OPTIMIZING UNEVEN-AGED MANAGEMENT OF LOBLOLLY PINE STANDS

Benedict J. Schulte, Joseph Buongiorno, and Kenneth Skog

ABSTRACT. Although interest in uneven-aged management is growing rapidly, our experience with, and scientific knowledge of, selection silviculture lags far behind that of even-aged. To help alleviate this disparity, we developed nonlinear programming models of uneven-aged loblolly pine and loblolly pine-mixed hardwood management using the model of Lin *et al.* (1998), a matrix growth and yield model that recognizes three species groups (pines and other softwoods, soft hardwoods, and hard hardwoods) and 13 2-inch diameter-at-breast height (d.b.h.) size classes. The optimization models identify steady-state management regimes which maximize (1) soil expectation value (SEV), (2) annual sawtimber production, (3) the Shannon index of tree diversity, or (4) SEV subject to a constraint requiring the Shannon index of tree diversity to be at least 75 percent of its theoretical maximum value. The optimal production and economic regimes each involve a guiding maximum diameter for pines and other softwoods and the complete control of all hardwoods each cutting cycle. The optimal production regimes yield low SEVs and moderate diversity; whereas the optimal economic regimes yield low diversity and moderate sawtimber production. Stands with a Shannon index of tree diversity near the theoretical maximum can be sustained in perpetuity but have low SEVs and sawtimber production. The compromise regimes identified by the constrained optimizations give good economic returns, sawtimber yields and diversity.

KEY WORDS. Optimization, uneven-aged, loblolly pine, growth model, diversity

INTRODUCTION

Clearcutting, when used with care and deliberation, is a reliable and efficient reproduction method for many species. Nevertheless, its use has been challenged increasingly by individuals and groups who object to the harsh visual impact of recent clearcuts. Opposition to clearcutting also reflects concerns about its potential impact on ecosystem functioning and biological diversity (e.g., Keenan and Kimmins 1993, Temple and Flaspohler, 1998). For many, the disfavor with clearcutting extends to all forms of even-aged management, which are often perceived as focusing on the maximization of economic return and short-term yield rather than on ensuring long-term sustainability. This growing sentiment against even-aged management has resulted in the more frequent adoption of selection silviculture by nonindustrial private forest landowners, forest industry; and the U.S. Forest Service (Emmingham 1998; Hill 1992); yet information to guide this management is still limited for most species and forest types.

Loblolly-shortleaf pine (*Pinus taeda* L.-P. *echinata* Mill.) is one forest type for which long-term research on uneven-aged management is available (Baker 1986; Baker and Murphy 1982; Baker *et al.* 1996; Brender 1973; Farrar *et al.* 1984a, 1984b, 1989b; Reynolds 1959, 1969, 1980; Reynolds *et al.* 1984). Several researchers have proposed uneven-aged management regimes for loblolly-shortleaf pine (Schulte and Buongiorno 1998), but their recommendations have been based primarily on personal experience (Baker *et al.* 1996, Farrar 1996, Farrar *et al.* 1984a, Reynolds 1959, Williston 1978) or simulation studies (Chang 1990, Hotvedt *et al.* 1989, Redmond and Greenhalgh 1990) rather than mathematical optimization. Consequently, other regimes are likely to prove better suited for specific management objectives. The purpose of this paper, then, is to identify optimal management regimes, under various objectives, for uneven-aged stands of loblolly pine and loblolly pine-mixed hardwoods.

METHODS

Growth and Yield Model

Model selection. Several growth and yield models have been developed for uneven-aged stands of loblolly pine (Murphy and Shelton 1994, 1996), loblolly-shortleaf pine (Murphy and Farrar 1982, 1983, 1988) and loblolly pine-mixed hardwoods (Farrar *et al.* 1989a, Lin *et al.* 1998). In this study, we use the model of Lin *et al.* (1998) because: (1) it recognizes the greatest number of species groups and size categories, (2) it can simulate management over the widest range of site productivity, (3) its results are applicable to the largest geographic area, and (4) its reproduction and mortality equations allow for the identification of sustainable, steady-state regimes'.

Growth model structure. The model is a site- and density-dependent, multi-species matrix model that was calibrated with data from 991 naturally regenerated, mixed-aged, loblolly pine re-measurement plots of the Southern Forest Inventory and Analysis data base. It recognizes three species groups (pines and other softwoods, soft hardwoods, and hard hardwoods) and 13 2-inch d.b.h. size classes. Size-classes range from 2 to 26+ inches, with each class denoted by its midpoint diameter. In matrix notation, the model has the form:

$$\mathbf{y}_{t+1} = \mathbf{G}_t(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{I}_t \tag{1}$$

where $y_t = [y_{ijt}]$ is a vector containing the number of trees per acre of species group i ($i = 1, 2, 3$) and size class j ($j = 1, ..., 13$) at the start of year t, $h_t = [h_{ijt}]$ is a vector containing the number of live trees cut per acre of species group i and size class j at the beginning of year t, G_t is a matrix containing the growth and mortality parameters for year t; and I_t is a vector containing its ingrowth parameters. The growth matrix and ingrowth vector each vary with the residual basal area of the stand and the productivity of the site.

Volume equations. Lin *et al.* (1998) also developed equations to predict pulpwood and sawtimber cubic-foot volumes, based on the stem volume tables of Clark and Souter (1994). The equations recognize two potential sources of pulpwood: from poletimber trees (softwoods 5 to less than 9 inches d.b.h. or hardwoods 5 to less than 11 inches d.b.h.) and from the tops of sawtimber trees (softwoods 9 inches d.b.h. and larger or hardwoods 11 inches d.b.h. and larger). Volumes, too, are a function of stand basal area and site productivity.

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[1] The equations of Lin *et al.*'s (1998) model have been incorporated into SouthPro, a computer program to simulate the uneven-aged management of loblolly pine and loblolly pine-mixed hardwood stands in the mid-South. It can be downloaded free of charge from the Web at <http://forest.wisc.edu/researchl/SouthPro/ >.

Optimization Models

Maximizing soil expectation value. Knowing the maximum economic return obtainable from a given stand provides a useful baseline for evaluating the economic performance of alternative management regimes. The appropriate measure of economic performance is the soil expectation value, the present value of all future harvests, net of all costs, including the opportunity cost of the growing stock. To ensure sustainability, only steady-state regimes (those in which the stand returns to the same pre-harvest distribution each cutting cycle) are considered here. The model for maximizing SEV is:

$$\max_{\mathbf{y},\mathbf{h}} SEV = \frac{\mathbf{s}'\mathbf{h} - F}{(1+r)^C - 1} - \mathbf{s}'(\mathbf{y} - \mathbf{h}) \tag{2}$$

subject to:

$$\begin{aligned} \mathbf{y}_1 &= \mathbf{G}_0(\mathbf{y}_0 - \mathbf{h}_0) + \mathbf{I}_0 \\ \mathbf{y}_2 &= \mathbf{G}_1(\mathbf{y}_1) + \mathbf{I}_1 \\ &\vdots \\ \mathbf{y}_C &= \mathbf{G}_{C-1}(\mathbf{y}_{C-1}) + \mathbf{I}_{C-1} \end{aligned} \tag{3}$$

$$\mathbf{y}_C = \mathbf{y}_0 \tag{4}$$

$$\mathbf{y}_0 - \mathbf{h}_0 \geq \mathbf{0} \tag{5}$$

$$\mathbf{h}_0 \geq \mathbf{0} \tag{6}$$

where $\mathbf{s} = [s_{ij}]$ is a vector in which s_{ij} is the stumpage value of a standing live tree of species group i and size j, $\mathbf{h} = [h_{ij}]$ is a vector representing the number of live trees harvested per acre each cutting cycle, F is the cost of harvesting per acre, r is the real interest rate per year, and C is the cutting cycle in years.

The values of trees are obtained by multiplying the volumes of pulpwood (cords) and sawtimber (board-feet) they contain by the appropriate stumpage prices. Cubic-foot sawlog volumes are converted to board-foot measures (Scribner log rule for softwoods and Doyle log rule for hardwoods) with Koch's conversion table (Koch 1972), while pulpwood volumes are converted to cords assuming 72 cubic feet per cord for softwoods and 79 cubic feet per cord for hardwoods. The stumpage prices used to compute tree values are the 1996 average prices for the Southeastern United States (Table 1, Timber Mart-South 1997). Harvesting costs not already reflected in the stumpage prices were assumed to be $55.00 per acre for hardwood control and $25.00 per acre for administration (Dubois *et al.* 1997). The value of r was set at 4%, the value used by the U.S.D.A Forest Service (Redmond and Greenhalgh 1990).

Equations (3) are the growth equations, with one equation for each year of the cutting cycle. Equation (4) is the steady-state constraint, and equation (5) ensures that the number of trees harvested does not exceed the number of trees in the stand. Together, equations (4) and (5) also ensure that the number of trees in, and harvested from, each species-size category is not negative.

In this and all subsequent optimization problems, the problem was formulated in the GAMS programming language and solved with the GAMS-MINOS solver. Each problem was solved independently for cutting cycles of from 1 to 20 years to determine which is optimal, for each of three categories of site productivity: low (loblolly pine site index of 60 to 79 feet, age 50), medium (80 to 94 feet) and high (95 to 109 feet).

Maximizing annual sawtimber production. Economic return is certainly not the only objective of forest management. Also of interest is knowing the average annual volume of sawtimber that can be produced sustainably by stands on different sites. The model for maximizing annual sawtimber production, *Vs*, is:

$$\max_{\mathbf{y},\mathbf{h}} V_S = \frac{\sum_i \sum_{j_S} \mathbf{v}_{\mathbf{i},\mathbf{j_S}} \mathbf{h}}{C}, \text{ for all } i \text{ and all sawtimber size classes, } j_s. \tag{7}$$

subject to: (3), (4), (5) and (6)

where, $v_{i,js}$ is the volume of a tree of species group *i* and sawtimber size class j_s.

Maximizing tree diversity. An increasingly common objective of forest management is the maintenance of biological diversity, the variations in biological processes, ecological niches, life forms and genetic makeup in a given area (Oliver, 1992). One of the most important components of the overall diversity of a stand is its tree diversity (MacArthur and MacArthur 1961, Wilson 1974, Franzreb 1978, Rice *et al.* 1984). The distribution of trees by species and size largely defines its structure and, thus, the ecological niches available to other organisms. A widely used and accepted index of diversity is Shannon's index. The model for maximizing Shannon's index of tree diversity, H_{trees}, is:

$$\max_{\mathbf{y},\mathbf{h}} H_{trees} = -\sum_i \frac{b_{ij}}{b+\varepsilon} \ln\left(\frac{b_{ij}+\varepsilon}{b+\varepsilon}\right) \tag{8}$$

subject to: (3), (4), (5) and (6)

where b_{ij} is the residual basal area of trees of species group *i* and size class *j, b* is the residual basal area of all trees, and ε is a small, positive constant (0.001) used to avoid natural logarithm of zero and division by zero errors. We define Shannon's index in terms of the distribution of basal area rather than individuals to give added weight to larger trees.

Shannon's index reaches its maximum value when the entities under consideration are distributed evenly among the chosen categories. As defined here, maximum tree diversity is obtained when the residual basal area is distributed evenly among each of the thirty-nine species-size categories: max H_{trees} = ln(39) = 3.66.

Compromise regimes. Forest management is rarely directed towards only one objective. More often, foresters must strike a balance between competing objectives. For instance, managing for tree diversity and managing for economic returns are generally not fully compatible activities. When objectives conflict, additional constraints can be added to mathematical programming models to set bounds on the acceptable levels of additional goals. To illustrate, we add a constraint requiring tree diversity to be at least 75 percent of it theoretical maximum to the model for maximizing SEV:

$$\max_{\mathbf{y},\mathbf{h}} SEV = \frac{\mathbf{s}'\mathbf{h} - F}{(1+r)^{c} - 1} - \mathbf{s}'(\mathbf{y} - \mathbf{h})$$

subject to: (3), (4), (5), (6) and

$$H_{trees} \geq 0.75 * \ln(39) \tag{9}$$

RESULTS AND DISCUSSION

Soil Expectation Value

The steady-state management regimes that maximize SEV on low, medium, and high productivity sites are in Table 2[2]. In each case, the optimal regime involves a guiding maximum diameter (Baker *et al.* 1996) for pines and other softwoods and the complete control of all hardwoods each cutting cycle. The optimal cutting cycle is 10 years for low sites, 13 for medium, and 12 for high. These regimes result in SEVs of $1,014, $1,131, and $1,286 per acre; sawtimber production of 354.1, 337.8, and 390.9 b.f./ac/yr; and Shannon indices of tree diversity of 1.67, 1.50, and 1.50 for low, medium and high sites, respectively. The optimal SEV is higher for medium sites than low ones, even though the low sites produce a greater volume of sawtimber, because the harvesting costs are incurred less frequently on the medium sites. Similarly, the SEV is greater for high sites than medium, even though more trees are harvested from the medium sites, because trees of a given diameter tend to be taller and have larger volumes on better sites (Lin *et al.* 1998). The low Shannon indices of tree diversity reflect the absence of hardwoods from residual stands and the small diameters of residual softwoods.

Sawtimber Production

The regimes that maximize the average annual sawtimber production are given in Table 3. Again, each regime involves a guiding maximum diameter for pines and other softwoods and the complete control of all hardwoods each cutting cycle. The guiding maximum diameter is 19 inches d.b.h. for low sites and 17 inches for medium and high sites. The optimal cutting cycle for each site is one year. These regimes result in SEVs of $-1,738, $-1,192, and $-1,195 per acre; sawtimber production of 426.5, 472.0, and 520.0 b.f./ac/yr; and Shannon indices of tree diversity of 1.99, 1.90, and 1.90 for low, medium and high sites, respectively. The one-year cutting cycles keep the stands in the distributions that produce the maximum volume of sawtimber but result in low SEVs because the harvest costs are incurred so frequently. If the regimes which maximize annual sawtimber board-foot production for a 10-year cutting cycle were adopted instead, the volume of sawtimber produced would be reduced by only 1.7%, 1.9%, and 2.3% for low, medium, and high productivity sites, respectively; whereas their SEVs would increase by $2,071, $1,490, and $1,465 per acre, respectively. The larger Shannon diversity indices, relative to those

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[2] All of the mathematical programming problems presented in this paper have non-concave response surfaces that variably arise from 1) the nonlinear nature of the growth model (Lin *et al.* 1998), 2) the recursive nature of the growth equations (Eq. (3)) when the cutting cycle exceeds one year, and 3) the use of Shannon's index to quantify diversity (Buongiorno *et al.* 1994, Onal 1995). This necessitates the use of nonlinear programming techniques. Consequently, it is not possible to know whether the optimal solutions identified by the models represent global optima or local optima.

for the optimal economic regimes, result from the larger maximum diameters of residual softwoods.

Tree Diversity

Table 4 shows the steady-state management regimes that maximize Shannon's index of tree diversity. The optimal cutting cycle for each site is one year. Relatively few trees are harvested each year, however, resulting in low average annual sawtimber production rates of 77.1, 85.7, and 96.5 b.f./ac/yr for low, medium, and high sites, respectively. These low production rates, combined with the short cutting cycles and large investments in growing stock, result in very low SEVs of $-2,698, $-2,708, and $-2,729 per acre, respectively. If the regimes which maximize Shannon's index of tree diversity for a 10-year cutting cycle were adopted instead, tree diversity would remain virtually unchanged at 3.66, but SEVs would increase by $1853, $1,847, and $1884 per acre, respectively.

Compromise Regimes

The steady-state regimes that maximize SEV subject to a constraint requiring the Shannon index of tree diversity to be at least 75 percent of its theoretical maximum (Table 5) demonstrate the feasibility of finding reasonable compromises between diversity and economic objectives. Here, the optimal cutting cycle is 13 years for low and medium sites and 11 years for high sites. The optimal harvests involve guiding maximum diameters for all three species groups, with maximum diameters ranging from 17 to 23 inches. By retaining relatively large trees in each species group, the optimal regimes attain the required tree diversity. In addition, they have SEVs of at least 77 percent and sawtimber production rates of at least 66 percent of their maximum sustainable levels.

CONCLUSION

Making wise forest management decisions requires an understanding of what is possible on a given site. The nonlinear programming models presented in this paper help define these limits by identifying steady-state, uneven-aged management regimes that maximum the soil expectation value, average annual sawtimber production, or Shannon index of tree diversity of loblolly pine and loblolly pine-mixed hardwood stands on low, medium or high productivity sites. They can also be used to help identify compromise regimes that balance competing objectives, as illustrated above. However, because our ability to predict accurately the highly stochastic processes of tree reproduction, growth, and mortality is limited, the optimal regimes identified by these models should be interpreted as tentative guidelines to help guide management, not as proven regimes to be followed unquestioningly.

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Table 1. Average 1996 stumpage prices for southeastern states (Timber Mart-South 1997).

Species group	Pulpwood ($/cord)	Sawtimber ($/Mbf*)
Softwoods	23.73	237
Soft hardwoods	13.73	124
Hard hardwoods	13.73	198

* Sawtimber prices are Scribner log rule for pines and other softwoods and Doyle log rule for hardwoods.

Table 2. Steady-state management regimes that maximize soil expectation value.

		Trees per acre					
		Low site		Medium site		High site	
Species group	D.b.h. (in.)	Pre-harvest	Post-harvest	Pre-harvest	Post-harvest	Pre-harvest	Post-harvest
Softwoods	2	126.1	126.1	137.3	137.3	138.4	138.4
	4	58.2	58.2	65.0	65.0	65.5	65.5
	6	35.6	35.6	40.3	40.3	40.6	40.6
	8	26.2	26.2	29.8	29.8	30.0	30.0
	10	21.7	21.7	24.7	24.7	24.9	24.9
	12	19.6	19.6	16.9	-	16.7	-
	14	12.2	-	8.5	-	8.0	-
	16	4.9	-	3.1	-	2.7	-
	18	1.3	-	0.8	-	0.7	-
	20	0.2	-	0.2	-	0.1	-
	22	-	-	-	-	-	-
	24	-	-	-	-	-	-
	26+	-	-	-	-	-	-
Soft hardwoods	2	62.4	-	79.6	-	73.3	-
	4	5.5	-	11.8	-	11.7	-
	6	0.5	-	1.6	-	1.6	-
	8	-	-	0.2	-	0.2	-
	10	-	-	-	-	-	-
	12	-	-	-	-	-	-
	14	-	-	-	-	-	-
	16	-	-	-	-	-	-
	18	-	-	-	-	-	-
	20	-	-	-	-	-	-
	22	-	-	-	-	-	-
	24	-	-	-	-	-	-
	26+	-	-	-	-	-	-
Hard hardwoods	2	84.1	-	72.9	-	59.8	-
	4	9.8	-	12.0	-	9.6	-
	6	1.1	-	1.9	-	1.5	-
	8	0.1	-	0.3	-	0.2	-
	10	-	-	-	-	-	-
	12	-	-	-	-	-	-
	14	-	-	-	-	-	-
	16	-	-	-	-	-	-
	18	-	-	-	-	-	-
	20	-	-	-	-	-	-
	22	-	-	-	-	-	-
	24	-	-	-	-	-	-
	26+	-	-	-	-	-	-
	Cycle	10		13		12	
	H_{trees}	1.67		1.50		1.50	
	Sawtimber	354.1		337.8		390.9	
	SEV	1,014		1,131		1,286	

Key: Cycle = cutting cycle (years); Shannon index of tree diversity, defined in terms of the residual basal area distribution; Sawtimber = annual sawtimber production (board feet/acre/year); SEV = soil expectation value ($/acre).

Table 3. Steady-state management regimes that maximize annual sawtimber yields.

		Trees per acre					
		Low site		Medium site		High site	
Species group	D.b.h. (in.)	Pre-harvest	Post-harvest	Pre-harvest	Post-harvest	Pre-harvest	Post-harvest
Softwoods	2	89.1	89.1	104.7	104.7	104.4	104.4
	4	38.5	38.5	46.2	46.2	46.1	46.1
	6	23.0	23.0	27.9	27.9	27.9	27.9
	8	16.6	16.6	20.3	20.3	20.3	20.3
	10	13.6	13.6	16.7	16.7	16.7	16.7
	12	12.2	12.2	15.0	15.0	15.0	15.0
	14	11.6	11.6	14.2	14.2	14.2	14.2
	16	11.6	11.6	14.1	14.1	14.0	14.0
	18	11.8	11.8	1.4	-	1.4	-
	20	1.1	-		-	-	-
	22	-	-	-	-	-	-
	24	-	-	-	-	-	-
	26+	-	-	-	-	-	-
soft hardwoods	2	6.0	-	6.4	-	6.4	-
	4	-	-	-	-	-	-
	6	-	-	-	-	-	-
	8	-	-	-	-	-	-
	10	-	-	-	-	-	-
	12	-	-	-	-	-	-
	14	-	-	-	-	-	-
	16	-	-	-	-	-	-
	18	-	-	-	-	-	-
	20	-	-	-	-	-	-
	22	-	-	-	-	-	-
	24	-	-	-	-	-	-
	26+	-	-	-	-	-	-
Hard hardwoods	2	9.3	-	6.5	-	5.5	-
	4	-	-	-	-	-	-
	6	-	-	-	-	-	-
	8	-	-	-	-	-	-
	10	-	-	-	-	-	-
	12	-	-	-	-	-	-
	14	-	-	-	-	-	-
	16	-	-	-	-	-	-
	18	-	-	-	-	-	-
	20	-	-	-	-	-	-
	22	-	-	-	-	-	-
	24	-	-	-	-	-	-
	26+	-	-	-	-	-	-
	Cycle	1		1		1	
	H_{trees}	1.99		1.90		1.90	
	Sawtimber	426.5		472.0		520.0	
	SEV	-1,738		-1,192		-1,195	

Key: Cycle = cutting cycle (years); Shannon index of tree diversity, defined in terms of the residual basal area distribution; Sawtimber = annual sawtimber production (board feet/acre/year); SEV = soil expectation value ($/acre).

Table 4. Steady-state management regimes that maximize tree diversity.

		Trees per acre					
		Low site		Medium site		High site	
Species group	D.b.h. (in.)	Pre-harvest	Post-harvest	Pre-harvest	Post-harvest	Pre-harvest	Post-harvest
Softwoods	2	89.7	89.7	89.3	89.3	89.1	89.1
	4	23.9	22.5	23.9	22.5	23.9	22.4
	6	10.3	10.0	10.3	10.0	10.3	10.0
	8	5.8	5.6	5.8	5.6	5.8	5.6
	10	3.7	3.6	3.7	3.6	3.7	3.6
	12	2.6	2.5	2.6	2.5	2.6	2.5
	14	1.9	1.8	1.9	1.8	1.9	1.8
	16	1.4	1.4	1.4	1.4	1.4	1.4
	18	1.1	1.1	1.1	1.1	1.1	1.1
	20	0.9	0.9	0.9	0.9	0.9	0.9
	22	0.8	0.7	0.8	0.7	0.8	0.7
	24	0.6	0.6	0.6	0.6	0.6	0.6
	26+	0.5	0.5	0.5	0.5	0.5	0.5
soft hardwoods	2	94.8	90.0	94.2	89.9	93.6	89.7
	4	23.2	22.5	23.6	22.5	23.8	22.4
	6	10.2	10.0	10.2	10.0	10.3	10.0
	8	5.7	5.6	5.7	5.6	5.7	5.6
	10	3.7	3.6	3.7	3.6	3.7	3.6
	12	2.5	2.5	2.5	2.5	2.5	2.5
	14	1.9	1.8	1.9	1.8	1.9	1.8
	16	1.4	1.4	1.4	1.4	1.4	1.4
	18	1.1	1.1	1.1	1.1	1.1	1.1
	20	1.0	1.0	0.9	0.9	0.9	0.9
	22	0.8	0.8	0.8	0.8	0.8	0.8
	24	0.6	0.6	0.6	0.6	0.6	0.6
	26+	0.5	0.5	0.5	0.5	0.5	0.5
Hard hardwoods	2	96.4	90.0	93.0	89.9	91.7	89.7
	4	23.5	22.5	23.5	22.5	23.5	22.4
	6	10.2	10.0	10.2	10.0	10.2	10.0
	8	5.7	5.6	5.7	5.6	5.7	5.6
	10	3.7	3.6	3.7	3.6	3.7	3.6
	12	2.5	2.5	2.5	2.5	2.5	2.5
	14	1.9	1.8	1.9	1.8	1.9	1.8
	16	1.4	1.4	1.4	1.4	1.4	1.4
	18	1.1	1.1	1.1	1.1	1.1	1.1
	20	0.9	0.9	0.9	0.9	0.9	0.9
	22	0.7	0.7	0.7	0.7	0.7	0.7
	24	0.6	0.6	0.6	0.6	0.6	0.6
	26+	0.5	0.5	0.5	0.5	0.5	0.5
	Cycle	1		1		1	
	H_{trees}	3.66		3.66		3.66	
	Sawtimber	71.1		85.7		96.5	
	SEV	-2,698		-2,708		-2,729	

Key: Cycle = cutting cycle (years); H_{trees} = Shannon index of tree diversity, defined in terms of the residual basal area distribution; Sawtimber = annual sawtimber production (board feet/acre/year); SEV = soil expectation value ($/acre).

Table 5. Steady-state management regimes that maximize soil expectation value, subject to a constraint requiring tree diversity to be at least 75% of its theoretical maximum.

		Trees per acre					
		Low site		Medium site		High site	
Species group	D.b.h. (in.)	Pre-harvest	Post-harvest	Pre-harvest	Post-harvest	Pre-harvest	Post-harvest
Softwoods	2	110.7	110.7	112.7	112.7	116.2	116.2
	4	51.3	51.3	52.4	52.4	53.8	53.8
	6	31.3	31.3	32.1	32.1	33.0	33.0
	8	22.9	22.9	23.5	23.5	24.2	24.2
	10	18.9	18.9	19.4	19.4	20.0	20.0
	12	14.2	6.1	14.0	3.6	13.5	2.8
	14	8.4	0.6	7.9	0.5	6.7	0.5
	16	3.8	0.1	3.4	0.1	2.6	0.2
	18	1.3	-	1.1	-	0.8	0.1
	20	0.3	-	0.3	-	0.2	-
	22	0.1	-	0.1	-	0.1	-
	24	-	-	-	-	-	-
	26+	-	-	-	-	-	-
Soft hardwoods	2	100.2	29.3	94.1	25.5	82.4	23.9
	4	19.2	10.5	20.8	9.5	19.2	9.2
	6	6.7	5.0	6.9	4.2	6.3	3.8
	8	3.2	2.2	3.1	1.9	2.8	1.8
	10	1.9	1.5	1.8	1.4	1.7	1.3
	12	1.5	1.5	1.4	1.4	1.3	1.3
	14	1.1	0.7	1.0	0.6	0.9	0.6
	16	0.6	0.3	0.6	0.3	0.5	0.3
	18	0.3	0.1	0.3	0.1	0.3	0.1
	20	0.1	0.1	0.1	0.1	0.1	0.1
	22	0.1	-	0.1	-	0.1	-
	24	-	-	-	-	-	-
	26+	-	-	-	-	-	-
Hard hardwoods	2	121.5	30.1	88.3	29.8	73.3	30.5
	4	25.4	11.7	21.3	11.4	18.7	11.7
	6	8.5	5.7	7.9	5.2	7.4	5.1
	8	4.1	2.8	4.0	2.8	3.9	3.0
	10	2.7	2.5	2.7	2.6	2.8	2.8
	12	2.2	2.2	2.2	2.2	2.3	2.3
	14	1.7	1.1	1.7	1.0	1.8	1.1
	16	1.0	0.4	1.1	0.4	1.1	0.5
	18	0.5	0.2	0.6	0.2	0.6	0.2
	20	0.2	0.1	0.3	0.1	0.3	0.1
	22	0.1	-	0.1	-	0.2	0.1
	24	-	-	0.1	-	0.1	-
	26+	-	-	-	-	-	-
	Cycle	13	-	13		11	
	H_{trees}	2.75		2.75		2.75	
	Sawtimber	281.4		321.1		362.9	
	SEV	780		882		1,004	

Key: Cycle = cutting cycle (years); H_{trees} = Shannon index of tree diversity, defined in terms of the residual basal area distribution; Sawtimber = annual sawtimber production (board feet/acre/year); SEV = soil expectation value ($/acre).

PROCEEDINGS

of the
Society of American Foresters

1998 NATIONAL CONVENTION

Traverse City, Michigan
September 19-23, 1998

Society of American Foresters
5400 Grosvenor Lane
Bethesda, MD 20814-2198
www.safnet.org

SAF Publication SAF 99-01
ISBN 0-939970-77-5