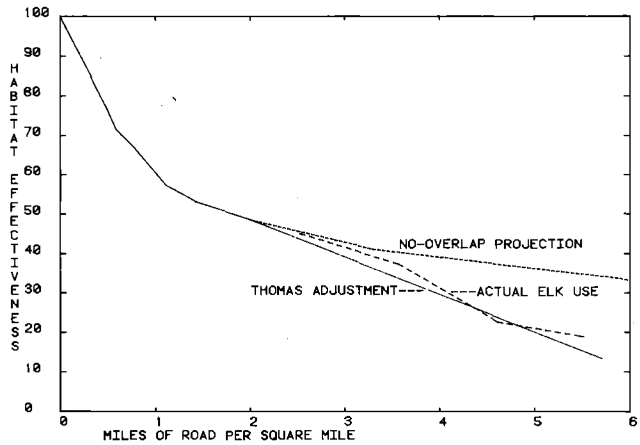

Figure 3. Composite road density model showing actual elk use at densities greater than two miles per section.

remain as high as 20 percent of potential with five and a half miles of road per square mile, it must be recognized that the full impact of a road does not occur until at least the third year after construction. Thus I have assumed that the best estimate of habitat potential for elk as influenced by traveled roads is represented by the average elk use in habitat with roads more than two years old. In the seven areas with an average road density of five and a half miles per square mile, elk use was 18.8 percent of potential.

Figure 3 shows a composite model of the Montana data using the no-overlap assumption for road densities under two miles per square mile and the *table 2* projections for higher road densities. In addition, I have used the Thomas et al. (1979) adjustment to produce a projection of the no-overlap calculations. The agreement between this road density model and the adjustment is coincidental, but the similarity does suggest that this approach may be valid in the absence of data taken in areas with high road densities.

Management Application

Once a graphic display such as the solid line in *figure 3* is developed, it can be directly applied to management of elk habitat. An evaluation area should be at least 3,000 acres; mileage of open roads can be determined from maps or aerial photographs. Roads that dead-end in less than half a mile need not be counted unless they receive unusually heavy traffic. The calculated road density—miles per section—is entered on the horizontal axis to predict habitat effectiveness on the vertical axis.

Avoidance of roads is presumed to be a behavioral response conditioned by vehicular traffic. Other factors, including better hiding cover and lower road standards, can be expected partially to mitigate the negative response by elk. However, the best method for attaining full use of habitat appears to be effective road closures. ■

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Optimum Stand Prescriptions For Ponderosa Pine

David W. Hann, J. Douglas Brodie, and Kurt H. Riitters

ABSTRACT—Two examples for a northern Arizona ponderosa pine stand illustrate the usefulness of dynamic programming in making silvicultural decisions. The first example analyzes the optimal planting density for bare land, while the second examines the optimal precommercial thinning intensity for a 43-year-old stand. Both examples assume that the manager's primary objective is maximization of the soil expectation value. A number of near-optimal solutions are also provided by the program, and may be preferable when the manager takes account of noneconomic considerations. The optimal solution then provides a standard for cost comparison of these noneconomic considerations.

Management of an even-aged stand requires decisions about planting density, timing and intensity of thinning (both precommercial and commercial) and of fertilization, and rotation length. Because these decisions are interrelated and complex, considerable research has been devoted to developing methods to assist the forest manager in making them. One such management method which has received substantial recent attention is dynamic programming (Hann and Brodie 1980, Martin and Ek 1981, and Riitters et al. 1982).

In this article, the use of dynamic programming in determining optimum and near optimum decisions will be demonstrated with two examples for a ponderosa pine stand (with Arizona fescue understory) on site index 88 land in northern Arizona. The first concerns the optimum planting density on bare land. The second addresses the intensity of precommercial thinning in an overstocked stand. In both examples, the analysis also determines the optimum thinning scheme and rotation length.

Dynamic Programming

Optimization of stand growth under a wide array of silvicultural treatments can be readily accomplished with dynamic programming. Analysis of silvicultural treatment is complex because of the high degree of interdependency between stand treatments over time. For example, an array of planting density alternatives would create an array of stands for first commercial thinning. Each of these stands can be thinned to a number of densities, each of which creates a slightly different stand for consideration at second thinning. The types of stands and possible sequences of treatments multiply with each successive set of possible decisions. Additional treatment options, such as precommercial thinning, types of thinning (high, low, mechanical), and fertilization, further increase the number of potential treatment schedules. There are literally millions of possible silvicultural sequences for a single stand.

Dynamic programming permits a manager to solve these potentially large problems by reducing the range of alternatives to a workable number through classification and elimination of similar stand conditions and through efficient searching of the set of possible treatment sequences (Hann and Brodie 1980). Its general structure can incorporate a wide array of primary objectives while the solution process can provide not only the optimal stand treatment scheme but also a number of alternative schemes that might better meet secondary management objectives. The primary advantage of a dynamic programming analysis over simulation analysis is the ability to identify the optimal management scheme for the set of assumptions made in the analysis. Only by knowing the optimal policy can the manager assess the cost to the primary objective of choosing alternative, suboptimal solutions. A simulation analysis in which the manager chooses alternative schemes by trial and error cannot guarantee that the optimal policy will be identified.

An integral part of any dynamic programming algorithm developed to aid in making stand decisions is a stand growth model. The limits to usefulness of the dynamic programming algorithm are defined by the limits of the growth model to predict stand development under the full range of treatment schemes to be examined. While the growth model must be carefully developed, many types of growth models have been successfully integrated with dynamic programming (Hann and Brodie 1980, Martin and Ek 1981, Riitters et al. 1982).

The algorithm used to make the following analyses is called PPOPT for ponderosa pine optimizer (Riitters et al. 1982). It incorporates the whole stand diameter-class growth model developed by Hann (1980). Data needed include the stand's site index, initial stand age, and initial number of trees per acre in each 1-inch diameter class, and the manager's choice of cutting cycle length and thinning type. In addition, economic analyses require the manager's choice of real alternative interest rate, fixed cutting entry cost per acre, and net stumpage value per tree by diameter class.

Both examples assume that the manager's primary objective is the maximization of the soil expectation value. Additional assumptions include a 3-percent interest rate, a $5 per acre fixed entry cost, a 20-year cutting cycle after first thinning, a minimum volume cut of 10 percent, and a silvicultural prescription calling for mechanical thinning. Net stumpage values per tree are given in *table 1*. It should be emphasized that PPOPT can be applied to a range of other site indices and to any set of economic and silvicultural choices that the manager wishes to examine, and that the decisions made can be sensitive to these choices.

Planting Density

Four planting densities (880, 680, 480, and 280 trees per acre) were analyzed to determine which would maximize the soil expectation value. These particular densities were chosen because they bracketed the 680 trees per acre recommended by Schubert (1974).

To obtain initial diameter distributions for each planting density, it was assumed that 15 years were required for all planted trees to reach or exceed breast height (Minor 1964), that only 50 percent of the trees would survive over that period (Schubert 1974), and that approximately 60 and 40 percent of the trees would fall in the 1- and 2-inch diameter classes, respectively. It was further assumed that planting costs would be $300, $250, $200, and $150 per acre for the four densities, and that the first thinning would occur at age 30.

A separate PPOPT run was made for each planting density, and the 10 treatment schemes that produced the highest soil expectation values are listed in *table 2* From this analysis, it can be concluded that a planting density around 480 trees per acre would maximize the soil expectation value under the stated assumptions. The resulting optimal stand treatment scheme can be found in *table 3*. The analysis prescribed removal of 27 trees per acre at age 30—probably an indication that 420 trees per acre would be even better than the 480.

While the treatment scheme in *table 3* represents the best that could be found in terms of soil expectation, it is also useful for the forest manager to examine suboptimal schemes that may better meet other secondary objectives. In the nine alternative treatment schemes found in *table 2*, the soil expectation values are within 10 percent of the optimal scheme, an indication that none of them would cause a severe loss in maximum soil expectation values. The three schemes with the highest soil expectations are all for the planting density of 480 trees per acre, further substantiating this density as the best of those analyzed. Because the fourth and fifth "best" schemes are for the 680 trees per acre planting density, a few more than 480 trees appear less harmful to the primary objective than a few less trees

Details concerning the second best treatment scheme are found in *table 4*. This scheme is of interest for four reasons. First, it avoids a light thinning at age 30 Second, the rotation length comes closer to the 120 years that is often found in the literature (Schubert 1974, Alexander and Edminster 1980). Third, the light residual stand at age 90 looks very much like a shelterwood cut, which has also been recommended for

Table 1. Net stumpage values per tree for both examples.

Diameter class	Net stumpage value per tree	Diameter class	Net stumpage value per tree
Inches	*Dollars*	*Inches*	*Dollars*
7	0.20	16	81.33
8	.81	17	101.09
9	3.85	18	122.87
10	8.55	19	148.80
11	14.77	20	177.04
12	22.49	21	216.84
13	33.35	22	260.04
14	45.86	23	301.79
15	62.60	24	346.41

Table 2. Ten largest soil expectation values, by planting density and rotation length.

Planting density per acre	Rotation	Maximum soil expectation	Rank	Change in maximum soil expectation per acre from optimal solution
Trees	*Years*	*Dollars*		*Percent*
280	90	553.52	6	−5.14
	110	547.62	8	−6.15
480	90	583.50	1	.00
	110	575.78	2	−1.32
	130	562.69	3	−3.57
680	90	558.76	5	−4.24
	110	562.07	4	−3.67
	130	551.11	7	−5.55
880	110	532.74	9	−8.70
	130	525.56	10	−9.93

Table 3. Optimal stand treatment scheme for planting density of 480 trees and rotation of 90 years. Values are per acre.

Total stand age	Residual			Removals		
	Basal area	Trees	Total volume	Basal area	Trees	Total volume
Years	*Square feet*	*Number*	*Cubic feet*	*Square feet*	*Number*	*Cubic feet*
30	32.6	210	199	4.2	27	25
50	56.1	120	626	40.3	86	449
70	37.7	45	573	60.9	73	925
90	.0	0	0	61.6	44	1,203

Table 4. Suboptimal stand treatment scheme for planting density of 480 trees and rotation of 110 years. Values are per acre.

Total stand age	Residual			Removals		
	Basal area	Trees	Total volume	Basal area	Trees	Total volume
Years	*Square feet*	*Number*	*Cubic feet*	*Square feet*	*Number*	*Cubic feet*
30	36.7	237	224	0.0	0	0
50	85.0	195	931	16.5	38	181
70	52.7	75	765	81.5	116	1,184
90	17.1	15	324	66.7	58	1,261
110	.0	0	0	28.2	15	667

ponderosa pine (Schubert 1974). The growth model in PPOPT does not incorporate a natural regeneration component for even-aged stands, and therefore this partial cut is not the result of silvicultural or economic gains due to natural regeneration produced by the shelterwood. Finally, the gains in silvicultural flexibility produced by this scheme come at the small cost of a 1.32-percent reduction in the soil expectation values.

Precommercial Thinning

In this example, the problem is to decide which intensity of thinning to initially apply to an overstocked stand 43 years old. To solve the problem six alternative initial thinning levels (ITL's) were analyzed in PPOPT to determine which initial stocking, and resultant thinning scheme and rotation length, would maximize the soil expectation value. It was assumed that, once the stand was harvested, the optimal bare land scheme previously discussed would be applied in perpetuity. It was also assumed that the initial thinnings would cost $90 per acre.

The six ITL's were based on the initial thinnings applied to Schubert's (1971) study of Taylor Woods growing stock levels. With these data as a guide, six after-thinning diameter distributions were constructed. The resulting basal area, mean diameter, and number of trees for each of Schubert's (1971) ITL's are found in *table 5*.

The 10 treatment schemes that produced the highest soil expectation values from the six PPOPT analyses are found in *table 6*. These values indicate that ITL number four would best meet the primary objective for the stand. They also demonstrate the added value that an existing stand, even an overstocked one, has over bare land (i.e., the existing stand is worth $1,890.06 per acre while an acre of bare land is worth $583.50). The corresponding optimal stand treatment scheme can be found in *table 7*.

An examination of the nine near optimal treatment schemes found in *table 6* illustrates the existence of a wide array of alternatives that do not appreciably reduce the primary objective. For example, the fourth best solution (ITL of 4 with rotation length of 103) has a treatment scheme identical to the optimal solution but with all trees being removed at age 103 (instead of the shelterwoodlike cut at that age recommended in the optimal solution). Discretionary implementation of this clearcut solution to better meet secondary objectives would cost less than 1 percent in reduced soil expectation value.

As a final observation, the fact that the top three treatment schemes in *table 6* have different ITL's but common rotation lengths indicates that the solution is more sensitive to changes in rotation length than in initial thinning intensity. The inference is that quality control on the initial thinning need not to be too exact

Table 5. After-thinning basal area, mean diameter, and number of trees for each of Schubert's initial thinning levels (ITL).

ITL	Basal area per acre	Mean diameter	Trees per acre
	Sq. ft.	*Inches*	*Number*
1	21.2	6.0	100
2	36.5	5.2	227
3	44.6	4.8	314
4	52.8	4.6	403
5	59.9	4.4	494
6	75.6	4.2	688

Table 6. Ten largest soil expectation values by initial thinning level (ITL) and rotation length.

ITL	Rotation length	Maximum soil expectation per acre	Rank	Change in maximum soil expectation per acre from optimal solution
	Years	*Dollars*		*Percent*
2	103	1,851.32	9	−2.05
	123	1,845.79	10	−2.34
3	103	1,869.71	6	−1.08
	123	1,878.91	2	− .59
	143	1,853.29	8	−1.95
4	103	1,872.92	4	− .91
	123	1,890.06	1	.00
	143	1,872.75	5	− .92
5	123	1,875.09	3	− .79
	143	1,866.76	7	−1.23

Table 7. Optimal stand treatment scheme for initial thinning level (ITL) of 4 and rotation length of 123 years. Values are per acre.

Total stand age	Residual			Removals		
	Basal area	Trees	Total volume	Basal area	Trees	Total volume
Years	*Square feet*	*Number*	*Cubic feet*	*Square feet*	*Number*	*Cubic feet*
43	52.8	403	508	0.0	0	0
63	77.5	225	1,005	58.7	170	762
83	53.4	90	862	77.5	131	1,250
103	14.9	15	297	72.6	73	1,447
123	.0	0	0	25.9	15	637

as long as the after-thinning diameter distribution can be analyzed to determine the subsequent optimal thinning scheme. This is useful because, in a dense stand of small trees, it is often difficult to make an initial thinning to exacting standards. ■

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Catfaces on Lodgepole Pine—Fire Scars or Strip Kills by the Mountain Pine Beetle?

R. G. Mitchell, R. E. Martin, and John Stuart

ABSTRACT—Basal scars on lodgepole pine, Pinus contorta, *are common in central Oregon forests. Although foresters have generally called them fire scars, many result from old strip-attacks by the mountain pine beetle,* Dendroctonus ponderosae *—attacks that kill only one side of the stem. Strip-kill scars are usually wide at the bottom and narrow at the top, less than 4 m long, and on the north and east sides of the stem. Dating the scars showed that central Oregon suffered a beetle outbreak between 1920 and 1925 and another between 1900 and 1905. Observations of ring widths in stem sections show that a current outbreak and the previous one started when stand growth was very slow. The mountain pine beetle is apparently an important thinning agent that relieves competition in overstocked stands.*

Catfaces on the lower bole of lodgepole pine are often referred to as fire scars. That is logical because they look like the fire scars on fire-tolerant species such as ponderosa pine, *P. ponderosa*. But we cannot help being skeptical about the number of scars on lodgepole pine—there are too many for a species that is generally considered sensitive to fire (Martin and Dell 1978).

In central Oregon, the chief source of scars on lodgepole pine is the mountain pine beetle, a pest with a long history of killing lodgepole pine in the West (Cole and Amman 1980). Although strip-attacks are seldom mentioned in the literature, we have found that attacks by the beetle commonly kill only one side of the stem, usually in a pattern that leaves a catface-like scar on the lower bole. The trees can survive for years with no obvious changes in the crown, even when less than 20 percent of the bole's lower circumference has living cambium and xylem.

This article presents observations showing that attacks by the mountain pine beetle often leave lodgepole pines with scars that can be confused with those made by fire We describe the pattern of the scars and their historical and ecological significance. Our information is from two independent studies in central Oregon.

Origin of Strip-Kills

Strip-killing occurs when the mountain pine beetle attacks and kills one or more sides of the stem but leaves enough undamaged cambium for the tree to survive. Sometimes the dead strip is only 6–10 cm wide; a more severe attack will nearly girdle the tree, leaving less than 10 cm of living cambium. Recently strip-killed trees look at first glance like "pitch-outs"—trees that force attacking beetles out with a copious flow of resin. While pitch-outs frequently occur in outbreaks, close examination of such trees in central Oregon showed that many were in fact strip-kills For example, when checking 139 trees heavily attacked in 1980 and 1981 on a 0.5-ha research plot, we found that 79 were killed and 60 strip-killed. Some strip-killed trees are reattacked and killed in the same outbreak episode, but stem analyses show that many infested trees survive and live for 60 or more years after being attacked.