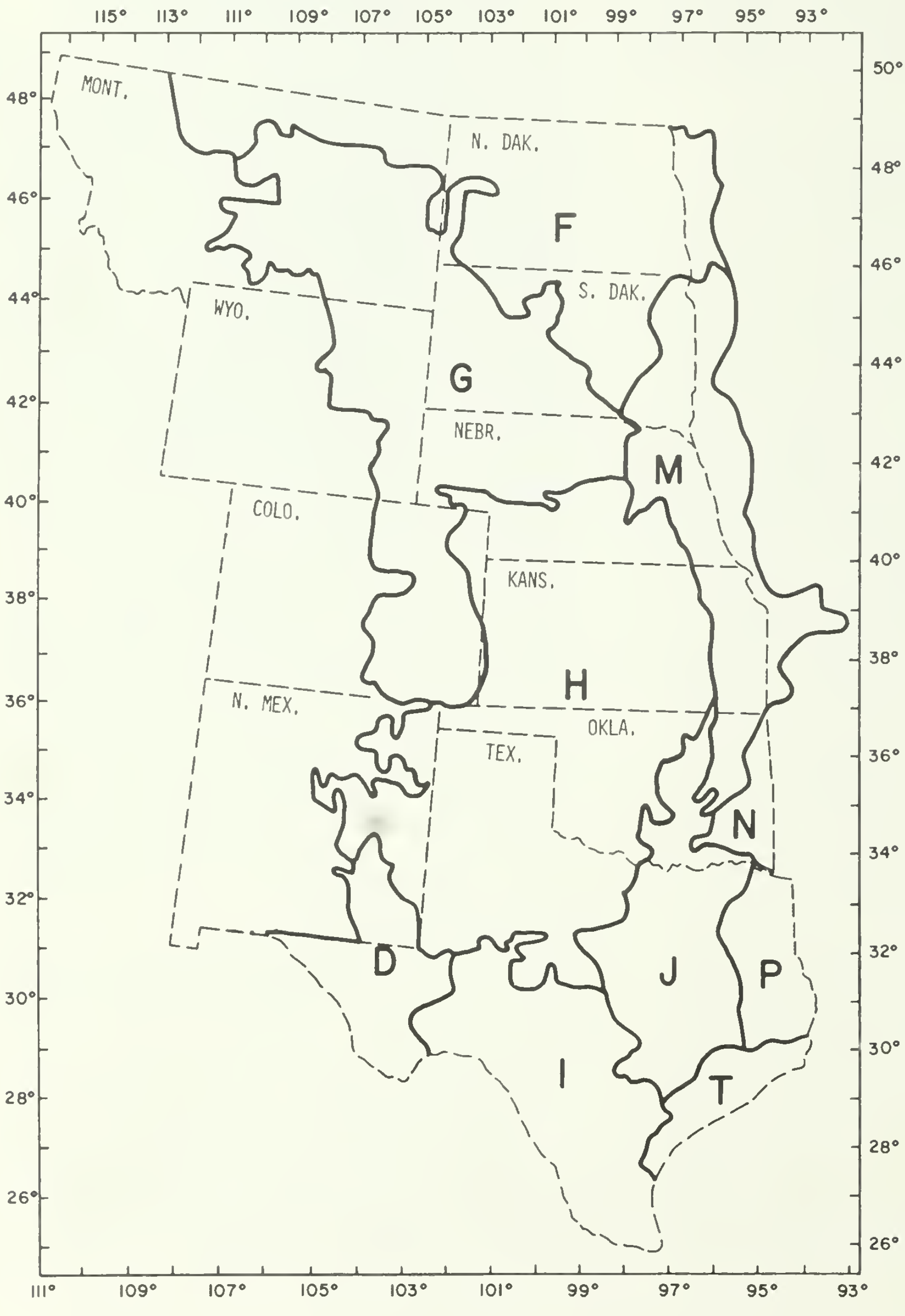

Figure 1.—Major land resource regions of the Great Plains (adapted from Austin 1972).

used as the base map for designating seed zones. Climatic data were taken from the "Climatic Atlas of the United States" (U.S. Department of Commerce 1968). The provisional seed zones were the result of superimposing the climatic data over the map of the major land resource areas (figs. 2, 3, 4).

Minimum winter temperatures were assumed to be the best measure of cold hardiness. Isopleths of mean January temperatures at 5-degree intervals were superimposed over the map of major land resource areas. This combination provided a good latitudinal division of many of the larger areas.

Isopleths of normal annual precipitation (4-inch intervals) were also superimposed over the land resource map. In most instances, longitudinal boundaries of the major land resource areas corresponded closely with isopleths of annual precipitation. The isopleths of annual precipitation were therefore used to subdivide the area only in instances where a seed zone would be larger than the 4-inch interval.

Boundaries of the seed zones were altered in some cases to make them conform to recognizable land features such as rivers, lakes, and highways. In several instances, several small major land resource areas were combined into one seed zone where differences among them were judged minor in their effect on tree growth and survival.

The proposed seed zones encompass an area somewhat larger than that normally considered the Great Plains, to provide at least a provisional system in those States with areas both within and adjacent to the Great Plains.

Numbering System for Seed Zones

The three- or four-digit designation (WXYZ) used in numbering the seed collection zones is a modification of the Soil Conservation Service's numbering system for the major land resource areas (Austin 1972). The major land resource areas are designated by two- or three-digit numbers in the XY and WXY positions. Division of the major land resource areas, which we designate as seed collection zones, are indicated by the digit in the Z position. Examples of this designation are:

Zone 552.—The **55** represents major land resource area 55 in the Northern Great Plains region. There is no thousand-digit in the W position. The **2** indicates seed collection zone 2 of land resource area 55.

Zone 1073.—Seed collection zone 3 in land resource area 107.

Land Resource Regions

The 10 land resource regions upon which this system of seed zoning is based (Austin 1972) are shown in figure 1. Regions D, M, P, and T are only partially within the area being considered, and therefore any references to these regions relate to individual land resource areas rather than the region as a whole. A brief description of each region follows.

D. Southern Desertic Basins, Plains, and Mountains (Seed Zones 421-422)

Broad desert basins and valleys range from 2,500 to 5,000 feet in elevation. Red Desert soils and Lithosols[3] are the dominant soils of the area. Annual precipitation averages 12 to 16 inches. Mean January temperatures range from 40° F in the north to 45° F in the south.

F. Northern Great Plains (Seed Zones 521-562)

Fertile soils and smooth topography characterize this region. Chernozems and Chestnut soils cover the western part. Other important soils are Lithosols on steep slopes, Solentz and Humic Gley soils on terraces and in depressions, and narrow bands of alluvial soils along major streams. Elevation varies from 1,000 feet in the east to 4,000 feet in the west.

Annual precipitation ranges from 10 to 24 inches; much of it falls during the growing season. Mean January temperature varies from 0° F in the north to 20° F in the south.

G. Western Great Plains (Seed Zones 581-700)

Unfavorable soils, strong slopes, or low moisture supplies make tree or shrub survival uncertain on all but the most favorable sites in this region. The topography rises from 2,000 feet elevation in the east to 6,000 feet in the west. Annual precipitation ranges from 11 to 24 inches, but fluctuates widely from year to year. Mean January temperatures vary from 10° F in the north to 40° F in the south.

[3] *For approximate equivalents of great soil groups, see appendix (table taken from Austin 1972, p. 81-82). In October 1973, the Soil Survey Staff prepared an interim publication for inservice use, "Preliminary abridged text—Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys," 330 p. USDA Soil Conserv. Serv., Wash., D.C.*

H. Central Great Plains (Seed Zones 710-803)

Soils, topography, and climate are more favorable for tree growth in this region than in the Great Plains to the north and west. Elevation increases from 1,000 feet in the east to 5,000 feet in the southwest.

The important soils in the north are in the Chernozem and Chestnut groups. Reddish Prairie and Reddish Chestnut soils are extensive in the south. Lithosols on steep slopes, Regosols in deep sands, and alluvial soils on flood plains are common throughout the area.

Average annual precipitation is 20 to 30 inches over much of the region, but ranges from 15 to 35 inches. Precipitation increases from northwest to southwest. More rain falls in summer than in the rest of the year. Mean January temperatures range from 25° F to 45° F, and increase from north to south.

I. Southwestern Plateaus and Plains (Seed Zones 811-833)

This region consists of the warmer part of the southern Great Plains. The moderate precipitation is accompanied by high temperatures so that precipitation effectiveness is low. Average annual precipitation is 20 to 30 inches over most of the region, but ranges from 15 to 35 inches; usually much of it falls in spring and autumn. Mean January temperatures range from 45° F to over 60° F.

Soils in the deeper coarse- and medium-textured materials are mostly in the Reddish Chestnut and Reddish Prairie great soil groups. Grumusols from limestones and marls and Lithosols and Calcisols in all kinds of parent material on hilly to steep slopes are also fairly extensive.

J. Southwestern Prairies (Seed Zones 841-871)

This region consists of the prairies and timbered areas of eastern Texas and south-central Oklahoma. Average annual precipitation ranges from 25 to 42 inches. Mean January temperature is 35° F to 55° F.

Grumusols, Rendzinas, and Lithosols from limestone and chalks are the more extensive soils. Red-Yellow Podzolic soils, Planosols, and Reddish Prairie soils are also important groups.

M. Central Prairies and Loess Drift Hills (Seed Zones 1021-1122)

Fertile soils and favorable climate make this region more suitable for tree survival and growth than almost any other region in the Great Plains. Annual precipitation is 25 to 35 inches over much of the region, but ranges from 20 inches in the extreme north to 45 inches in the south. Mean January temperature varies from 10° F in the north to 40° F in the south.

Chernozems are dominant in the north, while Brunizems are the major soils in the central area. Planosols are prevalent in the south. Alluvial and Humic Gley soils are common on flood plains.

N. Ouachita Mountains (Seed Zone 1191)

This region is characterized by steep mountains and narrow stream valleys with steep gradients. Elevation varies from 300 feet on the lowest valley floors to 2,700 feet on the highest mountain peaks. Lithosols and rough stony land occupy most of the steep slopes throughout the area. Red-Yellow Podzolic soils are on the gentle slopes of ridgetops, benches, foot slopes, and old stream terraces.

Annual precipitation averages 44 to 56 inches. Mean January temperatures vary from 42° F to 45° F.

P. Gulf Rolling Plain (Seed Zones 1331-1332)

This region of gently sloping to rolling plains varies in elevation from 100 to 300 feet, with small areas approaching 500 feet. Red-Yellow Podzolic soils are dominant throughout the region.

Annual precipitation averages 46 to 56 inches, with most of it falling in winter and spring. Mean January temperature varies from 45° F in the north to 55° F in the south.

T. Gulf Coast Prairies (Seed Zones 1501-1502)

This region consists of the nearly level low parts of the Gulf Coastal Plains. Elevation ranges from sea level to about 200 feet along the interior margin. Grumusols, Planosols, and Low-Humic Gley soils, all from calcareous clays and marls, are the dominant soils.

Annual precipitation averages from 26 inches in the west to 56 inches in the east. Mean January temperature varies from 55° F to 60° F.

Putting the Seed Collection Zones to Use

To be effective, the zones should be used by all agencies collecting and using tree and shrub seeds within the Great Plains region. Use of the zones not only will provide valuable information about the origin of the seed used to produce planting stock, but will also enable the consumer to select planting stock with adequate survival and growth potential.

Tree and shrub species not native to the Great Plains have been planted extensively in the region for many years. Many of these plantings are now bearing seed and, though often of unknown origin, are the only local source of seed available for these species. Seed collected from these plantings of untested exotics should be used with caution, since these populations have not been subjected to the long-term selection pressures of cold, drought, insects, and diseases that have resulted in locally adapted races of native species.

Plantings of exotic species that have attained at least three-fourths of their life expectancy and appear healthy and are growing vigorously may be used as seed sources with reasonable assurance they will produce planting stock adequately adapted to the seed zone in which the parent trees are growing.

This scheme for seed zoning is designed to make the process of identifying seed sources easier for the nurseryman. When seed is collected it should be labeled accurately as to origin, in as much detail as possible. Often this means specifying section, township, and range. In several States this information is mandatory under seed labeling laws. When the seed is planted by nurserymen, however, only the seed collection zone number need be used in identifying a particular lot of seedlings. Thus several different seed sources might be grown together in one lot of seedling stock, which would be designated as having been grown from seed of a particular seed collection zone. This procedure should vastly reduce the number of seed lots that must be kept separate in the nursery, but would still provide valuable information about the seed source.

This seed collection zoning system is provisional at this time. When sufficient information on racial variation within several tree and shrub species growing in the Great Plains is available, the system will be revised as necessary to reflect any changes suggested by analysis of such data.

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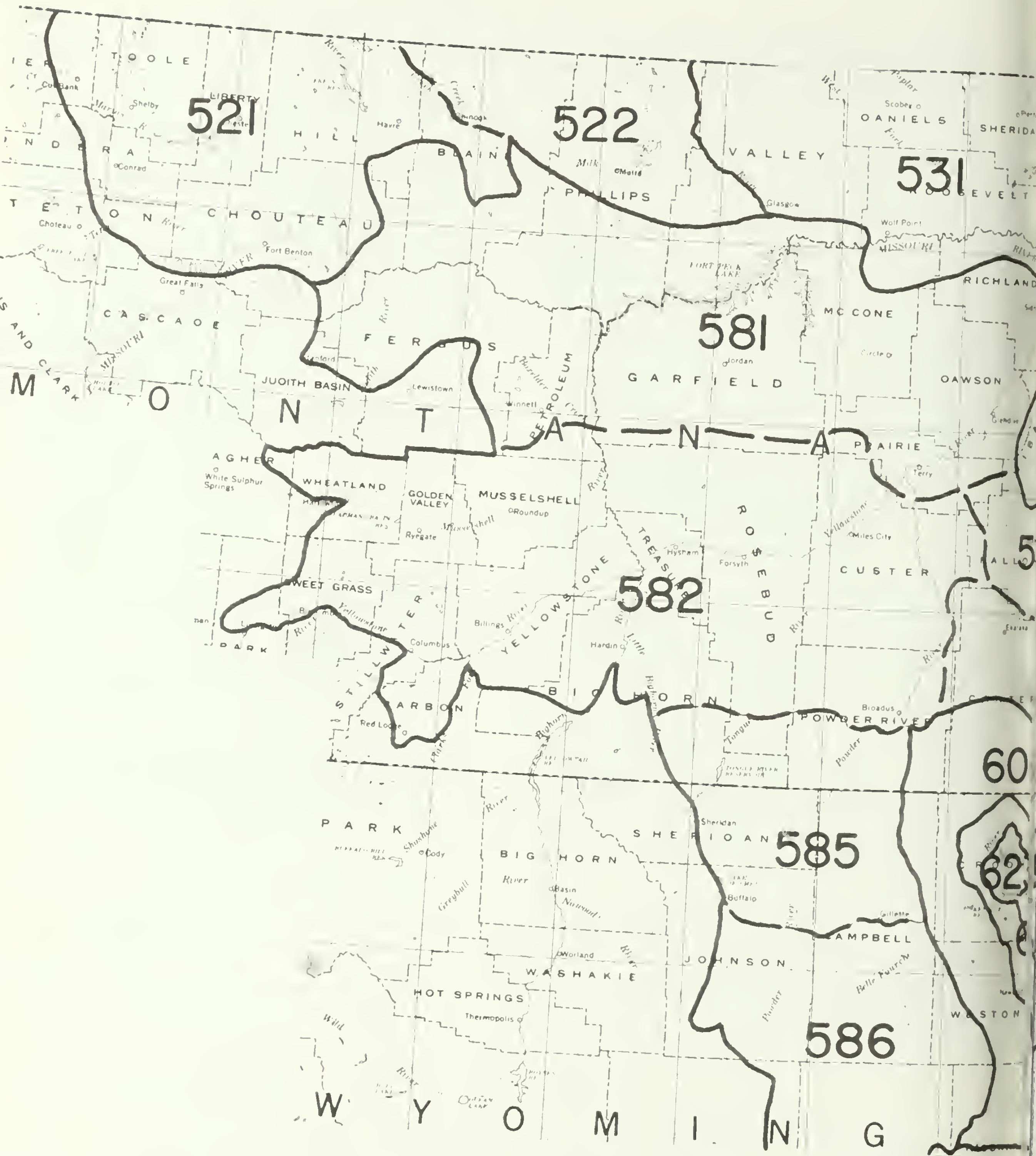
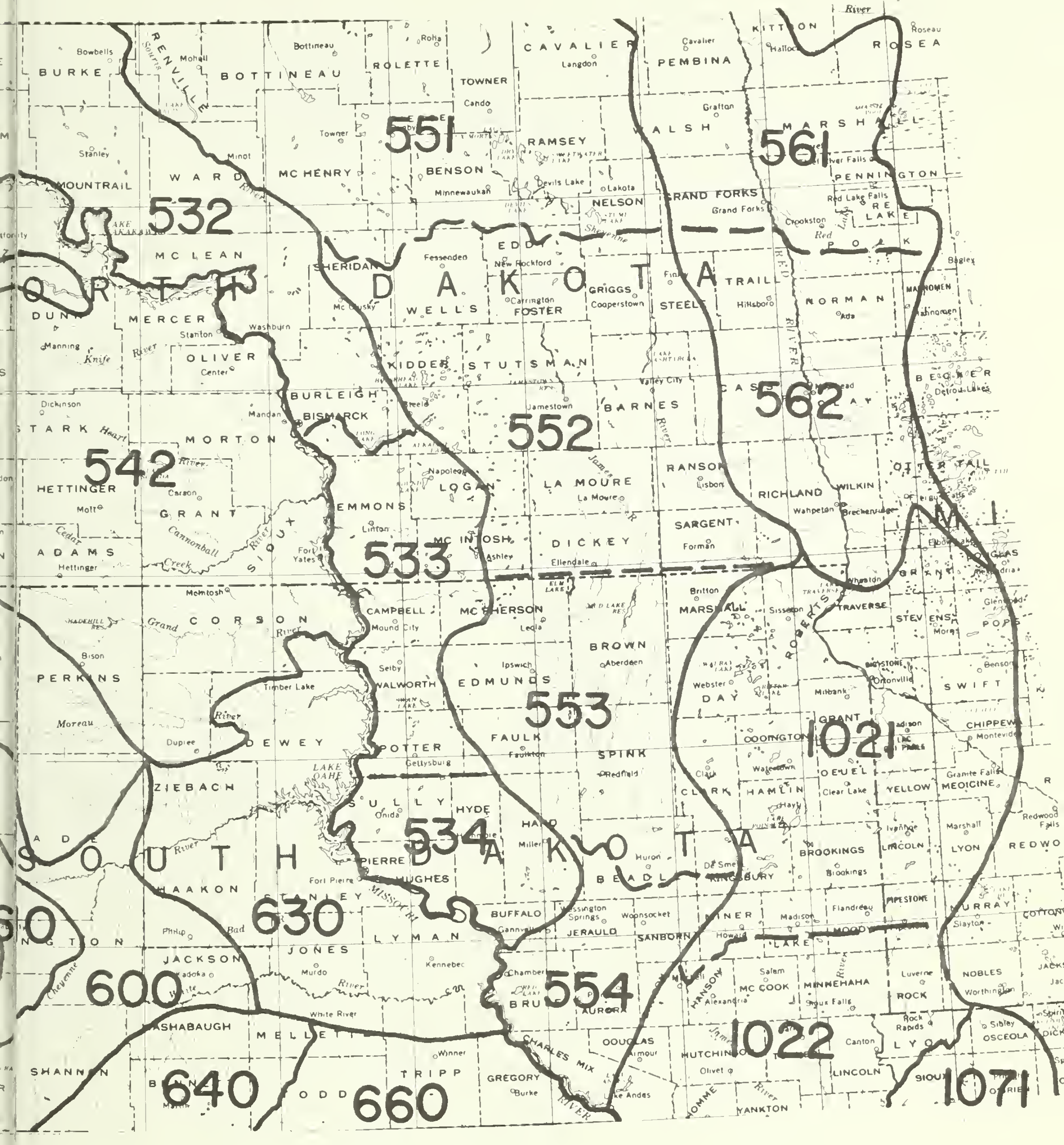


Figure 2.—Provisional seed zones for the Northern Great Plains.



NORTH DAKOTA
SOUTH DAKOTA
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640
660
1071
BURKE
RENVILLE
BOTTINEAU
ROLETTE
TOWNER
CAVALIER
PEMBINA
KITTSON
ROSEA
MARSHALL
RAMSEY
BENSON
MC HENRY
WARD
MOUNTRAIL
MC LEAN
NELSON
GRAND FORKS
PENNINGTON
RED LAKE
POLK
EDDY
SHERIDAN
WELLS
FOSTER
GRIGGS
STEELE
TRAILL
NORMAN
MAHNOMEN
DUNN
MERCER
OLIVER
KIDDER
STUTSMAN
BURLEIGH
BARNES
STARK
MORTON
HETTINGER
GRANT
EMMONS
LOGAN
LA MOURE
RANSOM
RICHLAND
WILKIN
OTTER TAIL
ADAMS
SIOUX
MC INTOSH
DICKEY
SARGENT
CORSON
CAMPBELL
MC PHERSON
BROWN
MARSHALL
ROBERTS
TRAVERSE
STEVENS
POPE
PERKINS
WALWORTH
EDMUNDS
DAY
GRANT
SWIFT
CHIPPEWA
DEWEY
POTTER
FAULK
SPINK
CODINGTON
DEUEL
YELLOW MEDICINE
ZIEBACH
SULLY
HYDE
HAND
CLARK
HAMLIN
LINCOLN
LYON
REDWOOD
HUGHES
BEADLE
KINGSBURY
BROOKINGS
HAAKON
STANLEY
BUFFALO
JERAULD
SANBORN
MINER
LAKE
MOODY
PIPESTONE
MURRAY
JONES
LYMAN
JACKSON
AURORA
HANSON
MC COOK
MINNEHAHA
ROCK
NOBLES
BRULE
DOUGLAS
HUTCHINSON
MELLETTE
TRIPP
GREGORY
CHARLES MIX
LINCOLN
SHANNON
BENNETT
TODD
YANKTON
LYON
OSCEOLA
O'BRIEN
SIOUX
Bowbells
Mohall
Bottineau
Rolla
Cando
Langdon
Cavalier
Hallock
Roseau
Grafton
Towner
Stanley
Minot
Minnewaukan
Devils Lake
Lakota
Grand Forks
Crookston
Red Lake Falls
Fessenden
New Rockford
Carrington
Cooperstown
Hillsboro
Ada
Washburn
Stanton
Center
Manning
Dickinson
Mandan
Bismarck
Steele
Jamestown
Valley City
Detroit Lakes
Carson
Mott
Hettinger
Napoleon
La Moure
Lisbon
Wahpeton
Breckenridge
Linton
Ashley
Ellendale
Forman
Fort Yates
McIntosh
Mound City
Leola
Britton
Sisseton
Wheaton
Bison
Selby
Ipswich
Aberdeen
Webster
Milbank
Ortonville
Benson
Timber Lake
Dupree
Gettysburg
Faulkton
Redfield
Watertown
Clear Lake
Montevideo
Granite Falls
Onida
Miller
Huron
De Smet
Brookings
Marshall
Ivanhoe
Pierre
Fort Pierre
Wessington Springs
Woonsocket
Howard
Madison
Flandreau
Slayton
Philip
Kadoka
Murdo
Kennebec
Chamberlain
Salem
Alexandria
Sioux Falls
Luverne
Worthington
White River
Armour
Canton
Rock Rapids
Sibley
Winner
Burke
Olivet
Lake Andes
Yankton
Missouri River
James River
Red River
Sheyenne
Cannonball
Grand River
Moreau
Cheyenne
Bad
White River
Lake Oahe

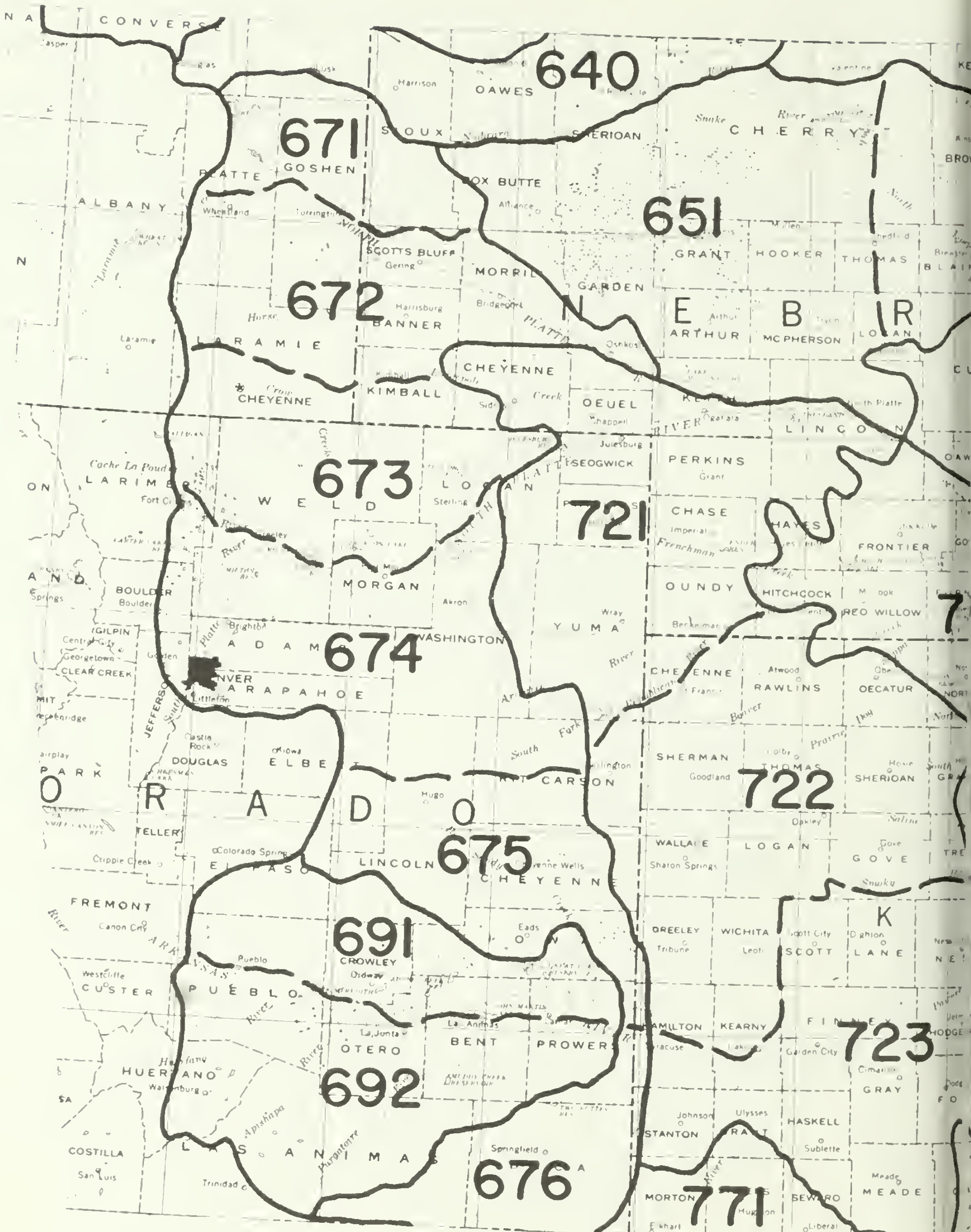
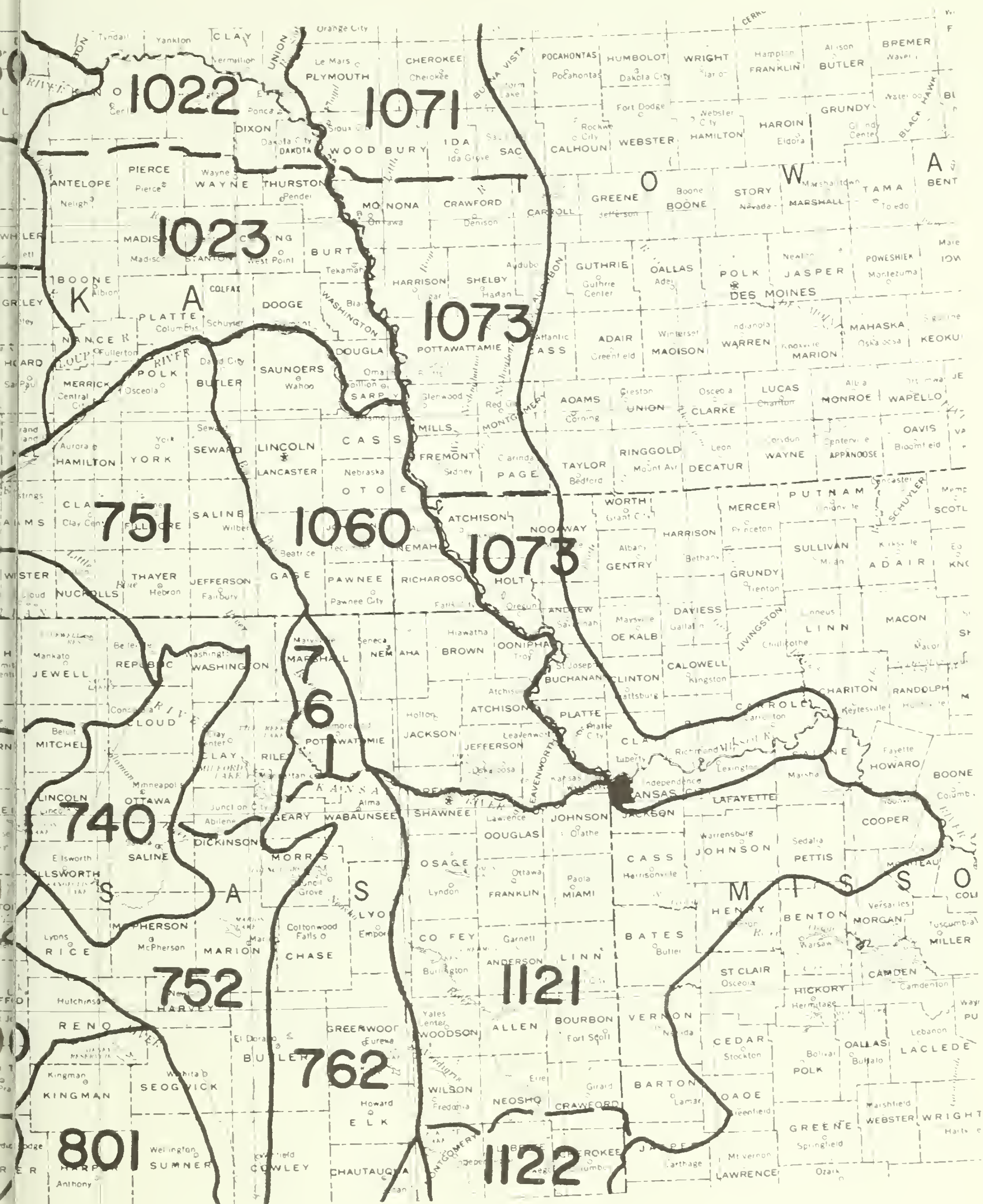


Figure 3.—Provisional seed zones for the Central Great Plains.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740
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762
1121
1122
801
NEBRASKA
IOWA
KANSAS
MISSOURI
DES MOINES

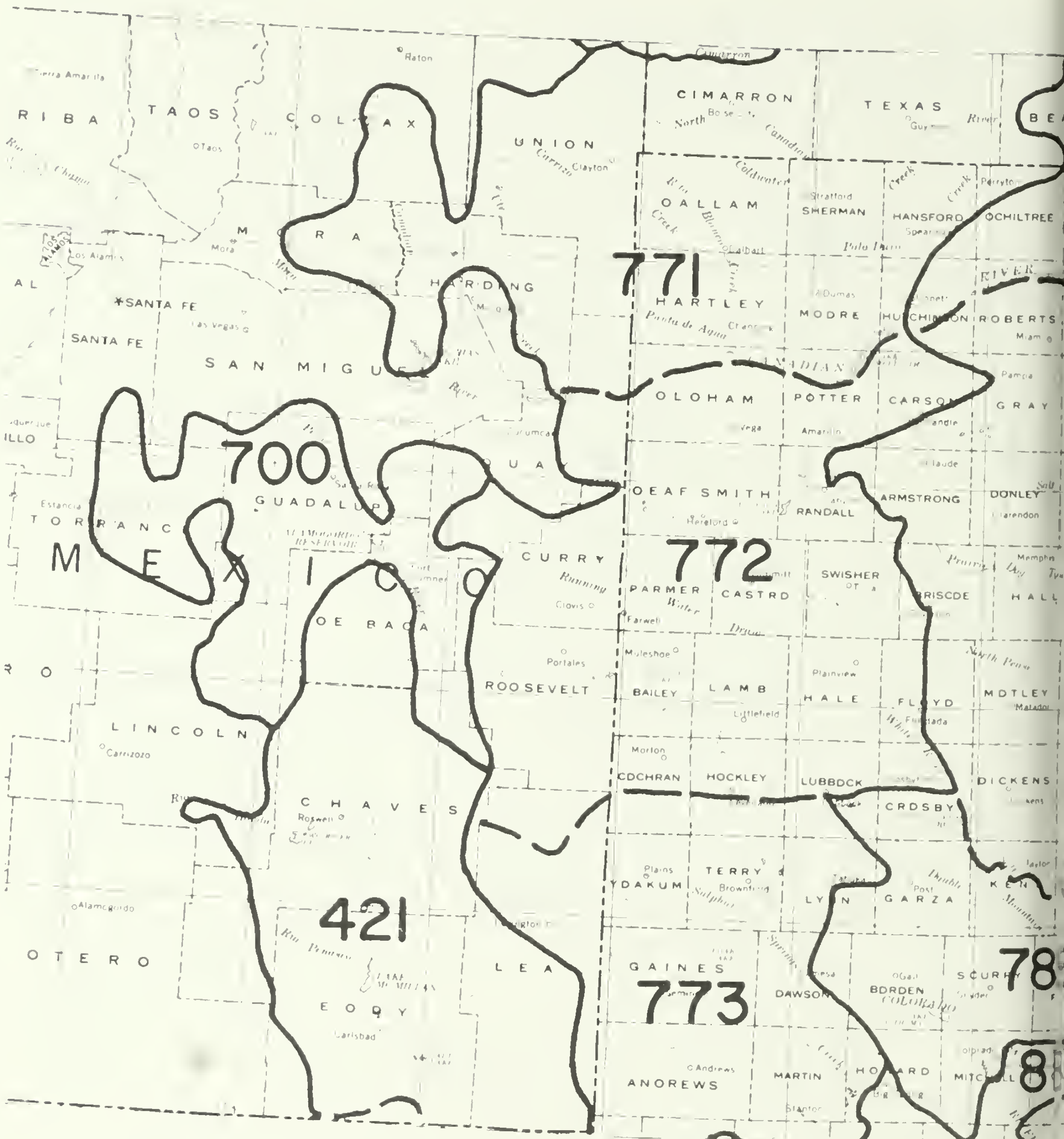
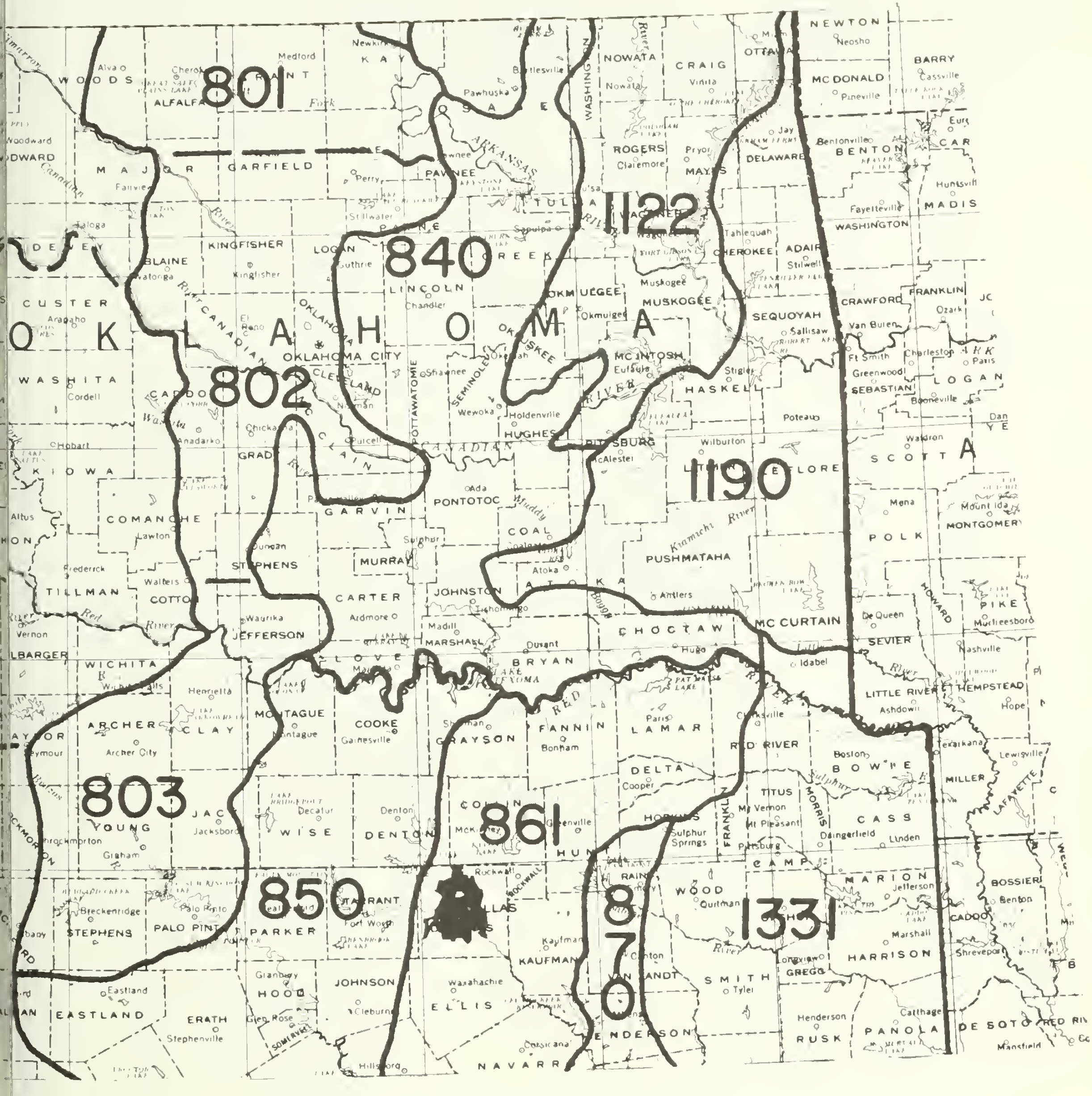


Figure 4.—Provisional seed zones for the Southern Great Plains (map 1).


801
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850
861
870
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1331
O K L A H O M A
OKLAHOMA CITY
WOODS
ALFALFA
MAJOR
GARFIELD
KAY
OSAGE
PAWNEE
WASHINGTON
NOWATA
CRAIG
OTTAWA
NEWTON
MC DONALD
BARRY
ROGERS
MAYES
DELAWARE
BENTON
WASHINGTON
MADISON
KINGFISHER
BLAINE
LOGAN
LINCOLN
CREEK
CUSTER
CHEROKEE
ADAIR
OKMULGEE
MUSKOGEE
SEQUOYAH
CRAWFORD
FRANKLIN
WASHITA
CADDO
MC INTOSH
HASKELL
SEBASTIAN
LOGAN
KIOWA
GRADY
HUGHES
PITTSBURG
LE FLORE
SCOTT
COMANCHE
GARVIN
PONTOTOC
COAL
POLK
MONTGOMERY
STEPHENS
MURRAY
PUSHMATAHA
TILLMAN
COTTON
CARTER
JOHNSTON
ATOKA
PIKE
JEFFERSON
MARSHALL
CHOCTAW
MC CURTAIN
SEVIER
BRYAN
LITTLE RIVER
HEMPSTEAD
WICHITA
ARCHER
CLAY
MONTAGUE
COOKE
GRAYSON
FANNIN
LAMAR
RED RIVER
BOWIE
MILLER
DELTA
TITUS
MORRIS
CASS
YOUNG
WISE
DENTON
COLLIN
HOPKINS
FRANKLIN
CAMP
MARION
STEPHENS
PALO PINTO
PARKER
TARRANT
DALLAS
ROCKWALL
RAINS
WOOD
HARRISON
BOSSIER
CADDO
EASTLAND
ERATH
HOOD
JOHNSON
ELLIS
KAUFMAN
SMITH
GREGG
RUSK
PANOLA
DE SOTO
NAVARRO
HENDERSON
Ada
Altus
Lawton
Duncan
Ardmore
Madill
Durant
Antlers
Hugo
Idabel
Paris
Sherman
Gainesville
Bonham
Cooper
Denton
McKinney
Greenville
Decatur
Jacksboro
Graham
Fort Worth
Weatherford
Cleburne
Waxahachie
Kaufman
Tyler
Longview
Marshall
Shreveport
Texarkana
Fort Smith
Muskogee
Tahlequah
Pryor
Claremore
Vinita
Nowata
Pawhuska
Perry
Stillwater
Guthrie
Chandler
Shawnee
Wewoka
Holdenville
McAlester
Atoka
Tishomingo
Wilburton
Poteau
Stigler
Sallisaw
Eufaula
Okmulgee
Sapulpa
Wagoner
Stilwell
Jay
Neosho
Pineville
Cassville
Bentonville
Fayetteville
Huntsville
Ozark
Van Buren
Paris
Booneville
Waldron
Mena
Mount Ida
De Queen
Nashville
Ashdown
Hope
Lewisville
Clarksville
Mt Vernon
Mt Pleasant
Pittsburg
Daingerfield
Linden
Jefferson
Quitman
Sulphur Springs
Henderson
Carthage
Mansfield
Benton
Corsicana
Hillsboro
Stephenville
Eastland
Granbury
Glen Rose
Breckenridge
Archer City
Henrietta
Montague
Wichita Falls
Vernon
Frederick
Walters
Cordell
Hobart
Anadarko
Chickasha
Purcell
Norman
El Reno
Kingfisher
Watonga
Arapaho
Taloga
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Alva
Cherokee
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Sulphur
Waurika
Coalgate
Tulsa
Boston

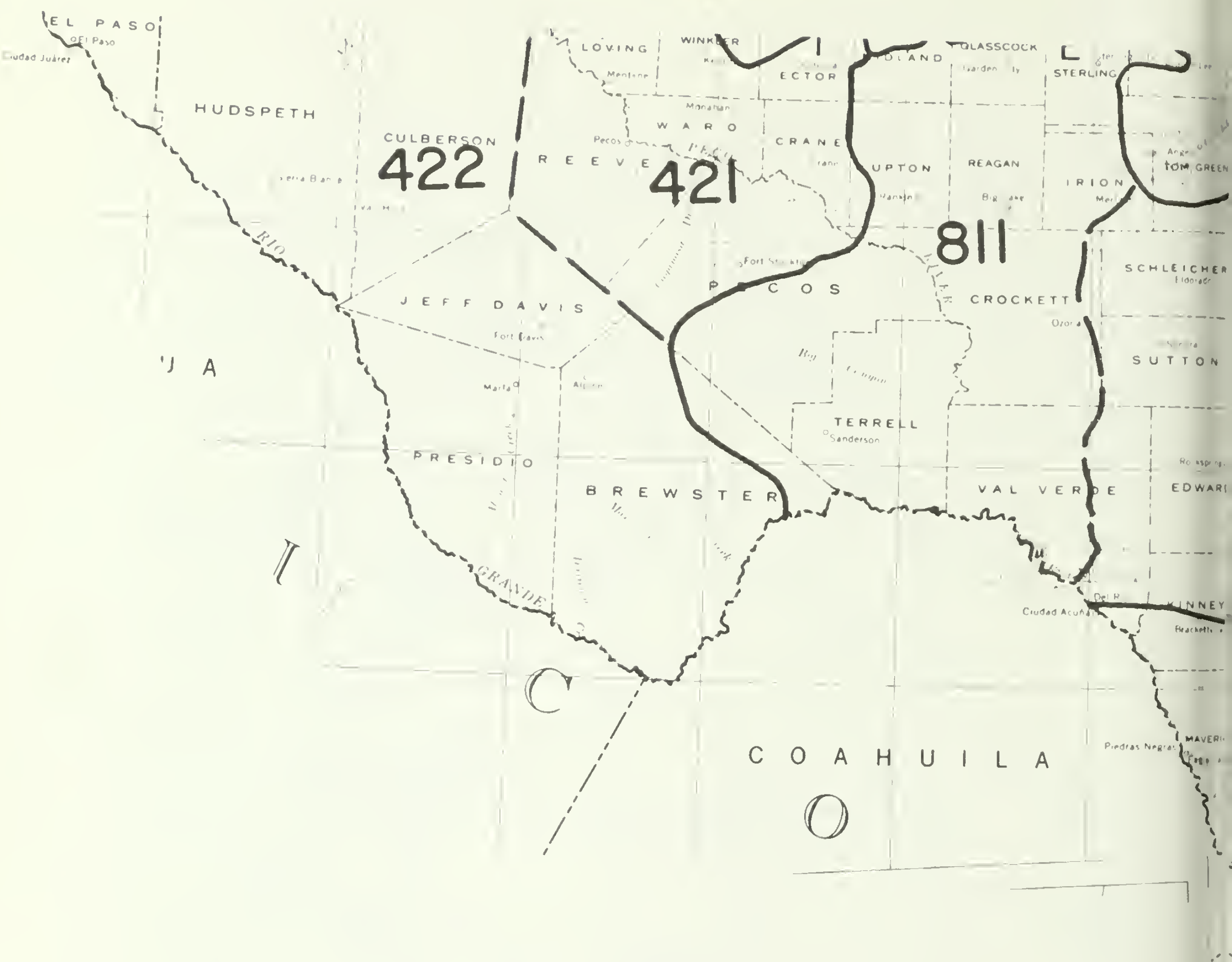
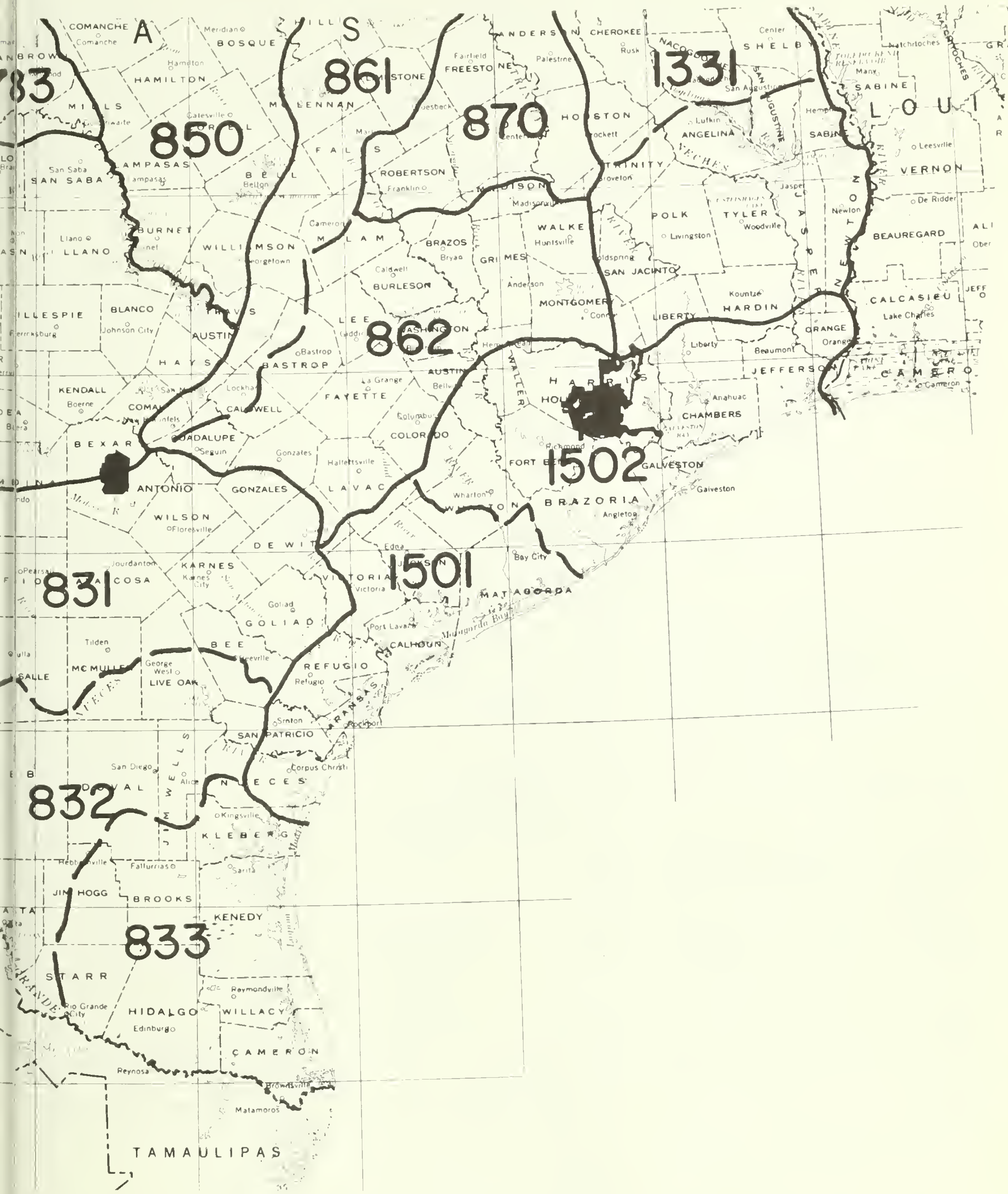


Figure 4.—Provisional seed zones for the Southern Great Plains (map 2).



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833
COMANCHE
BOSQUE
HAMILTON
MILLS
SAN SABA
LLANO
BURNET
WILLIAMSON
BLANCO
AUSTIN
HAYS
BASTROP
KENDALL
BEXAR
GUADALUPE
CALDWELL
GONZALES
WILSON
KARNES
DE WITT
GOLIAD
BEE
LIVE OAK
REFUGIO
CALHOUN
SAN PATRICIO
NUECES
KLEBERG
JIM HOGG
BROOKS
KENEDY
STARR
HIDALGO
WILLACY
CAMERON
TAMAULIPAS
ROBERTSON
BRAZOS
BURLESON
LEE
FAYETTE
COLORADO
LAVACA
VICTORIA
MATAGORDA
BRAZORIA
GALVESTON
CHAMBERS
JEFFERSON
ORANGE
HARDIN
LIBERTY
MONTGOMERY
SAN JACINTO
WALKER
POLK
TYLER
ANGELINA
TRINITY
CHEROKEE
SHELBY
SABINE
NEWTON
CALCASIEU
BEAUREGARD
VERNON
ANTONIO
Corpus Christi
Galveston
Beaumont
Lake Charles
Victoria
Port Lavaca
Bay City
Angleton
Huntsville
Livingston
Lufkin
Woodville
Jasper
Liberty
Anahuac
Orange
Seguin
Gonzales
Hallettsville
Refugio
Kingsville
Alice
San Diego
Falfurrias
Raymondville
Edinburg
Reynosa
Matamoros
Rio Grande City
Tilden
Goliad
Bastrop
La Grange
Llano
Boerne
Georgetown
Caldwell
Madisonville
Franklin
Palestine
Fairfield
Rusk
Center
Many
Leesville
Newton

Appendix

TABLE 2.—*Approximate equivalents of great soil groups of the modified 1938 Yearbook classification in the classes in Soil Taxonomy (from Austin 1972, p. 81-82)*

1938 classification [1]	Soil Taxonomy [2]	
Great soil groups	Most nearly corresponding taxa	Less common corresponding taxa
Alluvial soils	Fluvaquents Fluvents Fluventic subgroups of Inceptisols.	
Alpine Meadow soils	Cryaquods	Cryaquolls. Cryumbrepts.
Ando soils	Dystrandepts	Other great groups of Andepts.
Bog soils	Histosols	Histic subgroups of Aqualfs, Aquepts, and Aquolls.
Brown soils	Borolls (aridic subgroups) Ustolls (aridic subgroups) Xerolls (aridic subgroups) Aridisols (mollic subgroups)	Aridic Haploborolls. Durixerolls.
Brown Forest soils	Eutrochrepts	Haploxerolls. Hapludolls.
Brown Podzolic soils	Entic Haplorthods Entic Fragiorthods Cryandepts	Dystrochrepts. Fragiochrepts.
Brunizems (Prairie soils)	Udolls Argixerolls (typic subgroups) Haploxerolls (typic subgroups)	Udic Argiustolls.
Calcisols	Mollisols (calcic great groups) Aridisols (calcic great groups)	Ustochrepts. Xerochrepts.
Chernozem soils	Borolls (udic subgroups) Ustolls (udic subgroups)	Haploxerolls. Mollic Eutroboralfs. Boralfic Argiborolls.
Chestnut soils	Borolls (typic subgroups) Ustolls (typic subgroups)	Xerolls.
Desert soils	Aridisols (mesic and frigid families).	
Gray-Brown Podzolic soils	Udalfs	Aeric Ochraqualfs. Hapludults.
Gray Wooded soils	Boralfs	
Ground-Water Podzols	Aquods	Haplohumods.
Grumusols	Vertisols	Haplaquepts (vertic subgroups). Haplaquolls (vertic subgroups). Rendolls.
Humic Gley soils	Umbraqualfs Aquolls Humaquepts	Andaquepts. Haplaquepts (mollic subgroups). Ochraqualfs (mollic subgroups). Paleaquults (umbric subgroups).
Lithosols	Orthents (lithic subgroups) Psamments (lithic subgroups)	Lithic subgroups of Alfisols, Aridisols, Inceptisols, Mollisols, and Ultisols.
Low-Humic Gley soils	Aquents Aquepts Aquults	Aqualfs. Paleaquults. Psammaquents.
Noncalcic Brown soils	Xeralfs	Xerochrepts.

See footnotes at end of table.

TABLE 2.—*Approximate equivalents of great soil groups of the modified 1938 Yearbook classification in the classes in Soil Taxonomy*—Continued

1938 classification [1]	Soil Taxonomy [2]	
Great soil groups	Most nearly corresponding taxa	Less common corresponding taxa
Planosols	Albaquults Albaqualfs Albolls	Fragiaquults. Paleaquults.
Podzols	Orthods	Haplohumods. Dystrochrepts. Fragiochrepts.
Red Desert soils	Aridisols (thermic and hyperthermic families).	
Reddish-Brown Lateritic soils	Humults Rhodudults	Rhodic Paleudalfs. Rhodic Paleudults.
Reddish-Brown soils	Haplustalfs Paleustalfs Ustollic Haplargids	Aridic Argiustolls (thermic and hyperthermic families). Aridic Calciustolls (thermic and hyperthermic families). Aridic Haplustolls (thermic and hyperthermic families).
Reddish Chestnut soils	Haplustalfs Paleustalfs Typic and Aridic Argiustolls (thermic and hyperthermic families).	(warm) Haplustolls.
Reddish Prairie soils	Ustolls (udic subgroups, thermic and hyperthermic families). Paleudolls (thermic and hyperthermic families).	Eutrandepts.
Red-Yellow Podzolic soils	Udults	Paleudalfs. Haplustalfs (ultic subgroups). Paleustalfs (ultic subgroups).
Regosols	Great groups of Psamments Orthents (not lithic)	Grossarenic Paleudults. Xerochrepts.
Rendzina soils	Rendolls	Hapludolls. Eutrochrepts.
Sierozems	Aridisols (mollic great groups, mesic and frigid families).	Aridic subgroups of Mollisols.
Solonchak soils	Salorthids Calciaquolls	Halaquepts. Aquic Calciustolls.
Solonetz soils	Natric great groups	Natric subgroups.
Sols Bruns Acides	Dystrochrepts Fragiochrepts Haplumbrepts	Udorthent. Xerumbrept.
Subarctic Brown Forest soils	Cryochrepts	Cryoborolls.
Yellowish-Brown Lateritic soils	Umbrihumults Haplumbrepts	

[1] Concepts of great soil groups are those given in the 1938 Yearbook of Agriculture pp. 996–1001 as modified in Soil Sci. 67: 117–126, 1949, and as modified other publications and correlations prior to 1960.
[2] Soil Survey Staff, Soil Taxonomy. In preparation.*

*In October 1973, the Soil Survey Staff prepared an interim publication for inservice use, "Preliminary abridged text—Soil taxonomy: basic system of soil classification for making and interpreting soil surveys," 330 p., USDA Soil Conserv. Serv., Wash., D.C.

Agriculture—CSU, Ft. Collins

Cunningham, Richard A.
1975. Provisional tree and shrub seed zones for the Great Plains. USDA For. Serv. Res. Pap. RM-150, 15 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521

The Great Plains Region was subdivided into 86 seed collection zones on the basis of soil, topography, water, and climate. Seed should be collected from the zone to be planted, or, if unavailable, from a zone having similar soil and climate. Future provenance test results will be used to determine any need for adjustments in zone boundaries.

Keywords: Seed zones, Great Plains, forest seed planting.

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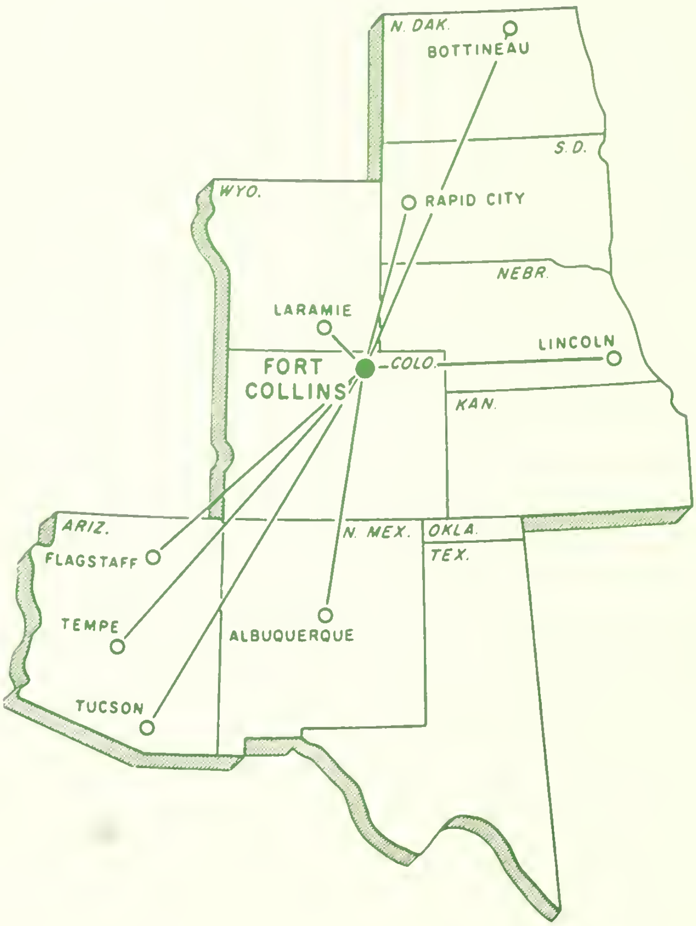
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LARAMIE
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FORT COLLINS
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ARIZ.
N. MEX.
OKLA.
TEX.
FLAGSTAFF
TEMPE
ALBUQUERQUE
TUCSON