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Quantifying Trade-Offs Between Economic and Ecological Objectives in Uneven-Aged Mixed-Species Forests in the Southern United States

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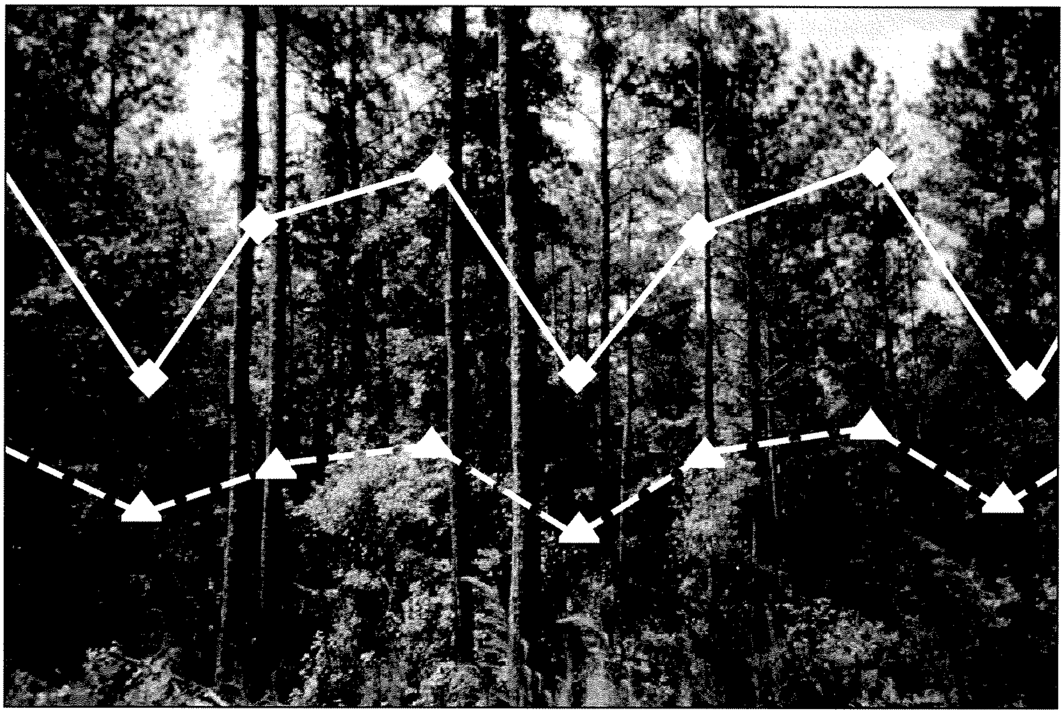

Abstract

This paper summarizes research on the management of uneven-aged loblolly pine–hardwood stands in the southern United States. This research was composed of three elements: (1) modeling of biological growth of uneven-aged stands of mixed loblolly pine and hardwood trees, (2) optimization to discover sustainable regimes that would best meet economic and ecological objectives such as stand diversity, and (3) simulations to predict the effects of optimal management guides, when applied to stands in different initial conditions. The findings suggest that uneven-aged systems are feasible for the mixed loblolly pine–hardwoods forest type. An infinite number of sustainable management regimes are possible, with different cutting cycles and/or cutting intensities. Regimes with the highest financial returns would lead to pure pine stands, a cutting cycle of about 13 years, diameter-limit cuts at 12 in. diameter at breast height for pines, and total removal of hardwoods. Near-maximum diversity of species and size of trees would be produced by a "hands off" policy, at a high opportunity cost. Intermediate regimes were designed to maximize income, while leaving a sufficiently diverse stand. A simple effective method for converting stands from their initial state to a desired future state is to cut all the trees and only the trees that currently exceed the desired state.

Keywords: uneven-aged, loblolly pine, hardwoods, south, silviculture, economics, linear programming, simulation, biometrics.

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Inch–pound unit	Conversion factor	SI unit
inch (in.)	25.4	millimeter (mm)
square foot (ft^2)	0.093	square meter (m^2)
cubic foot (ft^3)	0.0283	cubic meter (m^3)
acre	0.4047	hectare (ha)

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Introduction

There is a strong worldwide interest in management of uneven-aged forests. The main reason for this is the perception of uneven-aged systems as working "close to nature." These systems maintain a constant ground cover and use mostly natural regeneration. Uneven-aged systems favor a mix of many species and are meant to keep trees of very different ages on small tracts of land. The result is dramatically different from homogeneous plantations of a single species, which are even-aged and managed by clear cutting and artificial regeneration. The aesthetic quality of uneven-aged systems is appreciated by the general public, and the gain in biological diversity is well documented.

If uneven-aged systems are to be applied more extensively, their economic and ecological consequences must be predicted. This paper presents some results of research aimed at rigorously analyzing the transformation, with the ultimate goal of obtaining guidelines that could be applied readily in the field. Although this type of research has been done for several forest types, we were restricted to results obtained by the Wood Utilization for Ecosystems Management Project that pertain to mixed softwood–hardwood stands in the southern United States.

Quantification is important to clarify some issues pertaining to uneven-aged management. With mathematics and numbers, all the assumptions underlying a particular result and recommendation can be fully disclosed. Careful specification of all the equations helps improve communication between researchers. The gain in understanding facilitates critical review and should lead ultimately to faster progress. The availability of a quantitative model to experiment with, i.e., to "bring the world to the laboratory" (Holling and others 1986), also facilitates the relationship between researchers and practitioners. Nonetheless, quantification is useful only if it leads to improved practice, i.e., to operational management guidelines. In that spirit, the approach to quantifying the implications of uneven-aged stands proposed here has three steps:

Modeling the growth of the stand. This step involves the formulation of a particular model structure, i.e., a theory of growth and calibration of the model parameters with growth data from the particular ecosystem of interest.

Optimizing the target stand. Optimization of the stand is meant to help the selection of a particular management goal, given the growth model and management criteria, which may be purely economic, purely ecological, or a mix of the two.

Simulating the conversion to the desired state. Simulation is meant to quantify the economic and ecological effects of going from the initial stand to the desired target, according to a particular rule. The rule proposed here is simple heuristics, based on the choice of target in step 2.

Modeling Forest Growth

A particular class model (Model 1) that has been applied to a wide range of conditions uses a vector and matrix representation of stand state and growth (Usher 1969):

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

where $\mathbf{y}_t$ is a vector describing the stand state at instant t. The vector elements are the number of trees of different species and size per unit of land area. Sizes are categorized in a finite number of size classes. The variable $\mathbf{h}_t$ is the harvest vector, i.e., the number of trees of each species and size that are cut at time t. $\mathbf{G}_t$ is a matrix of parameters, and $\mathbf{c}$ is a constant vector.

The parameters are (1) the probability that a live tree of a particular species and size remains alive and grows from that size to a larger size during the interval t to $t+1$, (2) the probability that a live tree of a particular species and size remains alive and stays in that same size class from t to $t+1$, and (3) parameters representing the effects of the trees in each size class on the recruitment rate from t to $t+1$. Typically, recruitment is an inverse function of stand density and a direct function of the number of trees of the same species in the stand (Buongiorno and Michie 1980). The growth matrix can distinguish between species and may be a variable function of the stand state (Kolbe and others 1999). Variants of this model have been successfully applied to many different forests, and much is known on how to estimate them (Mengel and Roise 1990, Osho 1991, Lin and others 1996).

The model of loblolly pine–hardwood stands in the U.S. South was initially estimated with data from 796 naturally regenerated, mixed-aged, re-measured FIA plots of the loblolly pine forest type in seven U.S. states (Lin and others 1998). These lots were selected randomly from the 991 plots available. The resultant model was then used to predict the state of the remaining 20% plots at the time of the second inventory, given their state at the first inventory. There was little difference between the means of the predicted and observed number of trees in each size class. Figure 1 shows the predicted and actual number of trees for the softwood species.

The long-term validity of the model was also tested by simulating species succession over 300 years. For example, Figure 2 shows that without disturbance the stand basal area on a good site would stabilize at around 200 ft^2/acre and the stand would become primarily soft hardwoods. This is consistent with prior knowledge (Quarterman and Keever 1962, Switzer and others 1979).

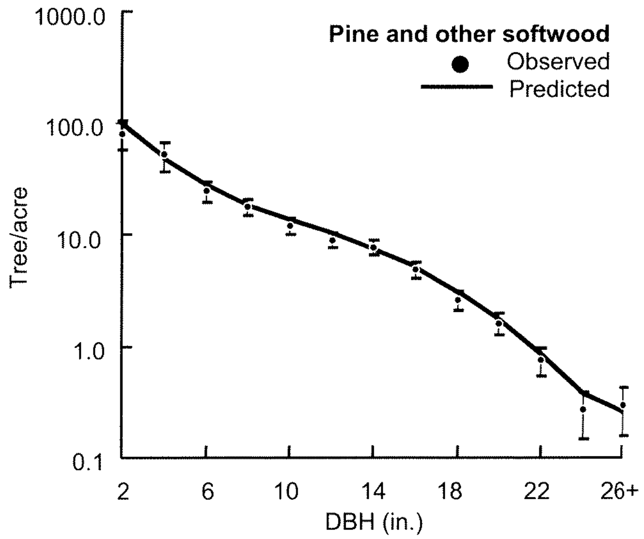

Figure 1—Observed and predicted average number of trees per acre on 195 plots in loblolly pine–hardwood stands in the South (Lin and others 1998).

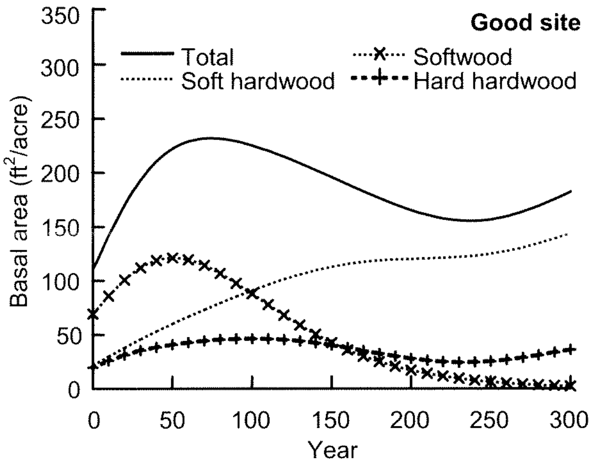

Figure 2—Basal area growth of undisturbed loblolly pine–hardwood stand on good site (Lin and others 1998).

Choosing Target Stand

Within Model 1, the number of trees in each size class and species group that the manager desires to maintain defines the target state. This state will usually be chosen on the basis of various economic and ecological criteria.

One fundamental criterion is that the stand state be sustainable, given the prescribed harvest and the potential growth of the forest. In terms of Model 1, this means that the stock vector $\mathbf{y}_t$, and the harvest vector $\mathbf{h}_t$ must satisfy a sustainability constraint, according to which the stand state at the end of the cutting cycle, of length T years, must be the same as the beginning state (Fig. 3).

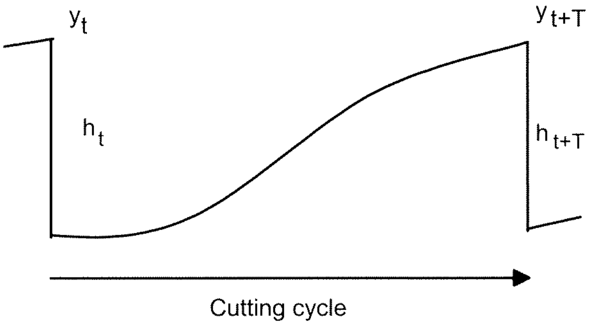

Figure 3—The steady-state regime is such that growth just replaces harvest over the cutting cycle.

Table 1—Management regime that maximizes land expectation value in mixed loblolly pine–hardwood stands on medium-size site[a]

Diameter at breast height (in.)	Volume (trees/acre)					
	Softwoods		Soft hardwoods		Hard hardwoods	
	Stock	Cut	Stock	Cut	Stock	Cut
2	137.3	—	79.6	79.6	72.3	72.9
4	65.0	—	11.8	11.8	12.0	12.0
6	40.3	—	1.6	1.6	1.9	1.9
8	29.8	—	0.2	0.2	0.3	0.3
10	24.7	—	—	—	—	—
12	16.9	16.9	—	—	—	—
14	8.5	8.5	—	—	—	—
16	3.1	3.1	—	—	—	—
18	0.8	0.8	—	—	—	—
20	0.2	0.2	—	—	—	—
22	—	—	—	—	—	—
24	—	—	—	—	—	—
26+	—	—	—	—	—	—

Cutting cycle	13 years
H	1.5
Sawtimber	338 board ft/acre/year
LEV	$1,131/acre

[a] *H* is stand diversity; LEV is land expectation value.
Source: Schulte and others (1998a).

Table 2—Management regime that maximizes diversity of tree size and species, in mixed loblolly pine–hardwood stands on medium site

Diameter at breast height (in.)	Volume (trees/acre)					
	Softwoods		Soft hardwoods		Hard hardwoods	
	Stock	Cut	Stock	Cut	Stock	Cut
2	89.3	—	94.2	4.3	93.0	3.1
4	23.9	0.4	23.6	1.1	23.5	1.0
6	10.3	0.3	10.2	0.2	10.2	0.2
8	5.8	0.2	5.7	0.1	5.7	—
10	3.7	0.1	3.7	0.1	3.7	0.1
12	2.6	0.1	2.5	—	2.5	—
14	1.9	0.1	1.9	0.1	1.9	0.1
16	1.4	—	1.4	—	1.4	—
18	1.1	—	1.1	—	1.1	—
20	0.9	—	0.9	—	0.9	—
22	0.8	0.1	0.8	—	0.7	—
24	0.6	—	0.6	—	0.6	—
26+	0.5	—	0.5	—	0.5	—

Cutting cycle	1 year
H	3.7
Sawtimber	71 board ft/acre/year
LEV	–$2,698/acre

Source: Schulte and others (1998a).

Economic Objective

There are many sustainable regimes. The most desirable can be selected from a wide range of choices. For example, the desired regime may be the best sustainable one in a purely economic sense. The economic criterion is the land value that results from a specific management regime, sometimes called the land expectation value (LEV). The LEV is the present value of all future returns, over an infinite horizon, minus the value of the growing stock needed to produce this return. The problem with a purely economic objective for uneven-aged management then consists in finding the stand state $\mathbf{y}_t$ and the corresponding harvest $\mathbf{h}_t$ that maximize LEV, while satisfying growth Model 1 and the steady-state constraints.

Table 1 provides an example of economic sustainable management. The regime of highest LEV is a diameter-limit cut, taking all the softwoods 11 in. in diameter at breast height (dbh) and larger every 13 years, and taking all the hardwoods regardless of size. This will lead to a constant production of 4,398 board ft/acre each cutting cycle, representing an average annual production of 338 board ft/acre per year. The drawback of this regime is that the diversity of the stand is low in terms of trees of different species and size.

Ecological Objective

A variety of ecological objectives can be expressed at stand level, based on the diameter distribution of trees, $\mathbf{y}_t$. The diversity of tree species and tree size is commonly measured with Shannon's index, *H* (Pielou 1977). In this application, *H* is largest when there is an equal proportion of tree basal area in each species and size class.

A stand management policy with a purely ecological objective can then be sought by finding the values of the stock $\mathbf{y}_t$ and harvest $\mathbf{h}_t$ that maximize stand diversity *H* while satisfying the sustainability constraints and the growth Model 1. An example of a solution that maximizes diversity is shown in Table 2. The best solution is to cut few trees, doing practically nothing. According to the model, in the long run, natural processes alone would produce a steady state or climax with a stand of highest possible diversity, in Shannon's sense. The diversity index *H* would be more than double that obtained by maximizing economic returns. The opportunity cost of this regime compared with the economic regime is quite high; $1,131 + $2,698 = $3,829/acre.

Table 3—Management regime that maximizes economic returns and keeps diversity at least 75% of its maximum, in mixed loblolly pine–hardwood stands

Diameter at breast height (in.)	Softwoods Stock	Softwoods Cut	Soft hardwoods Stock	Soft hardwoods Cut	Hard hardwoods Stock	Hard hardwoods Cut
2	112.7	0.0	94.1	68.6	88.3	58.5
4	52.4	0.0	20.8	11.3	21.3	9.9
6	32.1	0.0	6.9	2.7	7.9	2.7
8	23.5	0.0	3.1	1.2	4.0	1.2
10	19.4	0.0	1.8	0.4	2.7	0.1
12	14.0	10.4	1.4	0.0	2.2	0.0
14	7.9	7.4	1.0	0.4	1.7	0.7
16	3.4	3.3	0.6	0.3	1.1	0.7
18	1.1	1.1	0.3	0.2	0.6	0.4
20	0.3	0.3	0.1	0.0	0.3	0.2
22	0.1	0.1	0.1	0.1	0.1	0.1
24	—	—	—	—	0.1	—
26+	—	—	—	—	—	—

Volume (trees/acre)

Cutting cycle	13 years
H	2.8
Sawtimber	321 board ft/acre/year
LEV	$882/acre

Source: Schulte and others (1998a).

Mixed Objectives

The purely economic or ecological managements are extremes. More often, managers seek target stand states for the transformation that would yield both ecological and economic results. One might seek the target tree distribution and harvest that would maximize the land expectation value LEV while maintaining the diversity index *H* above a preset acceptable level. Or, symmetrically, one could search for the solution that would maximize diversity, subject to a lower bound on LEV.

For example, Table 3 shows a management regime that maximizes economic returns while maintaining diversity at 75% of its maximum. Thus, *H* must equal at least 2.8. The best cutting cycle is 13 years and the best cutting regime takes all the trees 11 in. dbh and larger, like in the purely economic regime. However, many more hardwood trees are left. The result is an LEV of $882/acre, 78% of the maximum LEV obtained without diversity constraint (see Table 1).

Converting Stand to Desired State

Like the target stand state, the transformation from the current state to the desired state can also be optimized (Buongiorno 2000). However, a simple heuristic procedure for the transformation consists in comparing the current stand state with the desired post-harvest state and cutting trees in the classes that have more trees than the desired state, while doing nothing in those classes that have less.

The SouthPro computer software (Schulte and others 1998b) can be used to make predictions of the economic and ecological consequences for this type of management strategy, for mixed loblolly pine–hardwood stands. An example of SouthPro output appears in Figure 4, which shows the evolution of the size distribution of softwood trees under a compromise regime, seeking both economic returns and ecological diversity. Figure 5 shows that the number of trees below size class 10 would decrease during the simulated 18 years, while the number in size class 10 and above would increase, thus increasing the size diversity of the stand.

Another example of SouthPro output appears in Figure 5, which shows the economic consequences of high grading compared with a diameter-limit cut. Only the commercial trees were harvested for high grading, thus producing a higher initial income. Diameter-limit cutting applied a regime very similar to the one described in Table 1. Figure 5 shows that the periodic income produced with the diameter-limit cutting policy was much greater in the long run than that obtained by high grading.

Conclusion

This research demonstrates that quantification of biological processes and management decisions is helpful for predicting the effects of different regimes for managing uneven-aged loblolly pine–hardwood stands in the southern United States. Quantification also facilitates the selection of the most appropriate regime for multiple objectives. Current models are still imperfect, but rigorous quantitative models are better than no model at all, because assumptions are transparent and can be improved by future research.

It is essential that management models, regardless of their form, lead to prescriptions that are practical, or else they will not be used. In that respect, the simplicity of the management prescriptions derived from this research (such as diameter-limit cuts) is encouraging. The strategy of developing general cutting guides and applying them regardless of the stand initial condition is also desirable. Even though this strategy may be sub-optimal, its simplicity of implementation may well make it the superior approach for practitioners.

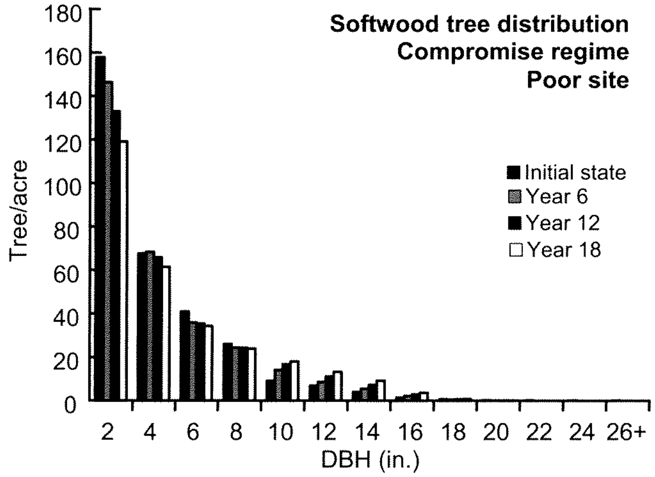

Figure 4—Evolution of diameter frequency distribution, as predicted by SouthPro for mixed economic and ecological objectives (Schulte and others 1998c).

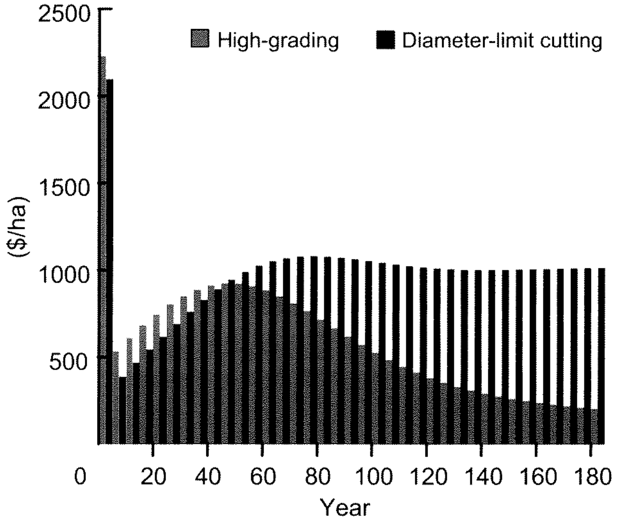

Figure 5—Periodic income obtained with a high-grading or a diameter-limit cutting policy for a loblolly pine–hardwood stand on site 4, over 180 years (Schulte and Buongiorno 1998).

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