ties they contain. Such information can aid visitors to select settings that meet their preferences. ■

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Volume versus Value Maximization Illustrated for Douglas-fir with Thinning

Kurt Riitters, J. Douglas Brodie, and Chiang Kao

ABSTRACT—Economic and physical criteria for selecting even-aged rotation length are reviewed with examples of their optimizations. To demonstrate the trade-off between physical volume, economic return, and stand diameter, examples of thinning regimes for maximizing volume, forest rent, and soil expectation are compared with an example of maximizing volume without thinning. The soil expectation criterion consistently accounts for the market premium and logging and other silvicultural costs.

Foresters frequently use maximum physical volume as a criterion for selecting even-aged rotations. This objective is often an implicit or official guideline in public forestry. Economic or value criteria for rotation length also have a long history. Proponents of the several criteria have enlivened professional debate and confused nonspecialists and students from the mid-nineteenth century to the present. Comparisons of the criteria are usually made by using simple computations and silvicultural regimes for regeneration and final harvest only. Recent developments in dynamic programming optimize both rotation and stand density at each thinning entry during the rotation. This article reviews various criteria for rotation and thinning intensity, explains their origins, and considers their implications.

Three criteria have been suggested for setting even-aged rotations. The first, "volume maximization," implies that the forester's long-term objective is to select a rotation for which average annual wood production is maximum. Rotation length is affected by the chosen unit of measurement, but prices and production costs, such as for planting, have no effect. A rotation determined in this manner is often referred to as a physical rotation or a rotation for maximum mean annual increment (MAI).

The second criterion is designed to maximize net revenue or average annual cash flow over time. As net revenue is affected by both prices and costs, such as for planting, there is incentive to average high planting costs over long rotations. Net revenue is also affected by quality premiums, which are differences in net value per unit of product (pulpwood, poles, sawlogs, veneer logs) from rotations of various lengths.

The major criticism of this criterion is that it ignores the opportunity cost of capital tied up in land and in stand treatments, such as planting, and the cost of not harvesting growing stock and reinvesting returns in the forest operation or elsewhere. Costs are incurred and growing stock retained until additional input yields a return or interest rate of zero. The average annual cash flow and MAI criteria give identical rotations when there are no costs or quality premiums. The classical name for the criterion of average annual cash flow is "forest rent." Although the criterion is not generally accepted by North American analysts, reasoning based on the concept still exists among foresters (Reed 1978).

The third criterion is designed to maximize the value of the site in timber production by taking into account the opportunity costs of investment in land, growing stock, and silvicultural measures, such as planting. The value of the site is the present net worth of all future rotations. The alternative rate of return (interest) must be earned on all investments in land, silvicultural measures, and growing stock. Rotation length is affected by the interest rate as well as by costs and quality premiums. Economists regard this as the only correct criterion from the perspective of capital theory. It is referred to as the "soil expectation," or "soil rent," criterion.

Soil expectation and forest rent criteria give the same rotation when the discount rate is zero (Bentley and Fight 1966). These economic criteria are reviewed in the historic study by Faustmann (1849), in standard texts (Davis 1966, Gregory 1972), and in several studies (Gaffney 1957, Bentley and Teeguarden 1965, Samuelson 1976).

Regulations issued pursuant to the National Forest Management Act of 1976 (P.L. 54-588) mandate the maximum MAI criterion for establishing rotations on national forests. The unit specified is total cubic feet, a physical criterion, but other sections of the act require cost-benefit efficiency, an economic criterion.

Decisions for intensive management, such as thinning regimes and fertilization, are motivated by concern for both quality and quantity of forest products, and quite different management regimes are indicated under the several criteria, as we will illustrate.

Maximizing Volume and Value With and Without Thinning

Volume can be easily maximized computationally or graphically with net yield tables alone, or value can be maximized with net yield tables and cost and quality premium data. Either criterion is much more difficult to maximize when thinning is an option because of the variable growth responses to thinning intensities and intervals, the potential for capturing mortality, and the large number of potential thinning regimes that must be tested.

When stand growth models are used to estimate mortality and response to thinning, computers can quickly test many potential thinning regimes. Unless all possible regimes are tested, however, there is no guarantee that the optimal regime will be found. Dynamic programming, an algorithm for efficient searching of the full range of density (number of trees and basal area) options, provides a solution. The use of dynamic programming to optimize thinning and rotation has been demonstrated in several recent studies (e.g., Brodie et al. 1978, Martin 1978, Rose et al. 1981) and has been reviewed by Hann and Brodie (1980).

The DOPT discrete-state dynamic program (Brodie and Kao 1979) incorporates Douglas-fir stand growth relationships that are abstracted from the DFIT model (Bruce et al. 1977). State intervals of 10 years, 15 trees per acre, and 20 square feet of basal area per acre provide adequate sensitivity for the DFIT model (Kao and Brodie 1979, Kao 1980). Ten-year mortality is captured with thinning but is lost without thinning. Logging costs and quality premiums are based on average stand diameter. We use the results of Brodie and Kao's study to demonstrate value maximization and the results obtained by converting their model to an MAI criterion to demonstrate volume maximization.

Table 1 shows yields with and without thinning under the criterion of maximum MAI. Yields were obtained from the modified version of the Brodie and Kao (1979) model. Thinning extended rotations by 10 to 20 years and increased productivity (MAI) by 17 to 21 percent—the higher relative gain occurring on poorer sites and the higher absolute gain on better sites. The gain comes primarily from capture of mortality and secondarily from reduction of excessive stocking. In these two physical maximizations, total cubic feet of stem was the measurement unit. A unit such as Scribner board feet in trees over 12 inches would lengthen rotations and a unit such as total biomass would shorten them.

Table 1. Rotation, total yield, and annual increment with and without thinning under the maximum MAI criterion.

Site index at 100 years (feet) and thinning regime	Rotation	Mean annual increment	Total harvest
	Years	*Ft³*	*Ft³*
110			
No thinning	60	102.5	6,149
Thinning	70	123.9	8,674
140			
No thinning	50	144.8	7,239
Thinning	70	170.4	11,926
170			
No thinning	50	187.9	9,397
Thinning	70	220.4	15,427
200			
No thinning	50	234.3	11,715
Thinning	70	273.7	19,158

In considering the trade-offs inherent in the selection of volume versus value criteria, the relationship between stocking and stand volume growth is important. This relationship may change with species, site, stand age, unit of measurement, and other factors (Assmann 1970), but in many cases a graph of stand volume growth versus stocking assumes a characteristic "plateau" shape (Mar:Möller 1954).

Volume growth decreases quickly when the site is not fully occupied, and also when high density results in excessive competition and mortality. Between these extremes, the form of the plateau represents the trade-off between average tree volume growth (i.e., "value") and total stand volume growth. When the form of the plateau is known, it can be used to compare thinning regimes arising from differences in maximization criteria, as we will illustrate.

In the DFIT model (Bruce et al. 1977), the plateau is an explicit relationship. A stand volume growth adjustment multiplier is computed from a ratio comprised of the current basal area divided by the maximum basal area that the current stand could sustain. At maximum basal area, complete stagnation occurs and growth is zero. Between maximum and zero basal areas, the growth adjuster rises to a plateau of about 1.0 between basal-area ratios 0.35 and 0.65.

The DFIT growth adjuster function is shown in *figure 1*, along with residual basal-area ratios for various maximizations. This graph compares the optimum residual basal areas of the several silvicultural regimes that result from the various criteria. The ratios at various ages for the four regimes show the relationship between

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the product objective and stocking over the rotation. The regime for economic maximization is example two from Brodie and Kao (1979); the maximum MAI regimes and forest-rent regime are modifications of the objective function of the same model. Details of these four silvicultural regimes are given in *table 2*.

The plateau in *figure 1* peaks at basal-area ratio 0.5.

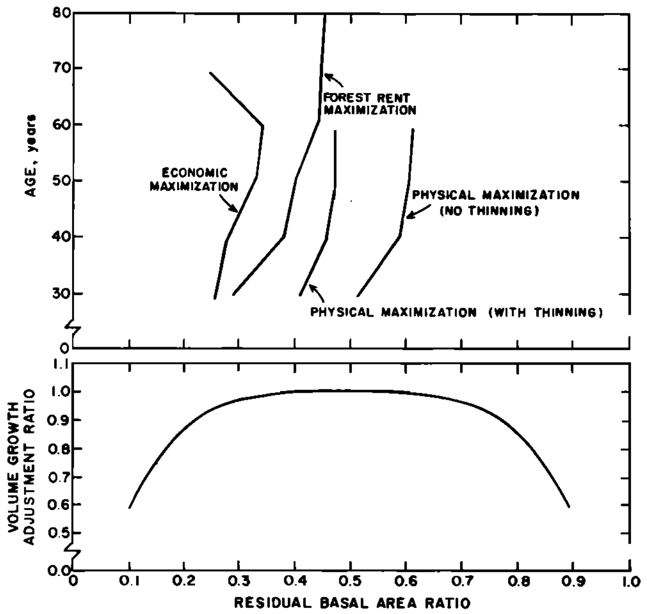

Figure 1. Residual stocking and volume growth of Douglas-fir Site III (140) for soil expectation (economic) maximization, physical maximization with and without thinning, and forest rent maximization.

The regime for volume maximization attempts to maintain stocking around this level by thinning at 10-year intervals. A classical silvicultural prescription would probably not select the mid-plateau regime indicated by the volume maximum in *figure 1*, but would choose a regime toward the left of the plateau. In this case, reduced stand growth is balanced against increased tree size, improvement of stand vigor, and less frequent entry. The economic examples make this type of qualitative reasoning explicit in cost and revenue terms by showing how much total growth should be sacrificed for rapid diameter growth when quality premium depends on tree diameter.

Any economic example is sensitive to cost, revenues, and other assumptions. Brodie et al. (1978) discuss the effects of varying these assumptions. When economic assumptions include a regeneration cost of $200 per acre, logging cost and selling value premiums to 20-inch diameter, and a discount rate of 3 percent, the stand is managed at basal-area ratios between 0.26 and 0.35, with growth adjustment in the range of 0.94 to 0.99. The MAI for this regime is 96 percent of that for volume maximization *(table 2)*, and final harvest diameter is 20.5 inches. Final harvest diameter with volume maximization is 14.4 inches.

The regime for forest rent maximization *(table 2, fig. 1)* maintains higher residual basal areas throughout a longer rotation (100 years) than the regime for soil expectation (80 years). The stand is thinned to a basal-area ratio of 0.29 at age 30 with a volume growth adjustment of 0.97. Subsequently, this ratio rises to 0.38, 0.39, 0.43, 0.44, 0.45, and 0.46. In each case, the density is higher than that for soil expectation maximization. Volume adjustment remains essentially at

Table 2. Optimal thinning regime for Site III (140) Douglas-fir under four criteria. Values except diameter are per acre.

Age (years)	Average diameter	Residual merchantable trees	Residual basal area	Harvest	Residual stocking	Mean annual increment
	Inches	*No.*	*Ft²*	*Ft³*	*Ft³*	*Ft³*
		MAXIMUM MEAN ANNUAL INCREMENT WITH THINNING				
30	6.4	450	101	618	2,539	
40	8.3	345	130	1,109	4,006	
50	10.5	255	152	931	5,377	
60	12.5	195	165	1,012	6,419	
70	14.4	0	0	8,256	0	170.4
		MAXIMUM SOIL EXPECTATION[1]				
30	6.4	285	64	1,549	1,608	
40	9.2	180	82	1,579	2,538	
50	12.3	135	111	824	3,929	
60	15.1	105	131	860	5,078	
70	17.7	60	102	2,623	4,259	
80	20.5	0	0	5,719	0	164.4
		MAXIMUM FOREST RENT[2]				
30	6.4	315	71	1,380	1,777	
40	9.0	255	112	868	3,438	
50	11.5	180	130	1,129	4,593	
60	13.6	144	152	0	5,911	
70	16.1	120	170	0	7,058	
80	18.0	103	185	0	8,067	
90	20.0	90	196	626	8,919	
100	21.7	0	0	10,256	0	142.6
		MAXIMUM MEAN ANNUAL INCREMENT WITHOUT THINNING				
30	6.4	560	126	0	3,156	
40	7.9	468	163	0	4,981	
50	9.7	0	0	7,239	0	144.8

[1]Economic assumptions: regeneration $200, discount rate 3 percent real, and net dollar revenue per cubic foot 0.078(D) − 0.62, where D represents average stand diameter at breast height in inches. For diameters greater than 20 inches, the unit net dollar revenue is 0.94.

[2]Economic assumptions are those for soil expectation without the interest cost.

the 1.00 level from age 40 to the end of the rotation. Considerable uncaptured mortality (77 trees per acre) occurs during the 40-year period (age 50 to 90) when no thinning is prescribed. Since thinning removes at least 15 live trees in addition to mortality, retention of growing stock is more desirable than capture of mortality during this time period.

Diameter at harvest is 21.7 inches; on the shorter economic rotation it is 20.5 inches. That the increase in diameter was not greater is a consequence of the limited thinning in the forest rent alternative. The MAI on this alternative is only 84 percent of the maximum MAI with thinning.

The final regime is no-thinning management of a normally stocked stand. The basal-area ratio rises quickly from 0.51 to 0.63 and stabilizes there because of mortality. Volume growth adjustment is essentially 1.00. However, the MAI is 19 percent less than volume maximization because of failure to capture mortality or to improve vigor with thinning. The average diameter with the 50-year rotation is 9.7 inches; with the maximum-volume regime it is 14.4 inches.

The actual soil expectation (3 percent) realized for each of the four criteria is maximum soil expectation $617.13, maximum volume with thinning $465.69, maximum forest rent $387.42, and maximum volume without thinning $33.11.

These examples show the fallacy of the common belief that economic rotations are shorter and produce smaller timber than volume rotations. The outcome depends on a complex of measurement unit, cost, quality premiums, discount rate, and silvicultural alternatives.

Volume versus Value Trade-offs

Part of the justification for determining rotation by volume or forest rent criteria lay in the ethical premise that, since old-growth stands were acquired without capital outlay, an investment return from land or growing stock should not be required. This premise is tenuous in the presence of market exchange. Until recently, current and projected prices of forest products tended to show low return on investment in management. They now show more favorable prospects, and projected price increases only enhance the desirability of investment in intensive forestry. A wide range of tree sizes is being used, and efficient methods are evolving for thinning or final harvesting and processing of different sizes of timber. Quality premiums are increasingly recognized in log markets and in internal processing by integrated firms. These factors can be accounted for with value maximization but not with volume maximization.

The analysis here was made in terms of controlling rotation and growing-stock through thinning. Parallel analyses could be made with other inputs, such as

(Continued on page 107)

Gypsy Moth in New Jersey Pine-Oak

Robert W. Campbell and Albert S. Garlo

ABSTRACT—Several pine-oak stands in southern New Jersey were defoliated by the gypsy moth, Lymantria dispar *(L.), during both 1972 and 1973. Oaks were much more heavily defoliated than pines,* Pinus rigida *Mill. and* P. echinata *Mill. Radial growth among the oaks was sharply reduced during and immediately following the outbreak. Pine growth did not appear to be affected during the outbreak, and it increased sharply during the immediate three-year postoutbreak period.*

Since the gypsy moth has decided food preferences, some tree species are consistently defoliated more heavily than others. For example, in the pine-oak communities of southern New Jersey, the insect has shown a preference for the foliage of oaks over that of the associated pines. Defoliated trees have both a higher than average probability of subsequent mortality (Nichols 1961, Kegg 1973, Campbell and Sloan 1977) and lower subsequent growth (Baker 1941), at least for a few years. Some relationships between this selective defoliation and short-term stand responses by the pine-oak forest of southern New Jersey are described below.

Our data were accumulated from four sites near Lakewood, New Jersey. The 40- to 55-year-old pine-oak stands on these sites appear representative of much of the forest of the New Jersey Coastal Plain. These four stands were our sampling units. *Table 1* shows average stem densities and basal area of these stands in 1972, by species group. Gypsy moth populations on each site were dense during both 1972 and 1973 (Campbell and Sloan 1978), and defoliation was severe.

Between 1972 and 1976, annual estimates were made of defoliation of each tree on five permanent 0.1-acre plots on each site. In the winter of 1976–1977, an increment core was taken from each living tree, at d.b.h. These cores were examined at Virginia Polytechnic Institute, Blackburg. Data on both defoliation and radial growth were merged into three species groups: white oaks (Leucobalanus), red oaks (Erythrobalanus), and the pines (primarily pitch pine, *Pinus rigida* Mill., and shortleaf pine, *P. echinata* Mill.). The data were merged by the Forest Insect and Disease Laboratory, Northeastern Forest Experiment Station, USDA Forest Service, Hamden, Connecticut.

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Table 1. Number of stems and basal area per acre in 1972.

Species group	Mean no. of stems	Mean basal area[1]
		Square feet
White oaks	341.5 ± 47.7[2]	20.1 ± 2.4
Red oaks	142.5 ± 33.6	16.9 ± 4.7
Pines	107.0 ± 34.1	16.1 ± 2.6

[1] *Stems > 2 inches d.b.h.*
[2] *Standard error.*

frequency and almost 25 times as productive as medium spread areas; high spread areas are almost 2½ times more productive than medium spread areas. Relative differences are even greater with a 10-year treatment duration.

Second, most of the *table 4* ratios are very high. Extreme spread ratios are substantially lower than the rest, but extreme fuel types constitute only a small proportion of the Northern Region (accounted for less than 3 percent of total ignitions). For the balance of the region, between 50 and 755 acres would have to be protected for each acre saved. Consequently, a return of $50 to $755 per acre saved would be required for every dollar spent per acre protected. A difference of a few dollars in average cost could, therefore, change the required value yield by hundreds or even thousands of dollars. For example, with a low ratio of 50 to 1 and a cost of $10 per acre protected, each acre saved would have to yield benefits with a present value of $500. A $20 per acre cost would require an average yield of $1,000, and so forth. Given these relationships, it appears that the proportion of the Northern Region which could be treated economically would vary greatly with even small differences in treatment cost.

These results represent, in effect, the hypothetical application of fuel management to a set of conditions which existed in the past. Differences in these conditions, particularly fire weather, may decrease their reliability in evaluating the current feasibility of fuel management. This problem, however, would be shared by even the most sophisticated fuel-management model, since future fire weather cannot be predicted. Results are also predicated on a set of assumptions about fuel management effectiveness, but refinement is impossible without a great deal more data on fuel treatment response than currently exist. ■

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Volume versus Value Maximization Illustrated for Douglas-fir with Thinning *(from page 89)*

fertilizer. For soil expectation maximization, fertilizer would be applied until the future increase in present net worth equals the present cost of the last unit applied. For volume maximization, fertilizer would be applied until the future growth response becomes zero, regardless of fertilizer cost. Although there may still be support for not recognizing opportunity costs of land and growing stock, few would consistently extend this reasoning to include such purchases as fertilizer, lavishly applied to the point of no volume growth response. For silviculturally tailoring a stand to product markets while accounting for logging technology and intensive silviculture, an economic approach is both necessary and consistent. ■

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Fuelbed Changes with Aging of Slash from Ponderosa Pine Thinnings *(from page 93)*

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