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Predicting Regeneration in the Grand Fir-Cedar-Hemlock Ecosystem of the Northern Rocky Mountains

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ABSTRACT. Conifer establishment following regeneration treatments can be predicted in the grand fir-cedar-hemlock ecosystem of the northern Rocky Mountains. Alternative treatments can be evaluated by a model that represents regeneration establishment and early development. This model is designed to be used with the Intermountain Forest and Range Experiment Station's Prognosis Model (Stage 1973). Mathematical equations representing most harvest and site preparation methods common in the northern Rocky Mountains predict the probability of stocking, trees per acre, species composition, and tree heights between 3 to 20 years following treatment. These relations were derived from a stratified random sample of areas managed by conventional harvest and site preparation treatments. However, the analysis and modeling methods are structured to permit combinations of treatments within a stand that might differ from past practices.

ADDITIONAL KEY WORDS. Succession, stand simulation, reproduction, conifer establishment, modeling.

INTRODUCTION

SILVICULTURISTS have many harvest and site preparation options for regenerating conifers in the grand fir-cedar-hemlock ecosystem. These options influence the establishment and early growth of 10 commercially valuable conifers (Table 1) which span a wide range of shade tolerances and other silvical characteristics. For many sites, almost any harvest method will produce adequate stocking of conifers if given enough time. Site preparation and planting can speed the process. Therefore, regeneration decisions are based on evaluation of the relative values and rates of establishment and growth of the competing species as conditioned by the characteristics of the site.

Results of regeneration practices vary considerably. Indeed, this variability has dissuaded many investigators from more than qualitative conclusions about alternative practices. As pressure for intensive management increases and as management goals become more varied, qualitative information must give way to quantitative comparisons of expected results.

Three ingredients are essential to our approach. First, we need insight into the basic silvical characteristics of tree species and the influence of site conditions. For example, Haig and others (1941) provide knowledge of silvical characteristics and the efficacy of silvicultural practices. Second, we need a system for classifying sites according to their ecological potential. The habitat type system developed by Daubenmire and Daubenmire (1968) provides the framework within which to represent successional trends. Third, we must have available a sufficient number of managed areas to represent the effects of time, sites, and silvicultural practices on the process of conifer regeneration.

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TABLE 1. Species of trees in the regeneration establishment model shown in approximate order of shade tolerance (least to most).[a]

Scientific name	Common name	Abbre-viation	Minimum established height		Percent advance
			feet	*cm*	
Pinus ponderosa Dougl. ex Laws. var. *ponderosa*	ponderosa pine	PP	1.0	30	3.8
Larix occidentalis Nutt.	western larch	L	1.0	30	8.5
Pinus contorta Dougl. ex Loud.	lodgepole pine	LP	1.0	30	14.1
Picea engelmannii Parry ex Engelm.	Engelmann spruce	S	0.5	15	21.2
Pseudotsuga menziesii var. *glauca* (Beissn.) Franco	Rocky Mountain Douglas-fir	DF	1.0	30	31.5
Pinus monticola Dougl. ex D. Don	western white pine	WP	1.0	30	31.6
Abies grandis (Dougl. ex D. Don) Lindl.	grand fir	GF	0.5	15	40.4
Tsuga heterophylla (Raf.) Sarg.	western hemlock	WH	0.5	15	42.1
Abies lasiocarpa (Hook.) Nutt.	subalpine fir	AF	0.5	15	43.4
Thuja plicata Donn. ex D. Don	western redcedar	C	0.5	15	60.0

[a] Best trees (see text for definition) were aged on each plot and percentage of advance regeneration calculated by species. Results are in almost the same order as lists of shade tolerances suggested by Haig and others (1941) and Minore (1979). Baker (1949) and Schmidt and others (1976) rank western larch as the least tolerant. Daubenmire and Daubenmire (1968) and Pfister and others (1977) agree that western hemlock is the most shade tolerant conifer of the group. Percentages do not solely reflect shade tolerances but do show relative differences among species and are a meaningful way to array results of this study.

Our study combines these three ingredients to produce a quantitative regeneration model. This model is designed as an extension to the Intermountain Forest and Range Experiment Station's Prognosis Model (Stage 1973, Wykoff and others 1982). The regeneration model predicts attributes of regenerated stands as they would appear if examined between 3 to 20 years after harvest and site preparation. The Prognosis Model then predicts subsequent accretion and mortality and implements user-specified stand management prescriptions. Combined, these models have many uses in forest planning:

1. To decide which silvicultural prescription meets the regeneration objective for a stand about to be harvested.
2. To evaluate the need for additional stocking in a harvested stand.
3. To set stocking goals for harvested areas as required by the National Forest Management Act of 1976, State forestry practices acts, or private ownership goals.
4. To aid harvest scheduling, especially where treatment of nearby stands must be deferred until regeneration is established.
5. To evaluate the suitability of cutover stands for uses besides timber production, e.g., wildlife habitat, creation of vistas, or forage production.
6. To identify areas having a high probability of regeneration failure, thereby helping to set priorities for intensive regeneration efforts.

STUDY AREA

The study area covers the northern Rocky Mountains in the Idaho Panhandle and adjacent portions of Montana and Washington (Fig. 1). This region includes the most productive forests in the Interior West (USDA Forest Service 1973).

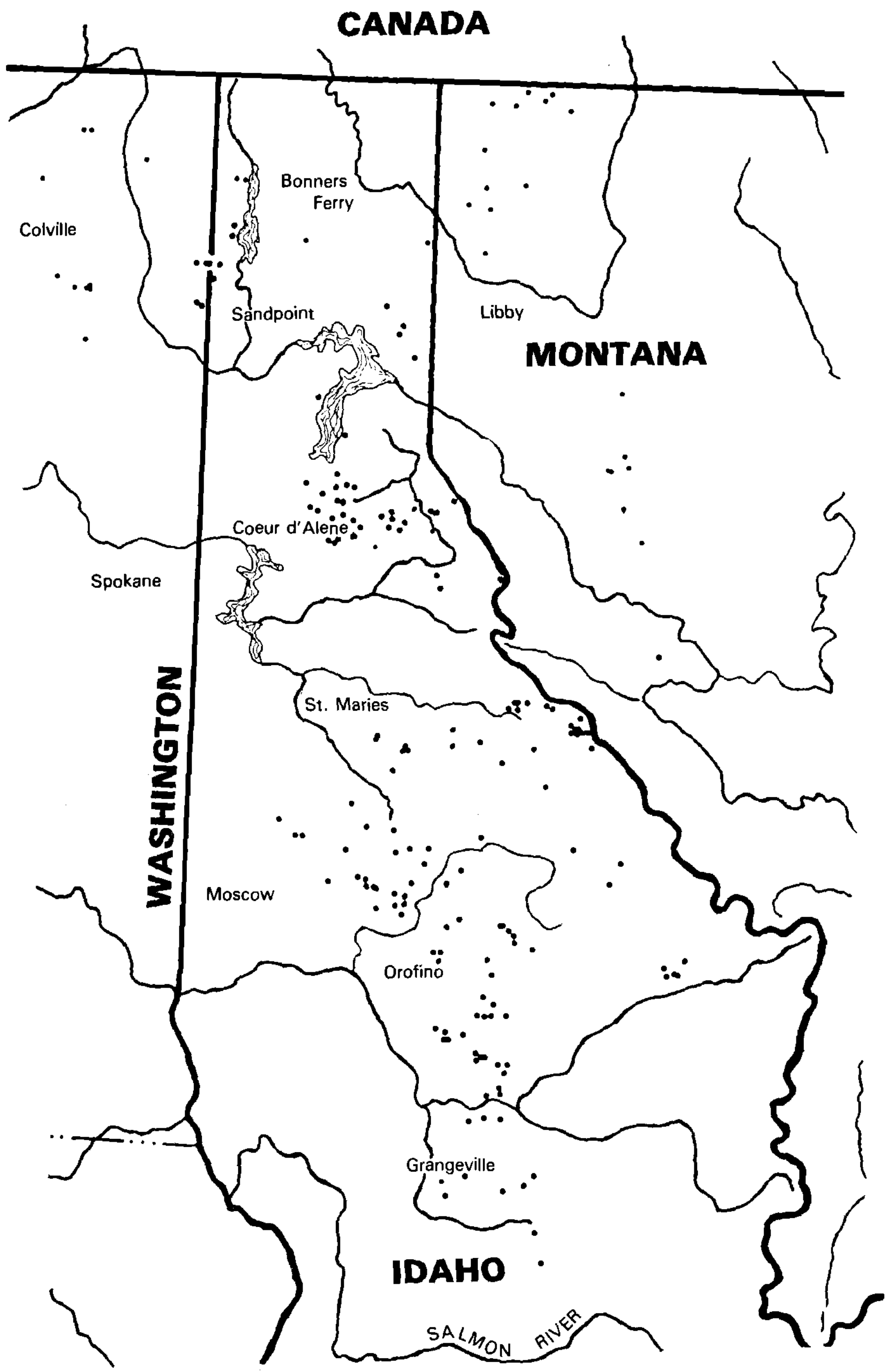
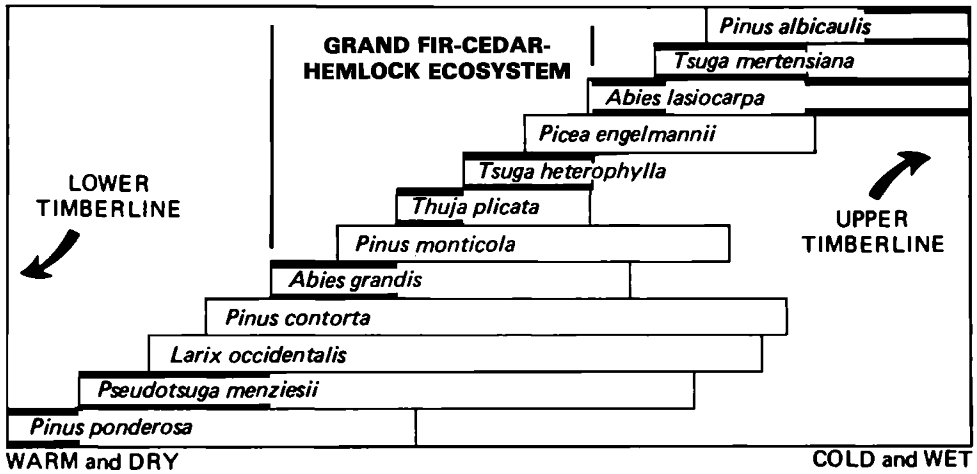


FIGURE 1. The study area and location of stands.

Conditions affecting plant growth vary within the study area, ranging from warm, dry conditions at lower elevational limits to cold and wet conditions at the upper limits. The grand fir-cedar-hemlock ecosystem occupies the middle elevations in these forested areas. Figure 2 shows the ecological context of the ecosystem. We



Coniferous trees in the area centered on eastern Washington and northern Idaho, arranged vertically to show the usual order in which the species are encountered with increasing altitude. The horizontal bars designate upper and lower limits of the species relative to the climatic gradient. That portion of a species' altitudinal range in which it can maintain a self-reproducing population in the face of intense competition is indicated by the heavy lines.

FIGURE 2. Range of the grand fir-cedar-hemlock ecosystem within the forested areas of northern Idaho, northwestern Montana, and northeastern Washington (modified from Daubenmire 1966. Copyright 1966 by the AAAS).

sampled the following predominant habitat types in the ecosystem as classified by Daubenmire and Daubenmire (1968): *Abies grandis/Pachistima myrsinites, Thuja plicata/Pachistima myrsinites,* and *Tsuga heterophylla/Pachistima myrsinites.*

A complex array of environmental conditions affects plant communities in the ecosystem. The reader is referred to Haig and others (1941), Daubenmire and Daubenmire (1968), Schmidt and others (1976), Pfister and others (1977), and Steele and others (1981) for excellent discussions of these factors. We shall highlight the important variables affecting vegetational patterns and regeneration in the study area.

1. There is an environmental gradient of increasing elevation from west to east to the top of the Bitterroot Divide (Idaho-Montana border), then decreasing elevation eastward into Montana.
2. Weather systems that bring moisture usually originate over the Pacific Ocean and approach the study area from the southwest. As they approach the Bitterroot Divide, orographic lift causes increasing moisture to be deposited with increasing elevation. In turn, there is a rain shadow effect east of the divide.
3. About half of the precipitation is snow. Storms from the southwest blow snow from windward slopes to the leeward side of ridges. There is virtually no summer precipitation. Potential evapotranspiration rates, which are high because of low humidity, must be met by drawing on moisture stored in the soil (Zahner and Stage 1966).
4. In addition to the east-west gradient, there is a north–south gradient. The northern areas are more maritime while the southern areas are more continental. Latitude is also a north–south gradient.

5. The steepness of mountainous slopes, in combination with aspect, creates a dramatic effect on solar energy flux. At night, movement of cold air masses causes large diurnal temperature fluctuations. Cold air masses collect in drainages and valley bottoms, often creating an inversion of the normal vegetation gradients. Frosts can occur at any time during the growing season.
6. Much of the area is covered by wind-deposited material from the west—volcanic ash from the Cascades and loess from the Columbia basin. As with snow accumulation, wind-deposited material is thicker on leeward slopes.
7. The composition of the ecosystem has been influenced by catastrophic, stand-replacing wildfires (Wellner 1970). A decline in their frequency is favoring the more shade-tolerant species.
8. Two introduced pests have influenced species distributions. White pine blister rust (*Cronartium ribicola* J. C. Fisch. ex Rabenh.) has decimated white pine stands although resistant strains are now emerging. The larch casebearer (*Coleophora laricella* Hbn.) has reduced growth and seed crops of western larch.

Habitat types have proven useful in classifying the net effect of a complex environment on the land. Daubenmire (1976) states "Each climax type indicates both the local and the geographic extent of land having essentially equivalent and permanent biologic potentialities."

REGENERATION STUDIES

Previous studies of regeneration establishment have followed two general approaches: (a) a controlled experiment where variables are held constant except those of interest, and (b) the case history method where many factors are allowed to vary and results are monitored. Larsen (1924) used a controlled experiment to test the effects of different seedbeds on germination and survival of western white pine. Haig and others (1941) summarized many years of research, much of it resulting from controlled experiments.

Roe (1952) used the case history method to study larch and Douglas-fir regeneration in Montana, and in western Montana, Steele and Pierce (1968) studied clearcuts using the case history method. Boyd (1969) also used this method in reporting 20-year results of regeneration methods while Boyd and Deitschman (1969) reported the effects of site preparation on regeneration success.

Neither study approach is fully suitable for developing a quantitative regeneration model. The controlled experiment does not allow all factors to interact during the regeneration period. Case histories are usually limited to unreplicated study sites that are almost always subjectively chosen. The missing element is the lack of a clearly defined sampling frame that defines the population for which inferences are to be made and from which sample areas can be drawn with known probability of selection. Without these rigorous sampling procedures, inferences about the relative proportion of regeneration successes and failures are meaningless.

Several studies used randomized sampling procedures in developing linear equations predicting stocking percent following harvest and site preparation treatments (Seidel 1979a, Seidel 1979b, Strothmann 1979, Stein 1981). Statistically derived equations relate stocking percentage to site conditions and management activities. However, these equations have not been used to develop a predictive model.

Our study used stratified random sampling from lists of managed stands to retrospectively examine stands, much like the case history method except for the rigorous selection process and the large sample size. Knowledge gained from controlled experiments and case history studies helped to develop the sampling design and to formulate hypotheses to test during equation fitting. Finally, the equations are linked into a predictive model.

REGENERATION MODELS

Shugart and West (1980) reviewed forest succession models and Kessell (1981) reviewed succession modeling approaches. Following is a review of regeneration establishment submodels that produce or augment an inventory in forest succession or growth and yield models.

An inventory of regeneration is the simplest way to introduce new trees into a simulation. Staebler (1949) was the first to link a regeneration inventory to future yields. Using tabular methods, an inventory of Douglas-fir regeneration is carried forward in time to cubic foot volumes at an age where conventional yield tables can be used. Where an inventory is absent, another table shows expected stocking at 15 years, partitioned by slope, aspect, and shrub cover.

Shugart, Crow, and Hett (1973) developed a succession model for the Great Lakes Region that uses an inventory of the number of acres in various forest cover types. The cover types are similar to successional stages. This model does not use a tree list, but cover types represent a classification based on a current stand inventory.

In an individual tree simulation model for Douglas-fir, Mitchell (1975) allows for the input of an inventory or planting. This model uses distant-dependent competition indices so the inventory must contain information on tree location. Planting can be simulated by specifying planting density and spatial pattern. A simpler approach is used in DFSIM, an even-aged Douglas-fir stand simulation model (Curtis and others 1981). The inventory of new trees is the number of stems per acre and stand age.

The second method used to produce or augment an inventory is to generate an expected inventory. STEMS (Belcher 1981) is an individual tree, distant-independent model that, following clearcutting, replaces the old tree list with a new one. Statistically derived equations are not used to predict the new stand; rather, an expected inventory is inserted based on characteristics of the previous stand.

Leak (1970) derived expected ingrowth from permanent sample plot data. Birth rates (the annual proportion of trees reaching 4.5 inches diameter at breast height [dbh]) for New England hardwoods were calculated by species. The rates are sensitive to overstory density. Leak and Graber (1976) included trees less than 4.5 inches dbh in their uneven-aged northern hardwoods stand model. The number of new seedlings is predicted from the inventory of established seedlings and saplings. Species composition is not considered.

Other modelers have concentrated on predicting species composition with less analysis on quantifying seedling density. Botkin and others (1972) developed JABOWA for the Hubbard Brook Forest in northeastern United States. Tree species that can survive and grow on the site comprise the available species pool. The pool is partitioned to reflect species shade tolerances. For each year being simulated, a random choice is made from the species pool, followed by another random choice to determine whether zero, one, or two trees are added to a subplot within the stand. Introduced trees then grow or die according to tree, stand, and site conditions.

Reed and Clark (1979) used many principles of the JABOWA model to develop SUCSIM. Here a maximum number of seedlings is set and reduced if the site is suboptimal. Seedlings are then introduced from a species pool according to light, temperature, moisture conditions of the site, and the timing and abundance of seed crops. Bartos and others (1983) also set a maximum number of seedlings in an aspen-to-conifer succession model. Movement of trees into the smallest height class is dependent on the biomass of aspen, conifers, herbs, and shrubs.

The third approach to regeneration establishment modeling is to explicitly deal with processes leading to an established seedling. Sequential steps are defined and survival rates for passing from one step to another are assigned. Five steps are used in Leak's (1968) theoretical birch regeneration model—flower development, seed development, seed dispersal, microenvironment, and seed response. Monserud and Ek (1977) use similar steps to predict the number of stems growing into the smallest height class of a northern hardwood simulation model. Sequential processes—seed production, dispersal, viability, and germination—use spatially dependent measures of competition.

Larson (1976) developed a process model for pure ponderosa pine stands in Arizona using site index as an independent variable. This presents no problem in predicting species composition since only one commercial species grows on these sites. However, in mixed species stands, a site index value gives few clues to the species of trees that are capable of becoming established on the site. Ecological land classification systems provide the logic to develop this predictive power.

The regeneration model we describe predicts an expected inventory of regeneration as a function of site-stand conditions and time since disturbance. The model explicitly represents the probability of stocking, seedling density, species composition, and seedling heights. Equations are sensitive to microsite conditions, site preparation activities, and overstory conditions. Linkage to future yields is provided by the Prognosis Model (Stage 1973).

STUDY DESIGN

Although the main objective of the study was to describe the changes through time that follow regeneration activities, several additional constraints guided the study design.

1. Inventory procedures and definitions commonly used in the northern Rocky Mountains should be followed so the model will be compatible with existing inventory practices.
2. Variables to be observed should be measurable at the end of the time interval or available from historical records.
3. The experimental unit should be an area sufficiently small so that the treatments and site conditions apply uniformly to the unit of observation. The plot size should also be guided by the usefulness of the stocked quadrat method for describing regeneration success (Haig 1931). A small plot size avoids the possible confounding of proportion of area treated with time since treatment. For example, although the proportion of stand subjected to site preparation may have varied because of changing practices, a small plot can be classified as treated or not treated.
4. Overstory density and species composition should be measured in the immediate neighborhood of each plot so that effects of within-stand variation on regeneration can be evaluated.
5. There should be a balanced design of treatments with respect to time since treatment.
6. Computational steps in the final model should follow logically from the study design and vice versa.

Selection of study sites in an unbiased manner was crucial. At the same time, we wished to include a variety of cultural and environmental conditions so that

TABLE 2. Information matrix for study site selection. Cells contain the number of plots sampled in that category. The Abies lasiocarpa/Pachistima myrsinites *habitat type was not a part of the study design but enough data were collected to include in the model.*

	Regeneration method and site preparation												
	Clearcut			Seedtree			Shelterwood			Selection			
Habitat type	none	mech	burn	none	mech	burn	none	mech	burn	none	mech	burn	Total
	Number of plots												
Northern portion habitat types:													
Abies grandis/Pachistima	105	90	64	73	55	27	135	13	17	88	21	0	688
Thuja plicata/Pachistima	84	104	173	29	92	2	87	24	13	43	4	0	655
Tsuga heterophylla/Pachistima	274	174	222	135	30	0	184	62	1	102	50	25	1259
Abies lasiocarpa/Pachistima	62	18	5	51	29	10	25	3	0	3	0	0	206
Southern portion habitat types:													
Abies grandis/Pachistima	133	198	175	141	91	14	58	22	0	77	18	0	927
Thuja plicata/Pachistima	179	144	122	118	76	0	229	55	10	229	52	0	1214
Abies lasiocarpa/Pachistima	7	6	1	0	0	0	1	0	0	0	0	0	15
Total	844	734	762	547	373	53	719	179	41	542	145	25	4964

most silvicultural practices were represented. A stratified random sample accomplished both of these goals. An information matrix (Table 2) was constructed from the major factors of interest: four regeneration methods (clearcut, seedtree, shelterwood, and selection); three broadly defined site preparation methods (none, mechanical, and burn); and the three major habitat types in the ecosystem. In order to insure geographic dispersion of study sites, the information matrix was replicated in the northern and southern half of the study area.

Next, a list of stands harvested from 1959 through 1972 was obtained from the Northern Region of the Forest Service, Potlatch Corporation, and the Idaho Department of Lands. The list was screened and 4,107 stands were classified into the cells of the information matrix. From each cell, four to five stands were randomly chosen for sampling. Although some cells were empty, such as selection-burns, plots within stands often did have the missing combinations. The time from harvest to the date of examination provided a minimum of three growing seasons since treatment during which trees could germinate and become established.

Both planted and naturally regenerated stands were included as candidates. To exclude planted stands could have biased the sample toward stands that regenerated well. Conversely, some hard-to-regenerate stands would not have been chosen for sampling.

The four regeneration methods were used to sample a range of overstory densities rather than to represent classic regeneration cuttings. Stands classified as clearcut often left advance regeneration, and true selection systems were not found. Those stands classified as selection represented multistoried stands in which light partial cuttings were done, often under the name of selective logging, sanitation/salvage, or perhaps the removal of a special product such as cedar poles. Shelterwood regeneration treatments were examined only after the first regeneration cutting.

After the stand was chosen for sampling, office records were used to verify historical information. Stands were rejected if historical information was insufficient.

A stereo pair of aerial photographs was used to subdivide each stand into areas relatively homogeneous as to site preparation, aspect, residual overstory density, or topographic position. Transect lines were drawn on the photographs to cross as many of these areas as possible. Easily identifiable starting and stopping points helped field crews ascertain transect locations. Twenty-five sample points were established equidistant along the transect (about 1 day's work). In stands less than 10 acres (4 ha) in size, only 15 points were set out. Stands larger than 50 acres (20 ha) were sampled with 35 points. The smallest stand sampled was 3 acres (1.2 ha), the largest 498 acres (202 ha).

The experimental unit was a 1/300-acre (0.00135-ha) circular fixed area plot. At each sample point, field crews installed a plot to record regeneration, microsite conditions, and other vegetation. Variables recorded were habitat type, slope percent, aspect in degrees from true north, topographic position, site preparation, distance and angle to seed walls surrounding clearcuts and seedtree cuts, shrub, grass, and forb competition, and regeneration. From each point, the overstory was sampled with a prism having a basal area factor of 10 ft^2/acre/tree (2.3 m^2/ha/tree). The overstory tree count was recorded by species.

Site preparation for each plot was the treatment that covered the largest proportion of the plot. Only four classes were used because the intensity of site preparation was difficult to determine for long periods of time since treatment. No site preparation meant the plot was not scarified or burned. All burned plots were assigned burn site preparation. Mechanical site preparation was caused either by the logging operation or as a deliberate treatment following harvest. Severe mechanical disturbance, such as major skid trails, road cuts, road fills, or unmaintained roadbeds, was classified as "road" site preparation.

A few factors were assumed to apply to all plots within a stand: year of cutting, year of site preparation, planting history, soil parent material, elevation, and geographic location. Plots within a stand were assigned the corresponding stand variables.

National Forest boundaries were used as geographic divisions within the study area. They serve as surrogates for phenomena that would have been time-consuming and expensive to measure. The Kootenai and Lolo National Forests lie east of the Bitterroot Divide where the winter climate is colder and drier. The Panhandle, Clearwater, and Nezperce National Forests divide the study area latitudinally, and the Colville National Forest in the westerly part of the study area is warmer and drier.

All established seedlings were recorded for each plot. Trees were established if at least 1.0-ft (30-cm) tall for shade-intolerant species and 0.5-ft (15-cm) tall for shade-tolerant species (see Table 1). Current year's leader growth was not included in determining established trees so that the same standard would apply to all trees sampled at any time during one growing season. Maximum size of regeneration for all species was 2.95 inches (7.5 cm) dbh. Trees larger than 2.95 inches dbh on the fixed plot were recorded as overstory trees.

Established regeneration was subsampled for detailed measurement of the best trees on the plot. Best trees were selected by identifying (a) the two tallest trees regardless of species, (b) the one tallest tree of each additional species present, and (c) the tallest of the remaining trees until at least four were sampled, or all trees were included. Height to the nearest 0.1 foot, age, and tree condition (damage, diseases, insects) were recorded for all best trees.

The reason for focusing attention on best trees is that often more trees occupy a stocking unit than will survive to rotation age (Wellner 1940). We feel that a more representative distribution of the growing stock is displayed by featuring a few trees on each stocked plot. The tallest trees are assumed to be the most likely to survive and grow well. Describing at least one tree of each species present shows the distribution of each species throughout the stand and allows for shifting dominance due to differences in growth rates among species.

Competition from shrubs, forbs, and grasses was characterized by recording average height (to the nearest 0.5 foot) and percentage (to the nearest 5 percent) of fixed plot coverage for species occupying at least 5 percent of the plot. Coverage could exceed 100 percent because of the layering of shrubs, forbs, and grasses.

During the summers of 1975 and 1976, 190 stands were sampled. In addition to the habitat types initially identified on the matrix, other habitat types were encountered as inclusions in the areas sampled. Of these habitat types, *Abies lasiocarpa/Pachistima myrsinites* was represented by sufficient data to be included in the analysis process. These data represent only the lower elevational limits of this habitat type where it abuts and intergrades with the *Tsuga heterophylla/Pachistima myrsinites* or *Thuja plicata/Pachistima myrsinites* habitat types. The result was 4,964 plots as shown in Table 2.

MODELING TECHNIQUE

The basic objective for developing the regeneration establishment model was to mathematically represent regeneration just as if it were possible to inventory the stand at a future date. The steps to reach this objective indicate the types of analyses to be done. We defined 14 steps as shown in Figure 3. Five of the model steps depend on empirical prediction equations statistically derived from the study

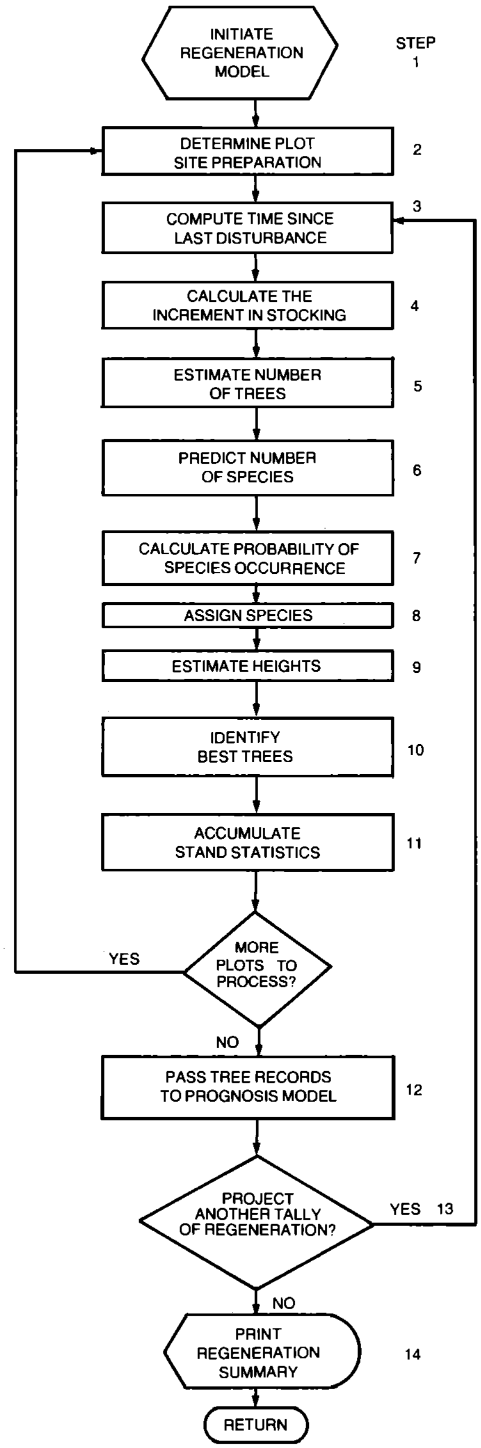


FIGURE 3. Steps in the regeneration establishment model.

data. To some degree, the order of the steps was determined by the need to predict one attribute to be used in another step. For example, the number of trees is determined before the number of species, and the number of species is used in assigning the species present on the plot.

Our modeling technique follows the methods applicable to two-state systems described by Hamilton and Brickell (1983). With this technique, one step (Step 4 of Fig. 3) predicts the probability that a plot would be in one of two states—stocked or nonstocked. Then steps 5 through 10 estimate the attributes of just the stocked plots. Probability of stocking (at least one established seedling on the plot) t years after disturbance is estimated by a logistic equation in the interval [0, 1]. Then the attributes of stocked plots are estimated. The probability of stocking is used to scale stocked plot attributes to a per-acre basis.

As an example, suppose that for a given 1/300-acre (0.00135-ha) plot the calculated probability of stocking is 0.60 and the results of the stocked plot analysis estimate 6 trees on the plot, each with an assigned species and height. Because the probability of stocking is based on a 1/300-acre plot size, each tree record represents 0.60×300, or 180 trees per acre. All plots within the stand are processed individually so that each plot has an estimated probability of stocking, number of trees, species composition, and tree heights. Stand statistics are produced by summarizing the attributes of this list of trees.

The regeneration model was designed to predict regeneration at two times during the regeneration period. The two times, called tally dates, are usually 10 and 20 years after harvest, but the dates can be changed by the user. The first tally reports regeneration from the time of harvest to the first tally date. The second tally reports additional regeneration becoming established after the first tally up to the time of the second tally date. The increment in the probability of stocking between the two tally dates represents plots that become stocked during the second time interval. Stocked plots at the end of the first tally also receive additional trees during the second time interval.

Logistic Regression

There are many dichotomously distributed dependent variables in our data. For example, a plot is either stocked or nonstocked, a species either occurs on a plot or it does not. Response surfaces are nonlinear, such as shown by Wellner (1940) for percent stocking. It is appropriate to use logistic regression to estimate probabilities from these data. Following are the procedures used to develop probability of stocking equations. These procedures also apply to other probability equations developed for the regeneration model.

Stocking summaries (percentage of stocked plots) were prepared for each cell of the information matrix and for all independent variables. This provided an opportunity to look at means and extreme values in the data. However, these averages are of limited value because the sample size within a cell is small.

Next, a stepwise screening algorithm was used to help select important independent variables (Hamilton and Wendt 1975). The algorithm is designed for analysis of a dichotomously distributed dependent variable. Variation among plots in any one independent variable was classified into discrete levels (Table 3); hence, each plot fell into one class for each independent variable.

The results of screening the data indicate significant variables and likely transformations. However, single variable analysis does not account for interactions between variables. Nor do the significance tests indicate a more meaningful placement of class boundaries when the classes are derived from a continuous variable. Therefore, the results shown in Table 3 are rudimentary but helpful in subsequent logistic regression analyses.

TABLE 3. Independent variables and number of plots by class used in screening analysis to predict the probability of stocking. Chi-square statistics presented in this table are corrected for degrees of freedom so that independent variables having different number of classes can be compared. All uncorrected chi-squares are significant at the 0.05 level.

Class	Number of plots
Time since disturbance (years) $\chi^2 = 16.63$	
3 years	440
4	485
5	382
6	557
7	451
8	367
9–10	896
11–17	1,386
Habitat type $\chi^2 = 15.35$	
Abies grandis/Pachistima	1,615
Thuja plicata/Pachistima	1,869
Tsuga heterophylla/Pachistima	1,259
Abies lasiocarpa/Pachistima	221
Aspect (degrees) $\chi^2 = 13.82$	
Flat	158
346–45	632
46–105	728
106–165	931
166–225	886
226–285	802
286–345	827
Residual basal area (ft²/a) $\chi^2 = 12.63$	
0	2,555
10	409
20	328
30–40	498
50–60	389
70–80	277
90–110	273
120–390	235
Elevation (feet) $\chi^2 = 9.51$	
2400–2500	147
2600–3000	568
3100–3500	973
3600–4000	1,268
4100–4500	1,356
4600–5000	467
5100–5500	161
5600–5800	24

Class	Number of plots
Site preparation $\chi^2 = 9.31$	
none	2,652
mechanical	1,035
burn	881
road cuts	49
road beds	248
road fills	99
Regeneration method $\chi^2 = 8.19$	
clearcut	2,340
seedtree	973
shelterwood	939
selection	712
Regeneration mode $\chi^2 = 6.27$	
natural	3,475
planted	1,489
Slope (percent) $\chi^2 = 5.04$	
Flat	187
1–10	1,307
11–20	1,627
21–30	1,291
31–40	465
41–50	79
51–60	8
Geographic location $\chi^2 = 4.50$	
northern portion	2,808
southern portion	2,156
Soil parent material $\chi^2 = 3.91$	
granite	716
belt metamorphic	2,888
batholith border meta.	730
Columbia basalt	397
alluvial/glacial outwash	233
Topographic position $\chi^2 = 1.56$	
bottom slope	256
lower slope	377
midslope	3,805
upper slope	417
ridgetop	109

Equations were then developed to predict the probability of at least one established seedling on a 1/300-acre (0.00135-ha) plot. A nonlinear logistic algorithm called RISK was used (Hamilton 1974). RISK was designed to estimate regression coefficients for a dichotomously distributed dependent variable. The dependent variable is 1.0 if the plot is stocked, 0.0 if nonstocked. The form of the equation is $P = (1 + e^{-(\Sigma\beta_i X_i)})^{-1}$ where "e" is the base of natural logarithms. Probability of stocking (P) is continuous and bounded within the interval [0, 1]. Up to 30 independent variables can be used.

Goodness of fit was evaluated at the 0.05 significance level. RISK reports Student-t ratios for all coefficients and provides an analysis of variance table that can be used to evaluate the overall equation. Also reported is a chi-square table of 21 divisions in the probability interval [0, 1] which help indicate where the model fit was inappropriate. Hamilton (1974) states that as the sample size increases for dichotomous variables, the limiting value of the error mean square is 1.0. Thus, another goodness of fit criterion was how close the error mean square was to 1.0. Final equations were evaluated qualitatively—did they reflect known biological relationships in a meaningful way?

Linear Regression

Linear regression was used to estimate heights of best trees. The data were screened for best possible independent variables and transformations of variables. Independent variables screened included habitat type, slope, aspect, elevation, topographic position, residual basal area, time since disturbance, site preparation, planting, and number of trees on the plot. Goodness of fit was evaluated at the 0.05 significance level.

Assumptions

Several assumptions were made in the study design and equation-fitting phases of this study. These were necessary at the time and can be tested by further field sampling. One assumption is that the sporadic effects of seed crops and weather are averaged out by sampling from a wide range of treatment dates (1959–1972). This seems a more reasonable approach than sampling from a narrow band of dates where weather would be more highly correlated with regeneration success.

We assumed that the influences of soils, diseases, insects, and so on, are represented unbiasedly through the random selection of sample stands. Epidemic disease/insect conditions were not encountered, with the exception of white pine blister rust. This introduced disease destroyed a great proportion of white pine in the ecosystem. Rust-resistant trees surviving in nature and rust-resistant planting stock should increase the proportion of white pine in the future.

Another assumption is that the effects of competition from shrubs, forbs, and grasses are represented by variables used to predict the attributes of trees and plots. For example, time since disturbance, site preparation, habitat type, aspect, slope, and elevation may incorporate the effect of shrub development on stocking, species composition, and tree heights. We did not include measures of shrub, forb, and grass competition in the modeling process because it was not possible to retrospectively determine coverage at the time of seedling germination. These data are being used to develop shrub succession models (Moeur 1985).

We recognize that plots within stands are not truly independent units of analysis. However, by sampling relatively few plots per stand, by locating transects so that they crossed variation discernible on aerial photographs, and by recording microsite conditions, each plot is as independent as possible. A separate analysis (Stage and Ferguson 1984) has shown that the assumption of independence of plots has not been violated.

Best trees were chosen from among the tallest trees on the plot. While tallest trees may not necessarily be the most vigorous on the plot, they are in the most dominant competitive position. Identifying best trees in this manner avoids the problem of making assumptions about present and future acceptability standards.

Other components of the Prognosis Model include measures of tree vigor on growth and mortality rates.

Model Features

The 14 steps in the model have been shown in Figure 3. To begin simulation, the regeneration establishment model uses a post-harvest stand inventory provided by the Prognosis Model. The regeneration model augments this inventory with expected regeneration. To accomplish this task, additional features of the model are important.

Several steps use a uniformly distributed pseudo-random number generator to make an unbiased but discrete choice among a list of alternative possibilities. The process is begun by predicting the probabilities of concern; for example, the probability for each species occurring on a stocked plot. The individual probabilities are totaled. Each probability is then divided by the total so that the sum of the adjusted probabilities equals 1.0. Adjusted probabilities are accumulated within the interval [0, 1] and a uniformly distributed pseudo-random number, also within the interval [0, 1], is chosen and compared to the accumulated probability. The alternative chosen is the one for which the accumulated probability first exceeds the random number. This procedure is used to make discrete assignments from an estimated distribution for site preparations, number of species per plot, and species composition.

A slightly different procedure is used to choose the number of trees (n) on a stocked plot. Equations, $P(n \geq k)$, were developed to predict the probability of two or more trees, three or more trees, and so on, up to 20 or more trees on a plot, resulting in 19 equations. The number of trees (n) to be assigned to the plot is chosen in a randomly stopped sequence. A pseudo-random number (x) in the interval [0, 1] is chosen for each plot. Then, for $k = 1, 2, \ldots, 19$, we compare x to $P(n \geq k+1)$, knowing that there will not be $0, 1, \ldots k-1$ trees on the plot. If the random number x is greater than $P(n \geq k+1)$, then there are $n = k$ trees on the plot; otherwise proceed to $k+1$. Whenever there are to be more than 20 trees on the plot, the distribution is assumed to be uniform up to 33 trees (95 percent of stocked plots had 33 or fewer trees).

Since these discrete choices must be made stochastically, there is a chance that if too few plots are processed, rare events might be chosen which would produce atypical stand averages. We guard against this possibility by replicating plots until at least 50 are available for processing.

The regeneration model can be entered more than once. On succeeding entries, the probability of stocking equations are used to predict the increment in stocking. Stocking probabilities are calculated at the beginning and end of the time interval. The proportion of plots becoming stocked in the time interval is calculated by subtracting the probabilities estimated for end points. The increment is used to scale the attributes of stocked plots. Advance regeneration is excluded on subsequent entries.

When a post-harvest inventory is supplied by the user, the inventory substitutes for the initial entry into the model. Stocking probabilities are scaled to match the inventory before the next increment in stocking is calculated. The model then estimates only the continued fill-in by subsequent regeneration.

RESULTS AND INTERPRETATION

Probability of Stocking

Probability of stocking equations were developed using all 4,964 plots. Separate equations were fit by method of site preparation, whether none, mechanical/burn,

TABLE 4. Definition of variables and abbreviations for equations.

Variable	Definition
Constant	β_0 (intercept)
ABGR/PAMY	Class variable for *Abies grandis/Pachistima myrsinites* habitat type. ABGR/PAMY = 1.0 if the plot habitat type is *Abies grandis/Pachistima myrsinites,* 0.0 if not this habitat type.
THPL/PAMY	Class variable for *Thuja plicata/Pachistima myrsinites* habitat type.
TSHE/PAMY	Class variable for *Tsuga heterophylla/Pachistima myrsinites* habitat type.
ABLA/PAMY	Class variable for *Abies lasiocarpa/Pachistima myrsinites* habitat type.
ELEV	Elevation above sea level to the nearest hundred feet, e.g., 35 = 3,500 feet.
ASP	Aspect in radians.
SLO	Slope tangent (slope percent divided by 100).
BA	Residual overstory basal area (ft^2/acre and set to 1.0 if no overstory).
TIME	Number of elapsed growing seasons since last disturbance. Disturbance date is the year of harvest or site preparation, whichever occurs last on the plot.
CUTTIME	Number of elapsed growing seasons since the harvest.
PLANT	Class variable for planted stands or trees. PLANT = 1.0 if planted, 0.0 if not planted.
NONE	Class variable for no site preparation.
MECH	Class variable for mechanical site preparation.
BURN	Class variable for burn site preparation.
ROAD	Class variable for road site preparation.
PREP	Class variable for MECH, BURN, and ROAD site preparations together.
BOTTOM	Class variable for bottom topographic position.
OVER	Class variable for the presence of the same species in the variable radius plot. OVER = 1.0 if the same species is present, 0.0 if not.
KOOTENAI	Class variable for areas nearest the Kootenai National Forest.
LOLO	Class variable for areas nearest the Lolo National Forest.
NEZPERCE	Class variable for areas nearest the Nezperce National Forest.
COLVILLE	Class variable for areas nearest the Colville National Forest.
TPP	Number of established regeneration-size trees on a plot.
ADVANCE	Class variable for advance regeneration. ADVANCE = 1.0 if the tree is advance, 0.0 if the tree is not advance.

or roads. Separate analyses were necessary to limit the number of independent variables to ≤ 30. Table 4 defines abbreviations for variables used for all equations shown in this paper, and probability of stocking equations are shown in Table 5.

Habitat types are important predictors for the probability of stocking. The *Abies grandis/Pachistima myrsinites* habitat type has the lowest probability of stocking relative to the other three habitat types. This habitat type is the warmest and driest in the ecosystem. The *Thuja plicata/Pachistima myrsinites* habitat type has a higher probability of stocking but lower than the *Tsuga heterophylla/Pachistima myrsinites* habitat type which has the highest probability of stocking. The *Abies lasiocarpa/Pachistima myrinites* habitat type has a lower probability of stocking than the *Tsuga heterophylla/Pachistima myrsinites* habitat type except for plots classified as "road" site preparation.

Time since disturbance is another important predictor of stocking. Rate of stocking differs over time for different aspects. North-facing slopes regenerate quickly; south-facing slopes slowly (Fig. 4a). East- and west-facing slopes are similar to each other and intermediate between north and south.

Slope and aspect interact quite dramatically. North-facing slopes have the highest probability of stocking while south-facing slopes have the lowest (Fig. 4b).

TABLE 5. Coefficients for probability of stocking equations by site preparation. The form of the equation is $P = (1 + e^{-(\Sigma\beta_i X_i)})^{-1}$, *where "e" is the base of natural logarithms = 2.71828.*

i	Variable (X)	No site preparation (β)	Mechanical or burn (β)	Road site preparation (β)
1	Constant	−5.339950	−6.09345	−1.287360
2	ABGR/PAMY[a]	0.0	0.0	0.0
3	THPL/PAMY	0.307207	0.030264	0.968724
4	TSHE/PAMY	0.480030	0.924321	1.256860
5	ABLA/PAMY	0.235986	0.725215	1.967890
6	ELEV	0.226578	0.246801	−0.047565
7	ELEV^2	−0.003138	−0.002826	—
8	SLO*COS(ASP)*BA	−0.013417	—	—
9	SLO*SIN(ASP)*BA	−0.006994	—	—
10	BA	−0.005566	0.010810	0.012272
11	Ln(BA)	0.226151	—	—
12	$\sqrt{\text{TIME}}$	0.528180	—	0.840981
13	TIME	—	0.074405	—
14	$\sqrt{\text{SLO}}$*COS(ASP)*TIME	0.190963	0.173786	—
15	$\sqrt{\text{SLO}}$*SIN(ASP)*TIME	−0.007184	0.017279	—
16	$\sqrt{\text{SLO}}$*TIME	−0.359765	0.077434	—
17	$\sqrt{\text{SLO}}$*TIME^2	0.018077	—	—
18	$\sqrt{\text{SLO}}$	1.624250	—	—
19	PLANT	−0.413301	0.234173	0.479440
20	BURN	—	−0.336089	—
	F-ratio	24.79	17.02	8.64
	Chi-square	6.36	21.75	14.11
	Error mean square	1.000	1.022	1.014
	Number of plots	2,652	1,916	396
	Number of stocked plots	1,720	1,025	223
	Optimum aspect[b]	358°	6°	n.s.[c]
	Amplitude[b]	0.48	0.44	

[a] Represented as part of the constant term to avoid a singular matrix.

[b] Optimum aspects and amplitudes were calculated using the procedure developed by Stage (1976). Figure 3b shows the optimum aspect for stocking is almost due north. The poorest aspects are 180° from the optimum. Amplitude is the depth of curve from the optimum aspect to the poorest aspect with SLO = 0.3, TIME = 10 years, and probability of stocking centered on 0.50.

[c] Not significant.

Steepness of the slope accentuates the effect of aspect. The interactive terms for slope and aspect do not make an *a priori* assumption about the optimum aspect (Stage 1976).

The response surface for elevation is quadratic (Fig. 4c). Stocking is least toward the low and high extremes within the ecosystem and highest at middle elevations. Optimum elevations occur from 3,500 to 4,500 feet (1,067 to 1,372 m).

Responses differ by site preparation. Undisturbed plots have a higher initial probability of stocking due to the presence of advance regeneration, but the increment in stocking over time for the no site preparation equation is less than the other site preparations (Fig. 4d). Mechanical site preparation has an intercept lower than the no site preparation equation but higher than burn preparation. Aspect influences the increment in stocking over time more than site preparation.

The effect of residual basal area varies according to slope and aspect (Fig. 5). Stocking on north aspects is not increased substantially by residual overstory

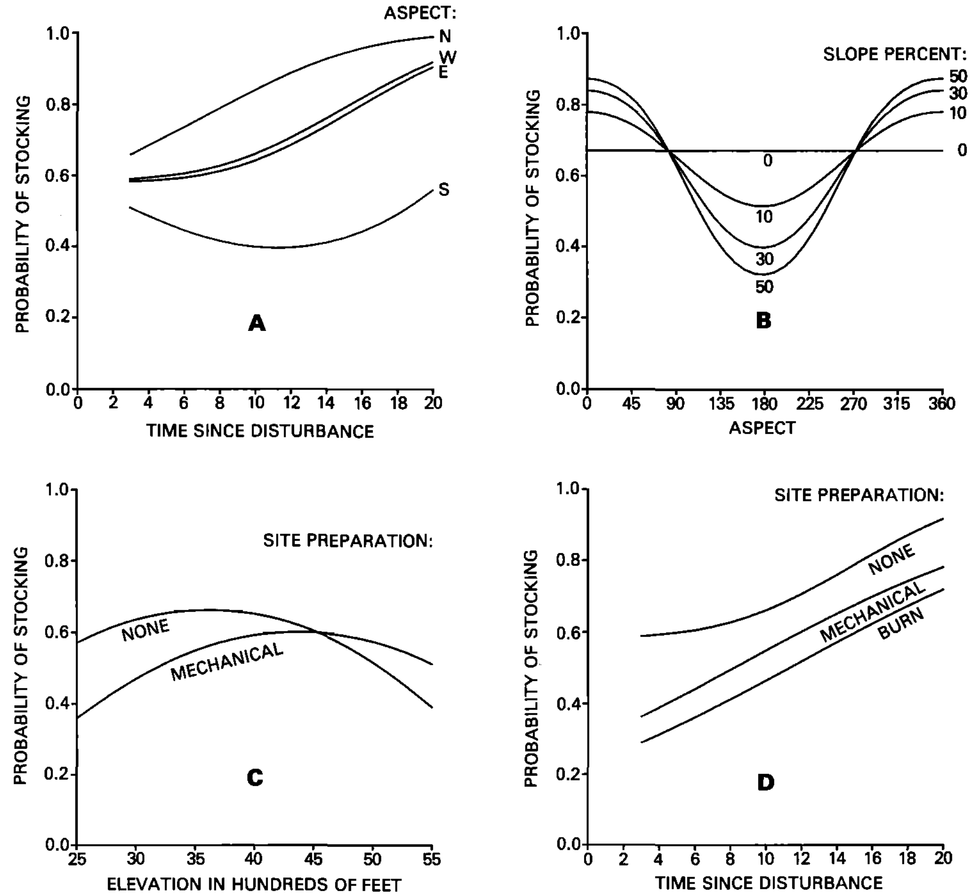


FIGURE 4. The effects of time since disturbance, slope percent, aspect, elevation, and site preparation on the probability of stocking. Graphs use equations shown in Table 5. Variables not shown in a graph were assigned the following values: 10 years time since disturbance, 30 percent slope, west aspect, 3,500 feet elevation, no site preparation, *Thuja plicata/Pachistima myrsinites* habitat type, no planting, and no residual overstory.

density, especially as the slope steepness increases. Stocking on south aspects is aided by increased residual overstory density. Again, east- and west-facing slopes are intermediate in response.

We found it difficult to model the effect of planting using retrospective examination procedures because available historical records were not detailed enough to provide a complete planting history. Because planted stands have natural and planted trees, we did not wish to discard data from plantations. Therefore, a class variable is used to represent plantation effects.

Two variables proved to be unimportant and were dropped from further analyses. The first was distance to seed walls. Distance alone does not quantify wind direction, species mix in the seed wall, or seed production. The effect is also masked by the presence of advance regeneration. The second was soil parent material. Within the ecosystem, the loess and ash cap acts to reduce the effect of soil parent material.

There may be a bias in the probability of stocking equations due to the method of site preparation. Stands could have been scheduled for site preparation but just

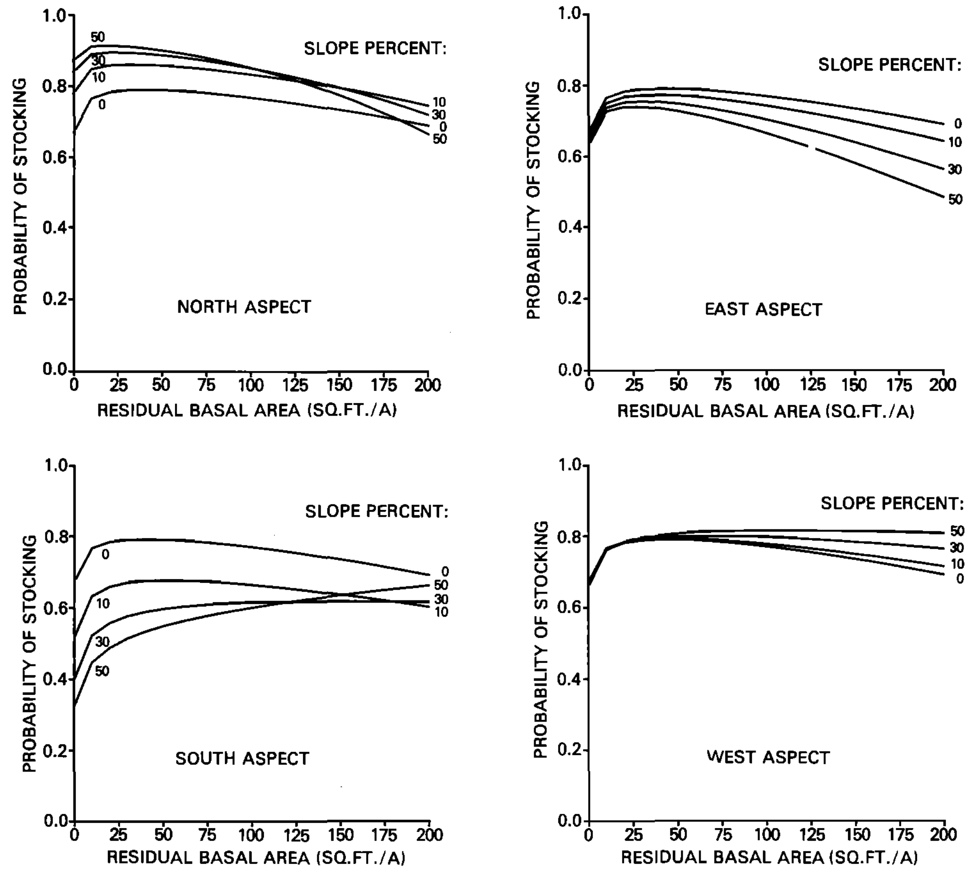


FIGURE 5. The effect of residual basal area on the probability of stocking for cardinal aspects. Graphs use the no site preparation equation shown in Table 5, with the following held constant: 10 years time since disturbance, 3,500 feet elevation, *Thuja plicata/Pachistima myrsinites* habitat type, and no planting.

happened to receive a good catch of natural regeneration, and the treatment was canceled. Stands or areas within stands may have been spared site preparation due to the presence of advance regeneration. In a like manner, plots and stands which did receive site preparation may be those needing extra efforts to obtain stocking. These biases affect only the intercept of the model and are removed by a calibration feature which adjusts the probability of stocking intercept to coincide with a user-supplied inventory. The probability of stocking equations are used to predict the next increment in stocking.

Table 6 shows the overall performance of the probability of stocking equations relative to the null hypothesis of a mean probability of stocking applicable to all plots. The equations produce estimates of stocking probabilities that span almost the full range between zero and one, and the chi-square for each interval of predicted probability is quite uniform. In contrast, the null hypothesis of a mean probability of stocking produces large chi-square values.

Although the usual interpretation for chi-square statistics is to decide whether to reject the null hypothesis, in these analyses, that role is not very interesting. A somewhat different interpretation is analogous to an analysis of residuals plotted over predicted values of linear regression equations for continuous dependent variables.

TABLE 6. Distribution of estimated probabilities and chi-square statistics for probability of stocking equations shown in Table 5.

Expected probability of stocking interval	No site preparation			Mechanical/burn			Road site preparation		
	No. plots	χ^2 about equation	χ^2 about mean	No. plots	χ^2 about equation	χ^2 about mean	No. plots	χ^2 about equation	χ^2 about mean
0.10–0.15	0	—	—	0	—	—	6	0.01	3.84
0.15–0.20	2	0.50	3.71	17	2.74	2.26	8	0.14	6.22
0.20–0.25	13	0.00	9.95	34	0.54	17.57	14	1.83	13.74
0.25–0.30	26	0.37	19.90	57	0.06	16.93	27	0.05	7.80
0.30–0.35	46	0.77	13.37	144	0.38	30.47	26	0.34	3.37
0.35–0.40	77	0.93	16.35	245	0.40	31.87	24	1.60	9.55
0.40–0.45	96	0.00	20.68	235	1.35	20.62	21	3.28	0.27
0.45–0.50	147	0.20	23.97	224	0.38	1.40	22	0.36	2.13
0.50–0.55	215	0.99	22.83	137	2.06	1.32	26	0.08	0.42
0.55–0.60	308	0.01	6.75	153	0.41	2.71	24	4.45	5.10
0.60–0.65	326	0.80	0.00	129	1.86	11.23	46	0.02	0.85
0.65–0.70	411	0.06	1.65	155	3.81	2.63	38	0.44	0.73
0.70–0.75	349	0.76	4.36	130	2.35	32.56	24	0.05	2.06
0.75–0.80	216	0.02	13.63	103	0.25	28.23	38	0.79	3.36
0.80–0.85	189	0.02	24.39	58	0.06	17.68	27	0.01	6.96
0.85–0.90	116	0.25	29.15	46	0.19	18.09	17	0.02	7.05
0.90–0.95	104	0.16	36.84	35	3.98	12.12	7	0.66	5.44
0.95–1.00	11	0.52	5.97	14	0.93	8.71	1	0.00	0.79
Total	2,652	6.36	253.50	1,916	21.75	256.40	396	14.13	79.68
No. cells (r)		34	34		34	34		36	36
No. parameters estimated (p)		17	1		13	1		8	1
$\Sigma \chi^2 \div (r - p - 1)$		0.40	7.92		1.09	8.01		0.52	2.34

Dividing each chi-square statistic by its associated degrees of freedom gives "mean-square errors of prediction," which are listed at the foot of Table 6. For example, for the equation representing sites mechanically prepared or burned, the normalized chi-square for the null hypothesis is 8.01 while the equation chi-square divided by its degrees of freedom is 1.09. Thus, we can say that the equation leaves $1.09 \div 8.01 = 0.14$ proportion of the overall variability of stocking unexplained.

Stocked Plot Analyses

Next, equations were developed to predict the attributes of the 2,968 stocked plots. Regression equations were developed to predict the

1. distribution of number of trees on the plot,
2. distribution of number of species,
3. probability of species' occurrence, and
4. heights of all trees on the plot.

Number of Trees per Stocked Plot

The number of regeneration-size trees on stocked plots is distributed as shown in Figure 6. The most probable occurrence is one tree per plot followed by two, three, four, and so on, up to 213 established trees on a plot. Equations were

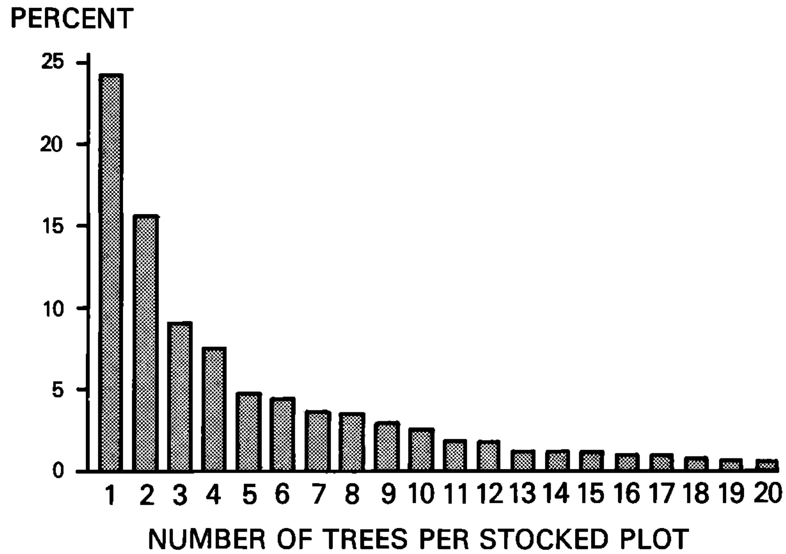


FIGURE 6. Distribution of number of regeneration-size trees for plots having up to 20 established trees.

developed to predict the probability of two or more trees per plot, three or more trees per plot, and so on, up to 20 or more trees per plot.

Each stocked plot has at least one established tree so this probability was not predicted. All stocked plots were analyzed to predict the probability of two or more trees. Plots having at least two established trees were assigned the value 1.0; those with only one tree were assigned the value 0.0. Again RISK (Hamilton 1974) was used to estimate this probability in the interval [0, 1].

Plots with three or more trees were assigned the value 1.0 (0.0 otherwise) to predict the probability of three or more trees. Plots with four or more trees were used to predict the probability of four or more trees, and so on, up to 20 or more trees on a plot. From the equations shown in Table 7, a distribution can be estimated for each plot. Figure 6 shows that the tail of the distribution becomes very flat, and for computational purposes we assume that it is.

Important variables used to predict the number of trees per stocked plot are habitat type, elevation, slope and aspect, time since disturbance, residual basal area, and planting. Cooler and wetter habitat types have more trees than warm, dry ones. Middle elevations and north aspects also have more trees per stocked plot. Planted stands have fewer trees per stocked plot.

Considering the equations shown in Table 7, it appears that some of the coefficients might be represented as functions of the number of trees per plot (n). Or, indeed, the distribution might be postulated to follow a conditional Poisson distribution. Although this study had enough data to estimate the logistic equations for values of n, a larger sample would be needed to test other hypotheses. These will be tested with additional data now becoming available for expanding the regeneration model to other ecosystems.

NUMBER OF SPECIES PER STOCKED PLOT

Determining the number of species on a plot is necessary because all 10 species do not occur on a 1/300-acre (0.00135-ha) plot. The highest number of species per plot was seven and this occurred only once. Figure 7 shows the distribution

TABLE 7. Coefficients for probability equations predicting the distribution of number of trees on a stocked plot. Equations for ≥7 to ≥20 trees are not shown but are similar to those below. Form of the equation is $P = (1 + e^{-(\Sigma\beta_i X_i)})^{-1}$, *where "e" is the base of natural logarithms = 2.71828.*

i	Variable (*X*)	≥2 trees (*β*)	≥3 trees (*β*)	≥4 trees (*β*)	≥5 trees (*β*)	≥6 trees (*β*)
1	Constant	−3.67557	−2.81144	−3.94160	−5.38434	−5.59725
2	ABGR/PAMY[a]	0.0	0.0	0.0	0.0	0.0
3	THPL/PAMY	0.28574	0.39729	0.42159	0.51627	0.62835
4	TSHE/PAMY	0.48956	0.69254	0.67249	0.75318	0.80553
5	ABLA/PAMY	0.61301	0.82606	0.99915	1.26830	1.34565
6	ELEV	0.19122	0.11256	0.15646	0.21467	0.21297
7	$ELEV^2$	−0.00236	−0.00154	−0.00217	−0.00296	−0.00297
8	SLO*COS(ASP)	1.81361	1.78352	1.94394	1.96557	2.02248
9	SLO*SIN(ASP)	−0.09944	−0.21204	−0.06599	−0.30227	−0.31900
10	SLO	−1.12503	−0.46962	−0.74018	−0.76096	−0.49739
11	TIME	0.10033	0.09485	0.09575	0.09344	0.08830
12	BA	—	−0.00446	−0.00467	−0.00518	−0.00584
13	Ln(BA)	0.19128	0.22213	0.24522	0.25210	0.25386
14	PLANT	−0.58582	−0.66283	−0.75727	−0.75718	−0.75961
F-ratio		69.03	33.27	30.18	32.29	35.58
Chi-square		15.26	29.63	21.82	18.23	38.70
Error mean square		1.002	1.005	1.006	1.012	1.023
Number of plots		2,968	2,968	2,968	2,968	2,968
No. of occurrences		2,247	1,782	1,511	1,288	1,147
Optimum aspect		357°	353°	358°	351°	351°
Amplitude		0.27	0.26	0.28	0.29	0.30

[a] Represented as part of the constant term to avoid a singular matrix.

summarized from the data. The most frequent occurrence is one species per plot, followed by two species, three, and so on.

Equations were developed to predict the probability of 1, 2, 3, 4, 5, and 6 species per stocked plot. The number of species is conditional on the number of trees. For example, to predict the probability of two species, only those plots with two or more trees were analyzed; three species, three or more trees, and so on. Table 8 lists the coefficients in the resulting logistic equations.

Important independent variables are habitat type, slope and aspect, and number of regeneration-size trees on the plot. Generally, the cooler and wetter the habitat type, the more species that occur. Slope and aspect have varying trends as the number of species being predicted increases. Also, as the number of regeneration-size trees on the plot increases, there is more opportunity for a greater number of species to be present.

Species Occurrence

We defined three subclasses for each of the 10 species listed in Table 1—advance, subsequent, and excess. Advance and subsequent trees are a further division of "best" trees. Excess trees are all other trees on the plot not chosen as best trees. Advance trees germinated more than 3 years prior to the harvest. Subsequent trees germinated after the cutoff date for advance trees. We included trees up to 3 years old at the time of harvest in the subsequent class for the following reasons. First, accuracy for aging small trees was felt to be ±1 year. Second, there was only one harvest date available for each stand (usually the completion date) and

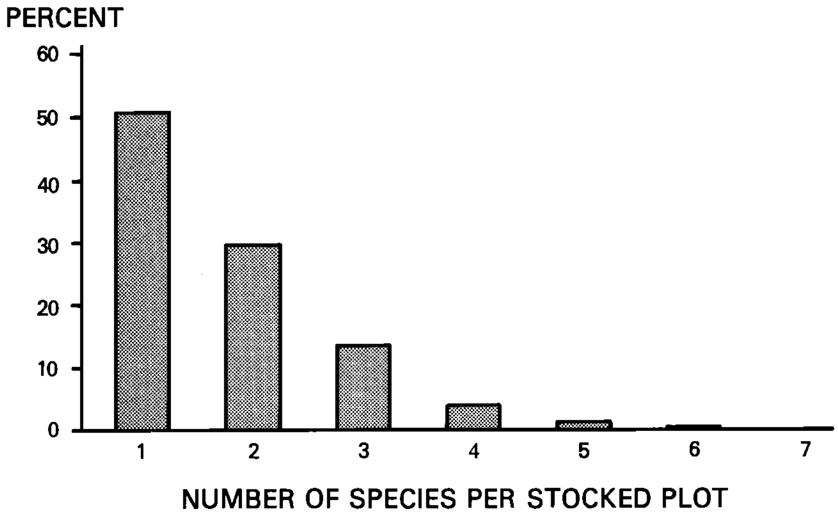


FIGURE 7. Distribution of number of regeneration-size conifer species on stocked plots.

TABLE 8. Coefficients for equations predicting probability of the number of species on a stocked plot. The form of the equation is $P = (1 + e^{-(\Sigma\beta_i X_i)})^{-1}$, *where "e" is the base of natural logarithms = 2.71828. The equation for 1 species is conditional on there being at least two trees on the plot while other equations are conditional on the number of trees being equal to or greater than the number of species being predicted.*

i	Variable (*X*)	1 species (β)	2 species (β)	3 species (β)	4 species (β)	5 species (β)	6 species (β)
1	Constant	−2.54129	−0.49314	−1.96409	−5.38426	−2.02433	−5.37123
2	ABGR/PAMY[a]	0.0	—	0.0	0.0	0.0	—
3	THPL/PAMY	−0.17100	—	0.19032	0.59396	0.0	—
4	TSHE/PAMY	−0.56874	—	0.65442	0.83153	0.0	—
5	ABLA/PAMY	−1.08551	—	0.94741	0.86060	1.96458	—
6	ELEV	0.22102	—	—	0.03721	−0.06813	—
7	$ELEV^2$	−0.00278	—	—	—	—	—
8	SLO*COS(ASP)	−0.35655	1.30182	—	−1.08140	—	—
9	SLO*SIN(ASP)	0.81267	0.26433	—	−1.68622	—	—
10	SLO	1.08417	−0.55392	−1.28920	0.07018	—	—
11	TPP	—	−0.01399	0.05255	0.05220	0.02509	0.01622
12	TPP^2	—	—	−0.00042	−0.00020	—	—
13	Ln(TPP)	−1.11604	—	—	—	—	—
14	TIME	−0.06166	0.03231	—	—	—	—
15	BA	0.00419	—	—	—	—	—
16	PLANT	—	—	0.31764	—	1.20018	—
	F-ratio	40.45	25.59	69.25	70.39	90.23	212.82
	Chi-square	17.14	6.79	31.47	16.34	22.48	1.55
	Error mean square	0.981	1.002	0.995	0.903	1.032	0.873
	Number of plots	2,248	2,248	1,783	1,512	1,289	1,148
	No. of occurrences	789	887	404	119	38	8
	Optimum aspect	114°	11°	n.s.	237°	n.s.	n.s.
	Amplitude	0.13	0.20		0.29		

[a] Represented as part of the constant term to avoid a singular matrix.

TABLE 9. Coefficients for equations predicting the probability of occurrence for advance regeneration on a stocked plot. The form of the equation is $P = (1 + e^{-(\Sigma \beta_i X_i)})^{-1}$, *where "e" is the base of natural logarithms = 2.71828.*

i	Variable (X)	Ponderosa pine (β)	Western larch (β)	Lodgepole pine (β)	Engelmann spruce (β)	Douglas-fir (β)
1	Constant	−6.80591	−4.52552	−4.48155	−8.16001	−2.02718
2	ABGR/PAMY[a]	—	0.0	0.0	—	0.0
3	THPL/PAMY	—	−1.74653	−1.23754	—	−1.01239
4	TSHE/PAMY	([b])	−1.57847	−1.71160	—	−1.25099
5	ABLA/PAMY	([b])	([b])	−0.35789	—	−0.70160
6	SLO*COS(ASP)	—	—	—	2.54785	0.36290
7	SLO*SIN(ASP)	—	—	—	−1.74797	−1.66416
8	SLO	—	—	—	−2.36330	0.12114
9	CUTTIME	—	—	—	−0.16763	−0.04658
10	BA	—	—	—	−0.02813	−0.01310
11	BA^2	—	—	—	—	—
12	Ln(BA)	—	—	—	0.67749	0.41802
13	ELEV	—	—	—	0.10941	—
14	$ELEV^2$	—	—	—	—	—
15	NONE[a]	—	—	—	—	0.0
16	MECH	—	—	—	—	−0.34994
17	BURN	—	([b])	—	([b])	−0.97810
18	ROAD	—	([b])	—	([b])	−0.80488
19	BOTTOM	—	—	—	—	—
20	OVER	2.55868	2.19790	3.11772	1.45849	0.83598
21	COLVILLE	—	—	—	—	—
22	KOOTENAI	—	—	—	—	—
23	LOLO	—	—	—	—	—
24	NEZPERCE	—	—	—	—	—
F-ratio		115.99	83.06	95.71	49.01	84.55
Chi-square		0.01	1.45	4.64	6.42	18.67
Error mean square		0.978	1.168	1.065	1.049	0.901
Number of plots		1,924	2,179	2,968	2,292	2,968
No. of occurrences		3	15	39	37	245
Optimum aspect		n.s.	n.s.	n.s.	326°	282°
Amplitude					0.43	0.25

[a] Represented as part of the constant term to avoid a singular matrix.
[b] Equation is undefined; probability = 0.0.

if it took more than 1 year to harvest the stand, some areas were harvested before others. Third, we felt that a 3-year-old tree would not have suffered major physiological setbacks due to suppression by the overstory. Fourth, nursery stock planted immediately after harvesting would appear to be advance regeneration unless the cutoff date allowed for this situation.

The three subclasses of regeneration are distributed quite differently. For example, shade-intolerant species seldom occur as advance regeneration. They have a higher probability of occurring as subsequent regeneration. Some species, such as grand fir, seem well adapted to occurring in all three subclasses. Shade-tolerant western redcedar most often is advance regeneration.

Equations were fit for the probabiltiy of each species and its subclass, resulting in 30 equations. The unit of analysis was the 1/300-acre (0.00135-ha) plot, the dependent variable being the presence or absence of an established seedling of each species subclass on a stocked plot. Equations for advance regeneration use

TABLE 9. Extended.

W. white pine (β)	Grand fir (β)	Western hemlock (β)	Subalpine fir (β)	Western redcedar (β)	Variable (X)	i
−0.98695	−3.04100	−2.12506	−3.07764	−2.32854	Constant	1
0.0	0.0	(b)	0.0	(b)	ABGR/PAMY[a]	2
−0.31863	−0.56122	(b)	−0.51106	—	THPL/PAMY	3
−0.69779	−0.57611	0.0	1.48041	—	TSHE/PAMY	4
0.97228	−0.11877	(b)	3.83211	—	ABLA/PAMY	5
−1.96990	—	3.95210	−1.04807	0.47197	SLO*COS(ASP)	6
−4.18866	—	−0.41781	−2.04533	−1.88846	SLO*SIN(ASP)	7
−1.76512	2.39807	1.61739	−1.50747	−0.38944	SLO	8
−0.26621	−0.14744	—	−0.15065	—	CUTTIME	9
0.02699	0.00884	—	—	0.00359	BA	10
−0.00030	−0.00004	—	—	—	BA^2	11
—	—	—	—	—	Ln(BA)	12
—	0.19906	—	—	—	ELEV	13
—	−0.00265	—	—	—	$ELEV^2$	14
—	0.0	0.0	0.0	0.0	NONE[a]	15
—	−1.15898	−1.29664	−1.10592	−0.73332	MECH	16
—	−2.36913	(b)	−1.34371	−1.61668	BURN	17
(b)	−1.41622	−1.66086	(b)	−1.63129	ROAD	18
—	—	—	—	1.14632	BOTTOM	19
—	0.62302	1.06142	1.38220	1.72412	OVER	20
(b)	—	—	—	—	COLVILLE	21
—	−1.84633	—	—	—	KOOTENAI	22
(b)	−1.84633	—	—	—	LOLO	23
(b)	—	—	—	—	NEZPERCE	24
70.80	49.19	37.60	50.17	77.75	*F*-ratio	
23.72	13.96	26.16	22.72	22.44	Chi-square	
0.989	0.972	0.943	1.082	0.936	Error mean square	
2,452	2,968	749	2,745	2,175	Number of plots	
122	963	150	83	340	No. of occurrences	
245°	n.s.	354°	243°	284°	Optimum aspect	
0.60		0.53	0.33	0.28	Amplitude	

time since the harvest, while subsequent and excess regeneration use time since harvest or time since site preparation, whichever occurred last on the plot.

Advance Regeneration.—Table 9 reveals that the probability of advance regeneration is primarily related to shade tolerance of the species, habitat type, slope and aspect, residual basal area and species composition, and time since harvest. Grand fir is by far the most prolific of the advance species with almost one in every three stocked plots having at least one advance grand fir.

The probability of five advance species decreases with increasing time since harvest. Three hypotheses are suggested. First, trees survive the harvest but some eventually die from the sudden exposure caused by overstory removal. Second, trees survive the harvest but do not respond well to release and, with time, become subordinate to a subsequent tree of the same species (the taller subsequent tree of the same species would have been chosen as a best tree). Third, mortality over time is caused by some other factor. This third reason could explain the negative

TABLE 10. Coefficients for equations predicting the probability of occurrence for subsequent regeneration on a stocked plot. The form of the equation is $P = (1 + e^{-(\Sigma\beta_i X_i)})^{-1}$, *where "e" is the base of natural logarithms = 2.71828.*

i	Variable (X)	Ponderosa pine (β)	Western larch (β)	Lodgepole pine (β)	Engelmann spruce (β)	Douglas-fir (β)
1	Constant	−8.19455	−5.52774	−0.50391	−8.70659	1.01851
2	ABGR/PAMY[a]	—	0.0	0.0	0.0	—
3	THPL/PAMY	—	0.77074	−0.67218	0.90764	—
4	TSHE/PAMY	([b])	0.65396	−0.32400	1.71613	—
5	ABLA/PAMY	([b])	0.50747	−1.28338	1.28910	—
6	SLO*COS(ASP)	—	1.24521	−1.49840	1.29052	—
7	SLO*SIN(ASP)	—	2.09357	0.99176	1.96506	—
8	SLO	—	−0.64194	−5.74293	−5.39479	—
9	TIME	0.24937	0.10416	−0.06940	0.09516	0.13792
10	BA	—	—	—	—	—
11	Ln(BA)	—	—	−0.56532	−0.28307	—
12	ELEV	—	—	—	0.09028	−0.19502
13	$ELEV^2$	—	—	—	—	0.00224
14	NONE[a]	0.0	0.0	—	0.0	0.0
15	MECH	2.17005	0.80855	—	1.37613	0.33971
16	BURN	1.99979	0.65130	—	1.14579	0.65070
17	ROAD	1.74700	1.61177	—	1.48491	0.61518
18	BOTTOM	—	—	1.25121	—	—
19	OVER	3.20311	0.84614	2.01735	2.52007	—
20	KOOTENAI	—	2.47869	—	—	—
21	LOLO	—	2.47869	—	—	—
22	COLVILLE	—	—	—	—	—
23	NEZPERCE	—	—	—	—	—
24	PLANT	5.65447	2.53744	2.83317	2.42091	0.91933
	F-ratio	50.91	70.12	81.41	56.75	135.30
	Chi-square	18.39	13.97	31.81	21.81	49.28
	Error mean square	1.057	0.971	0.951	0.824	0.958
	Number of plots	1,924	2,968	2,968	2,968	2,968
	No. of occurrences	74	155	177	138	593
	Optimum aspect	n.s.	59°	147°	57°	n.s.
	Amplitude		0.35	0.26	0.34	

[a] Represented as part of the constant term to avoid a singular matrix.
[b] Equation is undefined; probability = 0.0.

correlation with time for western white pine due to white pine blister rust. The first and second reasons might be acting on all species.

Site preparation decreases stocking by advance species with burn site preparation decreasing stocking further than mechanical preparation. Retrospective examination procedures prevented us from determining if advance regeneration was destroyed by the site preparation or if advance regeneration was absent or unacceptable and site preparation was deemed necessary.

Subsequent Regeneration.—Equations predicting the probability of subsequent regeneration were developed for each of the 10 species. The dependent variable is the presence or absence of at least one established subsequent seedling of the indicated species being chosen as a best tree. Coefficients for these equations are listed in Table 10.

Subsequent species occurrence is primarily related to habitat type, slope and aspect, time since disturbance, residual overstory density and species composition,

TABLE 10. Extended.

W. white pine (β)	Grand fir (β)	Western hemlock (β)	Subalpine fir (β)	Western redcedar (β)	Variable (X)	i
−2.25538	−1.29536	−14.6413	−9.36746	−3.70128	Constant	1
0.0	0.0	([b])	0.0	([b])	ABGR/PAMY[a]	2
0.75482	0.60318	([b])	0.0	0.0	THPL/PAMY	3
1.02397	0.31578	0.0	1.47516	0.0	TSHE/PAMY	4
1.17424	0.10346	([b])	3.51186	([b])	ABLA/PAMY	5
−0.41394	1.12247	2.55377	—	1.76063	SLO*COS(ASP)	6
−1.68455	0.74180	−0.58465	—	0.82295	SLO*SIN(ASP)	7
−1.59382	−0.99295	−1.28175	−4.76980	−2.69792	SLO	8
0.09214	0.13537	0.13957	0.14212	0.16084	TIME	9
−0.00901	−0.00403	—	—	—	BA	10
—	—	—	−0.41160	—	Ln(BA)	11
−0.03256	—	0.61338	0.10211	—	ELEV	12
—	—	−0.00786	—	—	ELEV[2]	13
0.0	0.0	0.0	—	0.0	NONE[a]	14
0.0	0.16997	0.42346	—	0.74276	MECH	15
0.0	0.03319	0.73262	—	1.19369	BURN	16
0.51987	0.76878	0.70174	—	1.51886	ROAD	17
—	—	—	—	—	BOTTOM	18
1.20803	—	0.88990	1.71843	1.03124	OVER	19
—	−1.84357	—	2.14761	—	KOOTENAI	20
([b])	−1.84357	—	—	—	LOLO	21
([b])	—	—	—	—	COLVILLE	22
([b])	—	—	—	—	NEZPERCE	23
1.97844	0.71928	—	—	—	PLANT	24
76.96	27.83	20.90	33.17	85.68	*F*-ratio	
15.15	27.83	13.34	20.91	11.33	Chi-square	
1.085	1.008	1.003	1.763	1.018	Error mean square	
2,663	2,968	907	2,968	2,038	Number of plots	
284	1,406	232	107	307	No. of occurrences	
256°	33°	347°	n.s.	25°	Optimum aspect	
0.25	0.20	0.37		0.28	Amplitude	

elevation, and site preparation. Grand fir is again abundant with almost half of all stocked plots having at least one subsequent grand fir.

Site preparation generally increases the probability of subsequent species as does the presence of the same species left as a seed source in the overstory. Time since disturbance has a positive relationship except for lodgepole pine. This species, due to cone serotiny, may regenerate only in the early years following the harvest. Lodgepole pine cone serotiny varies with the ecosystem, and we did not attempt to quantify it.

Excess Regeneration.—Probability of occurrence for excess trees was predicted using the same methodology as for advance and subsequent regeneration. The equations shown in Table 11 predict the probability of at least one excess tree of the species indicated being established on the 1/300-acre (0.00135-ha) plot. The presence of an excess tree of a particular species means a best tree of the same species is established on the plot.

TABLE 11. Coefficients for equations predicting the probability of occurrence for excess regeneration on a stocked plot. The form of the equation is $P = (1 + e^{-(\Sigma\beta_i X_i)})^{-1}$, *where "e" is the base of natural logarithms = 2.71828.*

i	Variable (*X*)	Ponderosa pine (β)	Western larch (β)	Lodgepole pine (β)	Engelmann spruce (β)	Douglas-fir (β)
1	Constant	−6.12619	−19.9935	−2.86744	−12.5327	−2.44811
2	ABGR/PAMY[a]	—	—	0.0	0.0	0.0
3	THPL/PAMY	—	—	−1.14639	2.04368	0.0
4	TSHE/PAMY	([b])	—	0.26777	2.98487	0.0
5	ABLA/PAMY	([b])	—	−0.97454	1.80442	1.39350
6	SLO*COS(ASP)	—	—	—	—	−0.22120
7	SLO*SIN(ASP)	—	—	—	—	−1.13115
8	SLO	—	−4.39821	−4.52382	−4.76309	1.71081
9	TIME	—	0.13760	—	—	0.10135
10	BA	—	—	—	—	0.00978
11	BA^2	—	—	—	—	−0.00008
12	Ln(BA)	—	—	−0.49520	—	—
13	ELEV	—	0.69640	—	0.15687	−0.04443
14	$ELEV^2$	—	−0.00829	—	—	—
15	NONE[a]	—	0.0	—	0.0	—
16	MECH	—	0.0	—	0.93614	—
17	BURN	—	0.0	—	0.54092	—
18	ROAD	—	1.74003	—	0.94599	—
19	BOTTOM	—	—	2.09163	—	1.40694
20	OVER	2.95997	—	3.90435	0.98474	0.68615
21	KOOTENAI	—	2.42932	—	—	—
22	LOLO	—	2.42932	—	—	—
23	COLVILLE	—	—	—	—	—
24	NEZPERCE	—	—	—	—	—
F-ratio		181.58	78.73	79.33	52.51	119.95
Chi-square		0.0	9.49	9.03	10.17	6.00
Error mean square		0.993	1.055	1.051	1.076	0.971
Number of plots		1,924	2,968	2,968	2,968	2,968
No. of occurrences		7	45	72	41	238
Optimum aspect		n.s.	n.s.	n.s.	n.s.	259°
Amplitude						0.17

[a] Represented as part of the constant term to avoid a singular matrix.
[b] Equation is undefined; probability = 0.0.

Probability of occurrence for excess species is primarily related to some combination of habitat type, slope and aspect, time since disturbance, elevation, and overstory density and species composition.

Tree Heights

The objective of this analysis was to relate heights of established seedlings to site and stand conditions, species, and time since disturbance. Log-linear regression equations were developed for each species and advance or subsequent subclass. The age of the tree was not used as an independent variable because this would necessitate an additional step in the model to predict the year each tree germinates.

Baskerville (1972) points out the bias of using logarithmic regression to estimate a mean on the original units of measure. We avoid this bias by adding to the prediction a variable representing the normal random component of the log-linear model. This variable is sequentially assigned +1, 0, and −1 times the standard

TABLE 11. Extended.

W. white pine (β)	Grand fir (β)	Western hemlock (β)	Subalpine fir (β)	Western redcedar (β)	Variable (X)	i
−3.20786	−8.66240	−2.86534	−6.30420	−3.06080	Constant	1
0.0	0.0	([b])	0.0	([b])	ABGR/PAMY[a]	2
0.0	0.59368	([b])	0.0	—	THPL/PAMY	3
0.33191	0.54585	0.0	2.17350	—	TSHE/PAMY	4
1.20402	1.22347	([b])	4.68847	—	ABLA/PAMY	5
−1.08906	1.95101	4.65331	—	1.88752	SLO*COS(ASP)	6
−3.06774	−0.02776	−0.92676	—	−0.53412	SLO*SIN(ASP)	7
−0.83508	0.22429	0.64135	—	−1.55900	SLO	8
—	0.07864	0.10546	—	0.07592	TIME	9
—	—	—	—	−0.00433	BA	10
—	—	—	—	—	BA^2	11
—	0.14108	—	—	0.13810	Ln(BA)	12
—	0.37341	—	—	—	ELEV	13
—	−0.00503	—	—	—	$ELEV^2$	14
—	0.0	0.0	—	0.0	NONE[a]	15
—	−0.23348	0.0	—	0.0	MECH	16
—	−0.68900	−0.62403	([b])	0.0	BURN	17
—	0.0	0.0	—	0.36785	ROAD	18
—	—	—	—	—	BOTTOM	19
0.69052	—	1.00690	0.86679	1.62521	OVER	20
—	−1.85349	—	2.34708	—	KOOTENAI	21
([b])	−1.85349	—	—	—	LOLO	22
([b])	—	—	—	—	COLVILLE	23
([b])	—	—	—	—	NEZPERCE	24
161.71	41.55	40.53	100.47	92.14	*F*-ratio	
8.40	26.13	11.29	38.43	16.17	Chi-square	
1.019	0.985	1.008	0.937	1.006	Error mean square	
2,663	2,968	907	2,515	2,175	Number of plots	
126	1,028	224	68	337	No. of occurrences	
250°	359°	349°	n.s.	344°	Optimum aspect	
0.45	0.28	0.61		0.29	Amplitude	

error of the log-linear prediction. These predictions, when transformed to the original unit of measurement, produce an unbiased distribution of tree heights. In addition, the variation in heights of trees provides the foundation for future differentiation into crown classes.

The equations presented in Tables 12 and 13 must be considered within the context of the study design. Some terms are not significant predictors because few data were available for analysis. Planting was not important for predicting the heights of subsequent subalpine fir, western redcedar, and western hemlock because these species were not planted in any of the sample stands. Similarly, residual basal area was not important in predicting heights of subsequent Engelmann spruce because Engelmann spruce was not common at high levels of basal area.

Heights of excess trees are assigned from a Weibull distribution function (Bailey and Dell 1973). Best trees were used to estimate the shape of the function. By definition, excess tree heights fall between the height of the tallest (best) tree of that same species on the plot and the minimum establishment height listed in

TABLE 12. Coefficients for equations predicting heights of advance regeneration. The form of the equation is Height in feet = $e^{(\Sigma \beta_i X_i)}$*, where "e" is the base of natural logarithms = 2.71828.*

i	Variable (X)	Ponderosa pine (β)	Western larch (β)	Lodgepole pine (β)	Engelmann spruce (β)	Douglas-fir (β)
1	Constant	s	s	0.95773	0.46429	0.73384
2	ABGR/PAMY	e	e	—	—	—
3	THPL/PAMY[a]	e	e	—	—	—
4	TSHE/PAMY			—	—	—
5	ABLA/PAMY	s	s	—	—	—
6	SLO*COS(ASP)	u	u	−1.60782	−0.03154	−0.52921
7	SLO*SIN(ASP)	b	b	3.07786	−2.45629	0.04281
8	SLO	s	s	—	−2.10023	−1.05836
9	$\sqrt{SLO}$	e	e	—	—	—
10	SLO*COS(2*ASP)	q	q	—	—	—
11	SLO*SIN(2*ASP)	u	u	—	—	—
12	TIME	e	e	—	—	0.10018
13	Ln(TIME)	n	n	0.56997	0.62485	—
14	BA	t	t	—	—	0.00556
15	BA^2			—	—	−0.00035
16	Ln(BA)			—	—	—
17	ELEV	m	m	—	—	—
18	Ln(TPP)	o	o	—	—	—
19	TPP	d	d	—	—	—
20	TPP^2	e	e	—	—	—
21	PREP	l	l	—	−0.88012	—
F-ratio				14.10	3.72	21.05
R-square				0.5203	0.3283	0.2793
Error mean square				0.4524	0.6423	0.4755
Number of trees		3	18	43	44	333
Optimum aspect[c]				118°	269°	175°
Amplitude (max. height/min. height)				8.03	4.37	1.38

[a] Represented as part of the constant term to avoid a singular matrix.
[b] No observations.
[c] Dual optimal aspects occur when trigonometric functions of twice the aspect are significant.

Table 1. For each tree, a random number is used to assign a height within this interval.

Advance Regeneration.—Heights of advance trees depend on the environment in the stand before harvest and the response of trees following the harvest. These two factors could easily confound the prediction of height. For example, one species might grow best on a southerly aspect before the harvest where sunlight penetrates the overstory canopy. After the harvest, when adequate sunlight is not limiting, that same species might respond better on a different aspect.

Too few advance trees were found to develop equations for western larch and ponderosa pine. These advance trees were pooled with subsequent trees of the same species.

Table 12 shows coefficients for predicting heights of advance regeneration by species. Important variables include slope and aspect, time since disturbance, and residual basal area or number of regeneration-size trees on the plot. Habitat types are not important in predicting heights of advance trees, except for western red-

TABLE 12. Extended.

W. white pine (β)	Grand fir (β)	Western hemlock (β)	Subalpine fir (β)	Western redcedar (β)	Variable (X)	i
0.24868	1.05802	−0.13629	1.42885	1.04648	Constant	1
—	—	([b])	—	([b])	ABGR/PAMY	2
—	—	([b])	—	0.0	THPL/PAMY[a]	3
—	—	—	—	0.17234	TSHE/PAMY	4
—	—	([b])	—	([b])	ABLA/PAMY	5
−0.84345	−0.31050	—	—	−0.11566	SLO*COS(ASP)	6
0.97231	−0.18939	—	—	0.38767	SLO*SIN(ASP)	7
−1.09990	−0.52367	−6.31494	−2.18021	−0.48242	SLO	8
—	—	4.32067	—	—	$\sqrt{SLO}$	9
−0.30429	—	—	—	—	SLO*COS(2*ASP)	10
1.11987	—	—	—	—	SLO*SIN(2*ASP)	11
—	0.08467	0.11898	—	—	TIME	12
0.43337	—	—	—	—	Ln(TIME)	13
—	0.00309	—	0.01977	—	BA	14
—	−0.00026	—	−0.00014	—	BA^2	15
—	—	—	—	0.04857	Ln(BA)	16
—	−0.01311	—	—	—	ELEV	17
0.16214	—	—	—	0.15620	Ln(TPP)	18
—	0.02153	0.02264	—	—	TPP	19
—	−0.00019	−0.00025	—	—	TPP^2	20
—	−0.14511	—	—	−0.18636	PREP	21
6.41	53.90	28.05	6.89	6.38	*F*-ratio	
0.2480	0.2433	0.3768	0.1658	0.0707	*R*-square	
0.4323	0.5121	0.3204	0.4919	0.4974	Error mean square	
144	1,687	238	108	595	Number of trees	
70°; 220°	211°	n.s.	n.s.	107°	Optimum aspect[c]	
	1.24			1.27	Amplitude (max. height/min. height)	

cedar. Aspects with the tallest advance trees are on east-to-south-to-west exposures.

The effect of time since disturbance was related to the species' shade tolerance. Shade-intolerant species have the largest initial responses following the harvest.

For moderate to very shade-tolerant species, some residual basal area or other regeneration-size trees on the plot are positively correlated with height. Either of these two variables has positive effects up to a point but are a disadvantage at high densities. Residual overstory provides beneficial shade for advance trees while they adjust to a new environment. However, optimum growth is not achieved if the residual overstory is retained too long.

The effect of increasing number of trees on a plot is not as easy to interpret as residual overstory density. More trees on a plot provide mutual shading following harvest, but too many trees may tax the limited resources of the microsite. Increasing numbers of trees on a plot may reflect favorable microsite conditions, and a best tree picked from a larger sample of the population will likely be taller than if picked from a smaller number of trees.

TABLE 13. Coefficients for equations predicting heights of subsequent regeneration. The form of the equation is Height in feet = $e^{(\Sigma\beta_i X_i)}$, *where "e" is the base of natural logarithms = 2.71828.*

i	Variable (X)	Ponderosa pine (β)	Western larch (β)	Lodgepole pine (β)	Engelmann spruce (β)	Douglas-fir (β)
1	Constant	−0.04744	−0.42948	−0.09824	−1.07323	−0.29112
2	ABGR/PAMY[a]	0.0	0.0	—	—	0.0
3	THPL/PAMY	−0.24641	0.06143	—	—	0.12492
4	TSHE/PAMY	([b])	0.39805	—	—	0.10133
5	ABLA/PAMY	([b])	−0.23950	—	—	−0.19296
6	SLO*COS(ASP)	—	−0.59289	−0.77354	−0.66836	−0.61099
7	SLO*SIN(ASP)	—	−0.34095	−0.10962	0.81854	−0.42000
8	SLO	—	−1.96722	0.07601	−0.85141	0.03441
9	SLO*COS(2*ASP)	−1.39382	−1.19159	—	—	—
10	SLO*SIN(2*ASP)	−0.77235	—	—	—	—
11	TIME	0.11856	—	0.12059	0.13871	0.07593
12	Ln(TIME)	—	0.80788	—	—	—
13	BA	−0.00789	—	−0.00748	—	−0.00227
14	ELEV	—	—	—	—	—
15	$ELEV^2$	—	—	—	—	—
16	PLANT	—	—	—	0.40809	0.33408
17	NONE[a]	0.0	—	—	0.0	0.0
18	MECH	0.32442	—	—	0.37365	0.0
19	BURN	0.0	—	—	0.38242	0.0
20	ROAD	0.0	—	—	−0.14412	−0.21479
21	Ln(TPP)	—	—	0.13649	—	0.12697
22	TPP	0.01106	—	—	—	—
23	ADVANCE	—	1.11978	—	—	—
F-ratio		16.73	13.01	19.05	19.76	23.09
R-square		0.5444	0.3658	0.3087	0.5050	0.2632
Error mean square		0.1765	0.4448	0.2399	0.2984	0.3387
Number of trees		106	213	263	164	723
Optimum aspect[c]		100°; 280°	100°; 260°	188°	129°	215°
Amplitude (max. height/ min. height)				1.60	1.89	1.56

[a] Represented as part of the constant term to avoid a singular matrix.

[b] No observations.

[c] Dual optimal aspects occur when trigonometric functions of twice the aspect are significant.

Subsequent Regeneration.—Ten equations were developed to predict heights of established subsequent regeneration. Again, two major factors control heights. First is the number of years between the harvest and germination of the tree, and second is growth following germination.

Table 13 lists coefficients for predicting heights of subsequent regeneration by species. Important variables are habitat type, slope and aspect, time since disturbance, residual basal area, site preparation, and other regeneration-size trees on the plot. The effect of habitat type varies by species and, just as for heights of advance regeneration, optimum aspects are on east-to-south-to-west exposures.

The optimum aspect for tree heights often differs from the optimum aspect for species occurrence. For example, the optimum aspect for occurrence of subsequent western redcedar is 25°, but the optimum aspect for its height is 189°. This is one

TABLE 13. Extended.

W. white pine (β)	Grand fir (β)	Western hemlock (β)	Subalpine fir (β)	Western redcedar (β)	Variable (X)	i
0.25659	−1.66456	−0.59753	−0.97356	0.23392	Constant	1
—	0.0	([b])	—	([b])	ABGR/PAMY[a]	2
—	0.06997	([b])	—	0.0[a]	THPL/PAMY	3
—	−0.02771	—	—	−0.17939	TSHE/PAMY	4
—	−0.08411	([b])	—	0.0	ABLA/PAMY	5
−0.48237	—	—	—	−0.83048	SLO*COS(ASP)	6
−0.03619	—	—	—	−0.12789	SLO*SIN(ASP)	7
—	—	—	—	1.17591	SLO	8
—	—	—	—	—	SLO*COS(2*ASP)	9
—	—	—	—	—	SLO*SIN(2*ASP)	10
—	0.06158	0.09229	0.08708	0.03937	TIME	11
0.32618	—	—	—	—	Ln(TIME)	12
−0.00251	−0.00396	−0.00471	—	−0.00209	BA	13
−0.01604	0.05838	—	—	−0.02369	ELEV	14
—	−0.00074	—	—	—	$ELEV^2$	15
0.54562	0.07264	—	—	—	PLANT	16
0.0	0.0	0.0	0.0	0.0	NONE[a]	17
−0.13474	−0.09922	−0.08951	0.30979	0.0	MECH	18
−0.46099	−0.11178	−0.39606	−0.02210	0.0	BURN	19
−0.21353	−0.21712	−0.11415	−0.49146	0.17106	ROAD	20
0.07663	0.27273	0.23666	0.25176	0.20426	Ln(TPP)	21
—	—	—	—	—	TPP	22
—	—	—	—	—	ADVANCE	23
9.85	83.89	23.58	13.28	15.97	*F*-ratio	
0.2471	0.2887	0.3079	0.3313	0.2708	R-square	
0.3196	0.3437	0.4832	0.3306	0.3733	Error mean square	
311	2,494	325	140	397	Number of trees	
184°	n.s.	n.s.	n.s.	189°	Optimum aspect[c]	
1.34				1.66	Amplitude (max. height/ min. height)	

reason the processes of regeneration establishment and growth are treated separately in the Prognosis Model.

Time since disturbance is important for all subsequent species. Western redcedar, the species having the largest percentage of advance trees (Table 1), has the smallest coefficient for time since disturbance. Haig and others (1941) state that western redcedar "never achieves dominance in a young stand."

Residual basal area has a negative effect on heights, but the number of regeneration-size trees on the plot has a positive effect. We feel the positive effect of regeneration-size trees is due to more trees being established on better microsites.

The type of site preparation also affects subsequent tree heights but varies according to silvical characteristics of the species. Although site preparation is beneficial in establishing some species, tree heights can be shorter due to a delay in obtaining stocking or slower growth. Heights of moderately shade-tolerant species are negatively impacted by site preparation.

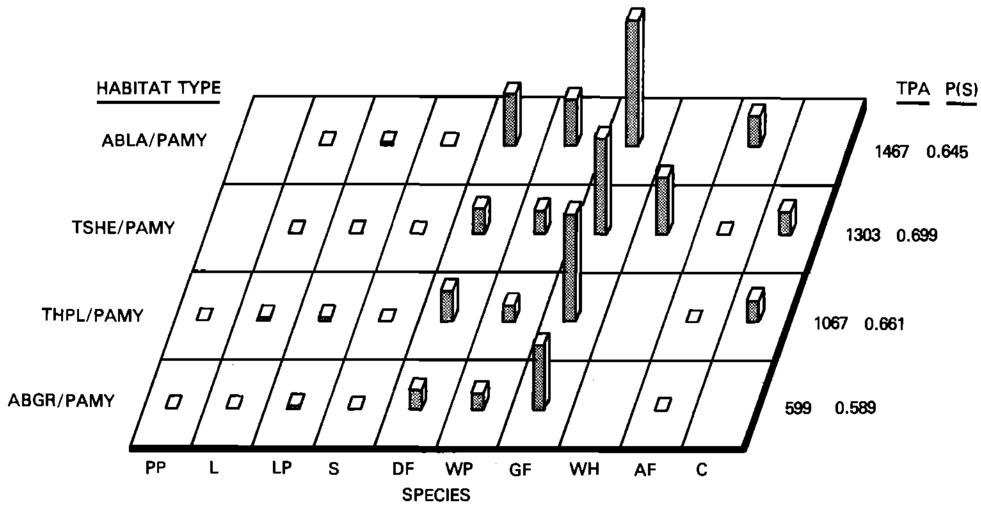


FIGURE 8. Predicted regeneration by species for four habitat types. TPA = trees per acre; P(S) = probability of stocking. See text for explanation of other stand characteristics.

MODEL BEHAVIOR

A great deal of effort has been devoted to evaluating model behavior, all of which cannot be detailed here. Three general methods were used. First, each equation was examined to insure it is statistically sound and makes biological sense. Second, the overall model was examined to see if predicted outcomes are reasonable. Third, suggestions were solicited from users of preliminary versions of the model. Many of these suggestions were incorporated into the model. Following are two examples of evaluating model behavior.

The probability of stocking equations shown in Table 5 were tested by averaging plot predictions in each stand and comparing this value to the actual ratio of stocked plots. Stands where the difference between predicted and actual was greater than ±0.20 were examined by reviewing the field sheets. After looking at the tree,

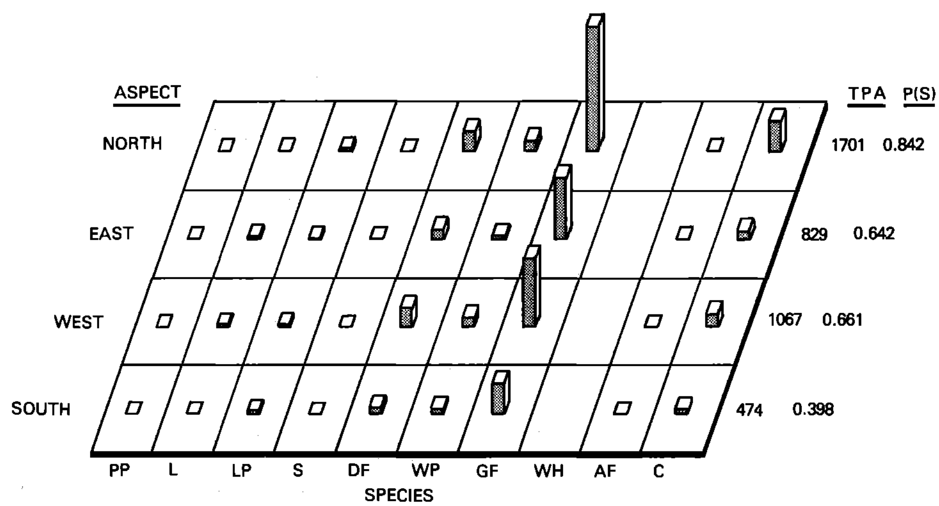


FIGURE 9. Predicted regeneration by species for four aspects. TPA = trees per acre; P(S) = probability of stocking. See text for explanation of other stand characteristics.

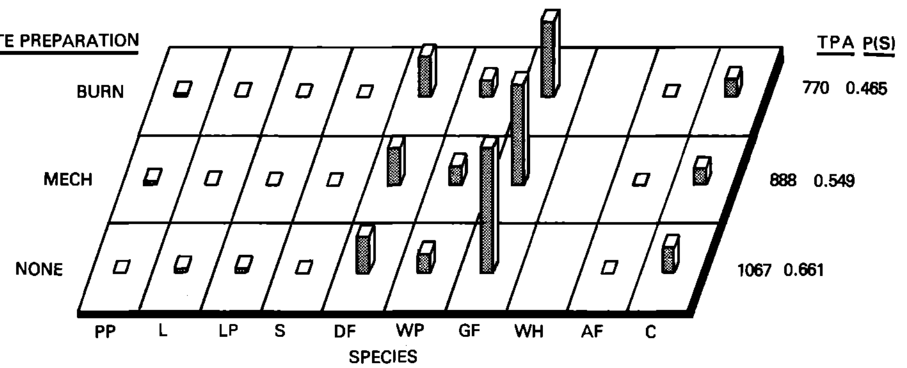


FIGURE 10. Predicted regeneration by species for three site preparation methods. TPA = trees per acre; P(S) = probability of stocking. See text for explanation of other stand characteristics.

shrub, forb and grass community, stand history, site characteristics, and field crew notes (a valuable source of information), we were able to subjectively classify why predictions were in error.

Fifty-five of 190 stands (29 percent) had prediction errors greater than ±0.20. Twenty of these 55 stands are near the ecological limits of the indicated habitat type. Variation within habitat types of the Daubenmire and Daubenmire (1968) classification system has been recognized for some time. The classification system is currently being revised (Cooper and others 1985).

In 17 stands, we could not find a reason for the prediction errors. The number of overpredicted and underpredicted stands was nearly equal.

In nine stands, pocket gophers were implicated in reducing regeneration. Pocket gopher activity was rated as moderate or high and the equations overpredicted actual stocking.

Five stands were considered to have too few plots for a meaningful comparison, and four stands had unique explanations such as a dozer-terraced stand or a salvage operation of a very hot wildfire.

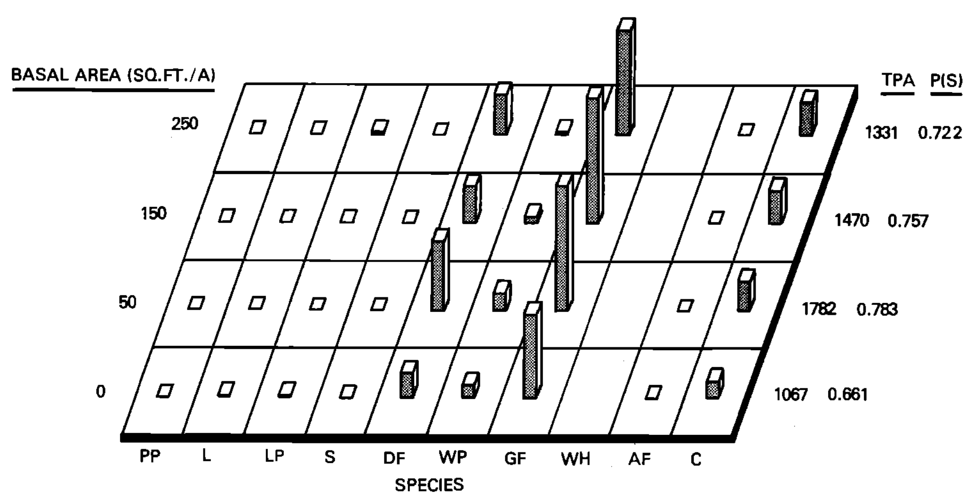


FIGURE 11. Predicted regeneration by species for four levels of residual overstory basal area. Leave trees are Douglas-fir and grand fir. TPA = trees per acre; P(S) = probability of stocking. See text for explanation of other stand characteristics.

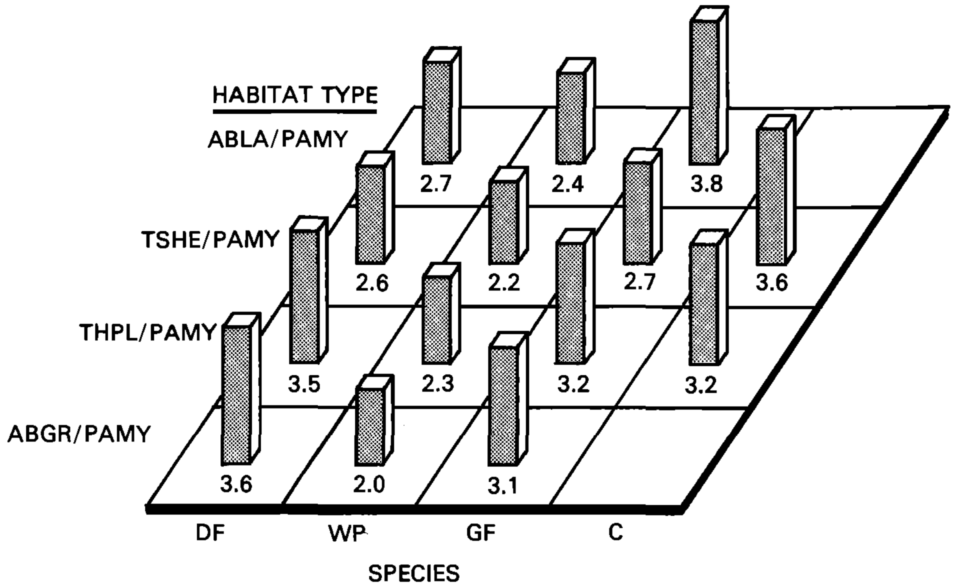


FIGURE 12. Average predicted heights in feet for best trees by species and four habitat types. See text for explanation of other stand characteristics.

It is also important to determine if the model predicts reasonable outcomes. Each equation in the regeneration establishment model has a multidimensional response surface. In turn, equations interact through the steps in the model (Fig. 3).

This area is explored by projecting stands which are identical except for one attribute such as habitat type, aspect, site preparation, or residual overstory density. The stand used is a naturally regenerating clearcut on the Clearwater National Forest, west aspect, 30 percent slope, 3,500 feet (1,067 m) above sea level, no site

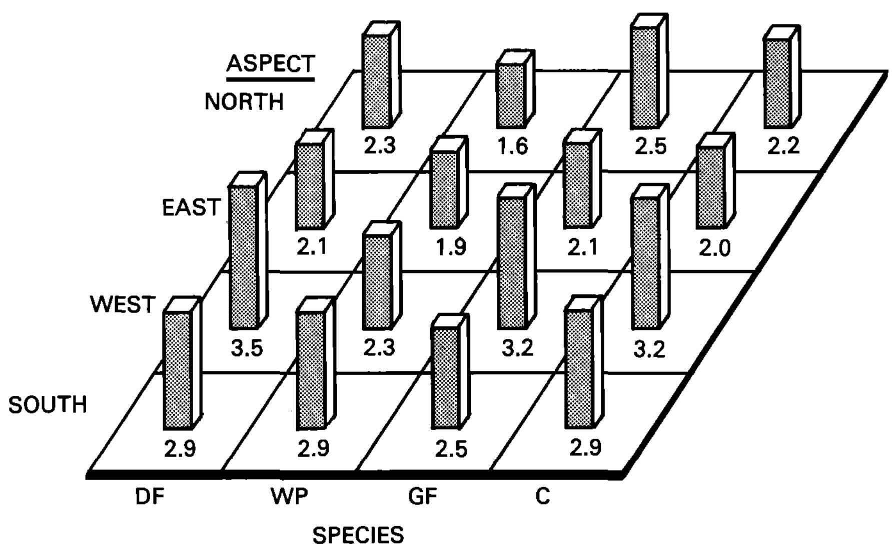


FIGURE 13. Average predicted heights in feet for best trees by species and four aspects. See text for explanation of other stand characteristics.

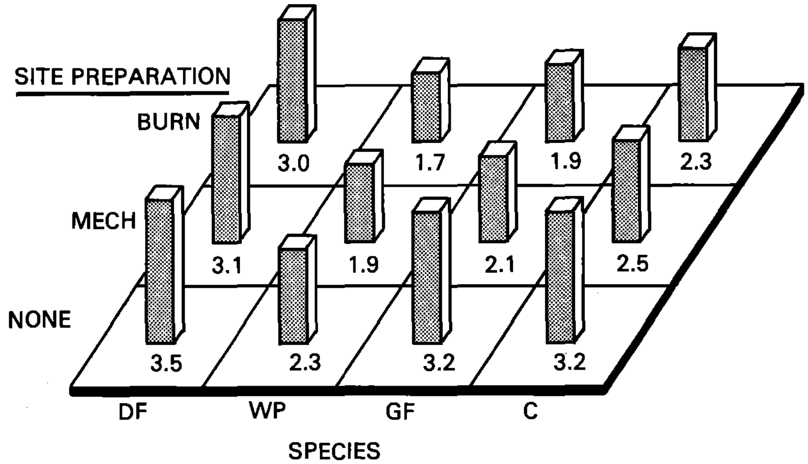


FIGURE 14. Average predicted heights in feet for best trees by species and three site preparation methods. See text for explanation of other stand characteristics.

preparation, 10 years time since the harvest, and a *Thuja plicata/Pachistima myrsinites* habitat type.

Figures 8, 9, 10, and 11 show the distribution of regeneration by species for four habitat types, four aspects, three site preparation methods, and four densities of residual basal area. Species of leave trees in the overstory are Douglas-fir and grand fir. Also shown is the total number of regeneration trees per acre and the probability of stocking.

In Figure 8, species composition, trees per acre, and the probability of stocking vary with habitat type. Western hemlock regenerates only on the *Tsuga heterophylla/Pachistima myrsinites* habitat type. High numbers of Douglas-fir, western white pine, and grand fir on the *Abies lasiocarpa/Pachistima myrsinites* habitat type are due to the fact that we sampled only the lower elevational limits of this habitat type.

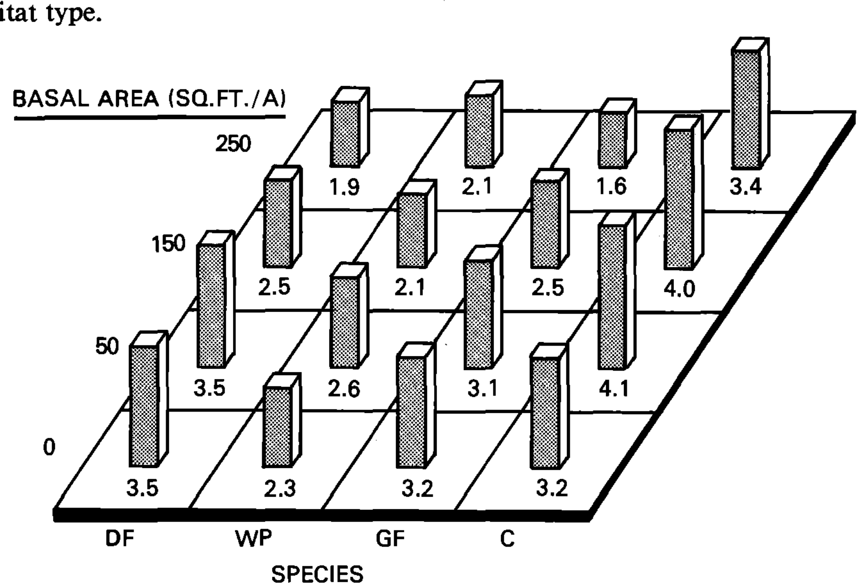


FIGURE 15. Average predicted heights in feet for best trees by species and four levels of residual overstory basal area. See text for explanation of other stand characteristics.

The probability of stocking and trees per acre change considerably with aspect (Fig. 9). These changes would be even more dramatic if the habitat type or slope had also changed when aspect did. The probability of stocking more than doubles on a north versus south aspect, and trees per acre are about 3½ times higher on the north versus south aspect.

Changes in site preparation did not cause large differences in projections as shown in Figure 10. The no-site preparation projection has more trees per acre and a higher probability of stocking because of advance regeneration.

Residual overstory density affects species composition as shown in Figure 11. Moderately shade-tolerant Douglas-fir and western white pine regenerate best under a light residual overstory. Grand fir continues to regenerate well as the overstory becomes more dense but eventually tapers off. Western redcedar regenerates best under a heavy residual overstory.

Note that ponderosa pine, western larch, lodgepole pine, and Engelmann spruce do not regenerate well under any of the options shown in Figures 8 through 11. Regenerating these species requires extra effort. Leaving a suitable seed source is important. Timing site preparation with a good seed crop can be critical. Also silviculturists need to recognize situations unique to their local circumstances. Natural regeneration of western larch is better in northwestern Montana than in northern Idaho. Within the ecosystem, lodgepole pine is more often found in areas of cold air drainage or where the stand has been severely disturbed. Engelmann spruce may be confined to recognizable portions of habitat types (phases). Knowledge of such factors can increase the chances for successful regeneration.

The projections shown in Figures 8 through 11 also produced estimates for tree heights of best trees. These results are shown in Figures 12, 13, 14, and 15 for Douglas-fir, western white pine, grand fir, and western redcedar. The other species did not reproduce in enough numbers to provide meaningful comparisons. Although none of these examples show dramatic results, they do point out differences associated with site characteristics. Figure 12 shows average heights for the four species by habitat type, Figure 13 varies the aspect, Figure 14 varies site preparation, and Figure 15 shows results by residual overstory basal area.

The model results shown in Figures 4d, 10, and 14 would seem to indicate site preparation is detrimental to regeneration establishment and subsequent growth. The no-site preparation options appear to be better because advance regeneration is present. Where advance regeneration is lacking, slow to respond to release, or of an undesirable species, site preparation is beneficial in obtaining stocking. In stands having advance regeneration, guidelines are needed to decide between acceptable and cull trees (Ferguson 1984).

DISCUSSION

The regeneration establishment model is designed to function as a submodel of the Prognosis Model (Stage 1973). Reproduction following a harvest can now be forecast and tree and stand development simulated from rotation to rotation. A user's guide explaining regeneration options is available (Ferguson and Crookston 1984) as is a Prognosis Model user's guide (Wykoff and others 1982).

Model results are based on an extensive field study using data collected by a rigorously randomized sampling procedure. Study sites were chosen from a list of all possible candidate stands using unbiased selection procedures. The data represent operational harvest and regeneration methods and show what can be expected under actual silvicultural prescriptions. Model output is reported in a format foresters are accustomed to using.

The model predicts the net result of harvest and site preparation treatments. Many important and interesting aspects of the regeneration process are represented only implicitly. This is the result of the intended use of the model—an extension of the Prognosis Model which supplies new tree records following a disturbance. Many questions are raised as to why some unfavorable results occur and how they can be improved. Regeneration problem areas can be identified and intensively studied to provide methods for obtaining desired results.

This method of modeling regeneration cannot be used in all situations. The retrospective nature of the study design may preclude measurement of some important variables. For example, if the composition of the previous stand were important, it would be difficult to reconstruct from postharvest inventories.

Retrospective examination procedures also mean that time is confounded with treatment efficacy. However, treatment efficacy changes over time (hopefully for the better) for both retrospective and prospective studies.

We found plantations difficult to model using retrospective examination procedures. Historical records often lacked detail regarding the number of times planted, trees per acre planted, whether the area was interplanted or center planted, and the species mix used throughout the stand. Field crews had difficulty identifying planted trees, especially if the planted species also reproduced naturally. Fiedler (1982) could not demonstrate a planting effect in western Montana clearcuts. In his study, almost half of planting attempts failed while the successful plantations were unnecessary due to adequate natural regeneration.

The assumptions made to develop this model can be verified (or not) and the resolution of the model improved through periodic updating. New data may be needed to keep current with changes in technology, to incorporate new silvicultural techniques, to account for long-term effects of weather patterns or disease/insect conditions, or to expand the model to other geographic areas or ecological zones.

It is essential that if we are to characterize the effects of treatments in more detail in the future, we must maintain good historical records of treatments in each stand. Good historical records will help us learn from experience.

LITERATURE CITED

Bailey, R. L., and T. R. Dell. 1973. Quantifying diameter distributions with the Weibull function. Forest Sci 19:97–104.

Baker, F. S. 1949. A revised tolerance table. J For 47:179–181.

Bartos, D. L., F. R. Ward, and G. S. Innis. 1983. Aspen succession in the Intermountain West: a deterministic model. USDA Forest Serv Gen Tech Rep INT-153, 60 p. Intermountain Forest and Range Exp Stn, Ogden, Utah.

Baskerville, G. L. 1972. Use of logarithmic regression in the estimation of plant biomass. Can J Forest Res 2:49–53.

Belcher, D. M. 1981. The user's guide to STEMS Stand and Tree Evaluation and Modeling System. USDA Forest Serv Gen Tech Rep NC-70, 49 p. North Central Forest Exp Stn, St Paul, Minn.

Botkin, D. B., J. F. Janak, and J. R. Wallis. 1972. Some ecological consequences of a computer model of forest growth. J Ecol 60:849–872.

Boyd, R. J. 1969. Some case histories of natural regeneration in the western white pine type. USDA Forest Serv Res Pap INT-63, 24 p. Intermountain Forest and Range Exp Stn, Ogden, Utah.

Boyd, R. J., and G. H. Deitschman. 1969. Site preparation aids natural regeneration in western larch-Engelmann spruce strip clearcuttings. USDA Forest Serv Res Pap INT-64, 10 p. Intermountain Forest and Range Exp Stn, Ogden, Utah.

Cooper, S., K. Neiman, and R. Steele. 1985. Forest habitat types of northern Idaho. Editorial draft, 295 p. USDA Forest Serv Intermountain Forest and Range Exp Stn and Region 1; Missoula, Mont.

Curtis, R. O., G. W. Clendenen, and D. J. DeMars. 1981. A new stand simulator for coast Douglas-fir: DFSIM user's guide. USDA Forest Serv Gen Tech Rep PNW-128, 79 p. Pacific Northwest Forest and Range Exp Stn, Portland, Oreg.

Daubenmire, R. 1966. Vegetation: identification of typal communities. Science 151:291–298.

DAUBENMIRE, R. 1976. The use of vegetation in assessing the productivity of forest lands. Bot Review 42:115–143.

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

FERGUSON, D. E. 1984. Needed: guidelines for defining acceptable advance regeneration. USDA Forest Serv Res Note INT-341, 5 p. Intermountain Forest and Range Exp Stn, Ogden, Utah.

FERGUSON, D. E., and N. L. CROOKSTON. 1984. User's guide to the Regeneration Establishment Model—a Prognosis Model extension. USDA Forest Serv Gen Tech Rep INT-161, 23 p. Intermountain Forest and Range Exp Stn, Ogden, Utah.

FIEDLER, C. E. 1982. Regeneration of clearcuts within four habitat types in western Montana. *In* Site preparation and fuels management on steep terrain (D. M. Baumgartner, ed), p 139–147. Co-op Ext, Wash State Univ, Pullman. 179 p.

HAIG, I. T. 1931. The stocked-quadrat method of sampling reproduction stands. J For 29:747–749.

HAIG, I. T., K. P. DAVIS, and R. H. WEIDMAN. 1941. Natural regeneration in the western white pine type. USDA Forest Serv Tech Bull 767, 99 p.

HAMILTON, D. A., JR. 1974. Event probabilities estimated by regression. USDA Forest Serv Res Pap INT-152, 18 p. Intermountain Forest and Range Exp Stn, Ogden, Utah.

HAMILTON, D. A., JR., and J. E. BRICKELL. 1983. Modeling methods for a two-state system with continuous responses. Can J Forest Res 13:1117–1121.

HAMILTON, D. A., JR., and D. L. R. WENDT. 1975. SCREEN: a computer program to identify predictors of dichotomous dependent variables. USDA Forest Serv Gen Tech Rep INT-22, 20 p. Intermountain Forest and Range Exp Stn, Ogden, Utah.

KESSELL, S. R. 1981. A review and evaluation of succession modeling approaches. Final report to: Coop agreement supplement No. 11 between Gradient Modeling, Inc. and Intermountain Station. 42 p. Intermountain Forest and Range Exp Stn, Ogden, Utah.

LARSEN, J. A. 1924. Some factors affecting reproduction after logging in northern Idaho. J Agric Res 28:1149–1157.

LARSON, F. R. 1976. Simulating growth and management of ponderosa pine stands. *In* Systems analysis and forest resource management (J. Meadows, B. Bare, K. D. Ware, and C. Row, eds), p 211–221. Proc of a Workshop, Systems Analysis Working Group, Soc Am For, at Univ Ga, Athens, Aug 11–13, 1975. Soc Am For, Bethesda, Md. 457 p.

LEAK, W. B. 1968. Birch regeneration: a stochastic model. USDA Forest Serv Res Note NE-85, 7 p. Northeastern Forest Exp Stn, Upper Darby, Pa.

LEAK, W. B. 1970. Successional change in northern hardwoods predicted by birth and death simulation. Ecology 51:794–801.

LEAK, W. B., and R. E. GRABER. 1976. Seedling input, death, and growth in uneven-aged northern hardwoods. Can J Forest Res 6:368–374.

MINORE, D. 1979. Comparative autecological characteristics of northwestern tree species—a literature review. USDA Forest Serv Gen Tech Rep PNW-87, 72 p. Pacific Northwest Forest and Range Exp Stn, Portland, Oreg.

MITCHELL, K. J. 1975. Dynamics and simulated yield of Douglas-fir. Forest Sci Monogr 17, 39 p.

MOEUR, M. 1985. COVER: A user's guide to the CANOPY and SHRUBS extension of the Stand Prognosis Model. USDA Forest Serv Gen Tech Rep INT-190, 49 p. Intermountain Forest and Range Exp Stn, Ogden, Utah.

MONSERUD, R. A., and A. R. EK. 1977. Prediction of understory tree height growth in northern hardwood stands. Forest Sci 23:391–400.

PFISTER, R. D., B. L. KOVALCHIK, S. F. ARNO, and R. C. PRESBY. 1977. Forest habitat types of Montana. USDA Forest Serv Gen Tech Rep INT-34, 174 p. Intermountain Forest and Range Exp Stn, Ogden, Utah.

REED, K. L., and S. G. CLARK. 1979. SUCcession SIMulator: A coniferous forest simulator. Model documentation. Coniferous Forest Biome Bull 11, 96 p. Univ Wash, Seattle.

ROE, A. L. 1952. Larch-Douglas fir regeneration studies in Montana. Northwest Sci 26:95–102.

SCHMIDT, W. C., R. C. SHEARER, and A. L. ROE. 1976. Ecology and silviculture of western larch forests. USDA Forest Serv Tech Bull 1520, 96 p.

SEIDEL, K. W. 1979a. Regeneration in mixed conifer clearcuts in the Cascade Range and Blue Mountains of eastern Oregon. USDA Forest Serv Res Pap PNW-248, 24 p. Pacific Northwest Forest and Range Exp Stn, Portland, Oreg.

SEIDEL, K. W. 1979b. Regeneration in mixed conifer shelterwood cuttings in the Cascade Range of eastern Oregon. USDA Forest Serv Res Pap PNW-264, 29 p. Pacific Northwest Forest and Range Exp Stn, Portland, Oreg.

SHUGART, H. H., JR., and D. C. WEST. 1980. Forest succession models. Bio Sci 30:308–313.

SHUGART, H. H., JR., T. R. CROW, and J. M. HETT. 1973. Forest succession models: a rationale and methodology for modeling forest succession over large regions. Forest Sci 19:203–212.

STAEBLER, G. R. 1949. Predicting the volume and normality of reproduction stands of Douglas-fir. J For 47:828–833.

STAGE, A. R. 1973. Prognosis model for stand development. USDA Forest Serv Res Pap INT-137, 32 p. Intermountain Forest and Range Exp Stn, Ogden, Utah.

STAGE, A. R. 1976. An expression for the effect of aspect, slope, and habitat type on tree growth. Forest Sci 22:457–460.

STAGE, A. R., and D. E. FERGUSON. 1984. Linking regeneration surveys to future yields. *In* New forests for a changing world: proc of the 1983 convention Society of American Foresters, October 16–20, 1983, Portland, Oreg, p 153–157. Soc Am For, Wash, D C. 640 p.

STEELE, R. W., and W. R. PIERCE. 1968. Factors affecting regeneration of western Montana clearcuts. Montana Forest and Conservation Exp Stn Bull 33, 26 p. Univ Mont, Missoula.

STEELE, R., R. D. PFISTER, R. A. RYKER, and J. A. KITTAMS. 1981. Forest habitat types of central Idaho. USDA Forest Serv Gen Tech Rep INT-114, 138 p. Intermountain Forest and Range Exp Stn, Ogden, Utah.

STEIN, W. I. 1981. Regeneration outlook on BLM lands in the southern Oregon Cascades. USDA Forest Serv Res Pap PNW-284, 68 p. Pacific Northwest Forest and Range Exp Stn, Portland, Oreg.

STROTHMANN, R. O. 1979. Regeneration of Douglas-fir cutblocks on the Six Rivers National Forest in northwestern California. USDA Forest Serv Res Pap PSW-142, 9 p. Pacific Southwest Forest and Range Exp Stn, Berkeley, Calif.

USDA FOREST SERVICE. 1973. The outlook for timber in the United States. USDA Forest Serv Forest Resour Rep 20, 367 p.

WELLNER, C. A. 1940. Relationships between three measures of stocking in natural reproduction of the western white pine type. J For 38:636–638.

WELLNER, C. A. 1970. Fire history in the northern Rocky Mountains. *In* The role of fire in the Intermountain West, p 42–64. Sch For, Univ Mont, Missoula. 229 p.

WYKOFF, W. R., N. L. CROOKSTON, and A. R. STAGE. 1982. User's guide to the Stand Prognosis Model. USDA Forest Serv Gen Tech Rep INT-133, 112 p. Intermountain Forest and Range Exp Stn, Ogden, Utah.

ZAHNER, R., and A. R. STAGE. 1966. A procedure for calculating daily moisture stress and its utility in regressions of tree growth on weather. Ecology 47:64–74.

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