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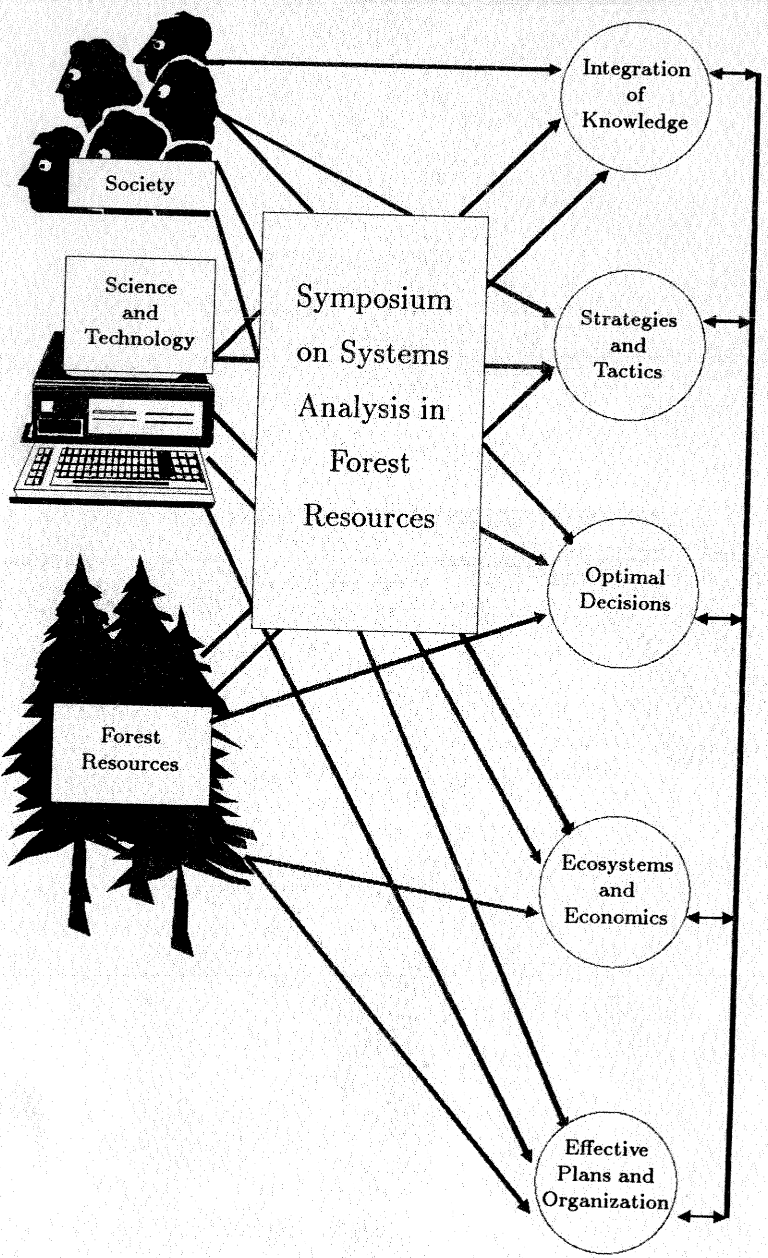

March 3–6, 1991
Charleston, South Carolina

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A STOCHASTIC MODEL FOR SIMULATING DAILY GROWING SEASON WEATHER VARIABLES FOR INPUT INTO ECOLOGICAL MODELS[1]

PAUL V. DESANKER and DAVID D. REED[2]

ABSTRACT. A stochastic model is presented to generate daily values of precipitation, solar radiation, maximum temperature and minimum temperature. Precipitation is modeled by a Markov chain-exponential model. Solar radiation, maximum and minimum temperature are modeled using a multivariate generating model conditioned on the wet or dry state of the day and time period. The model is formulated such that outputs can be used in simulation exercises to test the effect of changing climatic conditions on forest ecosystem processes.

Keywords: daily weather, ecological modeling, climate change

1.0 INTRODUCTION

The objective of this study is to develop a model which can simulate daily weather variables of a known dependency structure for use in ecological models. By controlling the properties of the daily weather variables, scenarios of changing climate can be implemented, and information generated for use as input into ecological models utilized in climate change studies. Daily weather data are frequently needed to calculate many ecological processes like photosynthesis, evapotranspiration, and respiration, or as input parameters to models, for instance growing degree days, soil moisture and drought indices. The meteorological variables needed most include air and soil temperature, incoming solar radiation, humidity, and precipitation for each site of interest. The daily data are rarely available for the particular site of interest or only long term regional averages may be available.

In the past, on sites where daily weather data were not measured directly, data were extrapolated from routine National Weather Stations (NWS) or regional long term averages were used. For example, Running et al.(1987) extrapolate NWS data to adjacent mountainous terrain. Their method relies on the daily data for adjacent stations to be complete for all variables of interest, and of course, available to the user.

It is possible to collect daily data over several years and carry out required calculations over short time periods. However, this becomes impractical over longer periods, such as those required to evaluate ecological processes. We demonstrate how several years of measurements and other available long term data can be used to construct a stochastic simulator for daily weather conditions.

The model that we implement simulates daily values of maximum and minimum temperature, precipitation and solar radiation. The technique recognizes and guarantees the observed serial and cross correlation in and between the variables. The model treats precipitation as the primary variable and then conditions the other variables for a given day on whether the day was wet or dry.

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[1] Presented at the 1991 Systems Analysis in Forest Resources Symposium, Charleston, South Carolina, March 3-7,1991.

[2] The authors are Ph.D. Candidate and Professor of Forest Biometrics, School of Forestry and Wood Products, Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931, (U.S.A.).

2.0 DATA COLLECTION

This study was part of a larger project that is attempting to determine the effects of an imposed factor (in this case electromagnetic fields), against a background of natural variability in climate and other factors (Mroz et al. 1990). Each of 3 sites located in the Central Upper Peninsula of Michigan, was equipped with an automated data collection platform. These platforms monitor precipitation, air and soil temperature, relative humidity, and solar radiation. Data were retrieved 8 times daily via the National Earth Satellite System (NESS) transmissions at three-hour intervals. These data were processed to obtain information such as maximum and minimum daily air temperatures, total daily precipitation and solar radiation, as well as growing degree days on a 4.4 degree Centigrade basis. Growing degree days were calculated on a daily basis and summed up for weekly or monthly totals. Data collected this way over 5 growing seasons (April to October,1985-1989) were used in the present analysis. Nineteen years of data on precipitation and temperature from an adjacent NWS at Crystal Falls as published monthly in 'NOAA Climatological Data for Michigan', were also used.

Two of the three sites are located in the southwestern part of Marquette County, at approximately 46°20′ N latitude and 88°10′ W longitude. The third site is in Iron County about 5 miles south of Crystal Falls at approximately 46°10′N latitude and 88°30′ W latitude. There are no outstanding topographic features close to any of these sites.

3.0 DAILY WEATHER MODEL

The basic daily weather model formulation follows the conceptual relationships described by Richardson(1981). The stochastic relationships underlying the meteorological processes of rain, maximum and minimum temperature, and solar radiation are developed as follows:

i. The processes are time depedendent within each variate.
ii. The processes are interdependent among themselves.
iii. The processes exhibit seasonal oscillations for each variable.

Temperature and radiation are more likely to be below normal on rainy days than on dry days. Maximum and minimum temperature on any given day will be related because of heat storage in the soil and surrounding atmosphere. Maximum temperature should be serially correlated because of heat storage from one day to the next.

Precipitation is modeled seperately from the other variables. The full model considers precipitation as the primary variable and then conditions the other three variables for a given day on whether the day was wet or dry. We develop the precipitation process first. In order to account for seasonality, the year was divided into 14-day periods with period 1 starting January 1st of each year. We assume the process is stationary over each 14-day time period.

3.1 PRECIPITATION MODEL

The modeling of rainfall has a large literature, reviewed by Waymire and Gupta(1981). Markov chains have been used to model the sequence of wet and dry days, and have been extended to allow for non-stationarity by fitting seperate chains to different periods of the year (e.g. Dummont and Boyce, 1974), and by fitting continuous curves to transition probabilities (Woolhiser and Pegram, 1979). The orders of the Markov chains and number of states used vary from study to study. In this paper we use a two state Markov chain and test first and second order Markov chains. For the wet days, the amount of precipitation has been modeled using the exponential, gamma, and mixed exponential distributions. We tested the gamma, Weibull, and exponential distributions for precipitation amounts. We define a day to be wet if the amount of precipitation is 0.01 inches or more.

3.1.1 Precipitation Occurrence

We consider a sequence S, of observations $x_1,...,x_n$ from a Markov chain, each observation assuming one of two states, and denoted by 1 if wet, or 0 if dry. A Markov chain is said to be of 'order' **k** if the following equation relating the conditional probabilities is satisfied where **k** is the smallest integer such that

$$P(x_t | x_{t-1}, x_{t-2}, \ldots) = P(x_t | x_{t-1}, x_{t-2}, \ldots, x_{t-k}) \qquad (1)$$

for all n.

In the above, **k** is assumed to be an integer greater than zero. However, the chain is said to be of order 0 if it is a sequence of independent random variables. We assume that the chain is *ergodic* so that the final chain is stationary within each period. A unique stationary distribution, in which all probabilities are non-zero, independent of the initial conditions is assumed.

Estimation

Let $X_t = 1$ if day t is wet, t=1,2,...,n
$= 0$ if day t is dry,

where n is number of days in a period, (14 here).

We will consider first- and second-order Markov chains (everything follows for higher order chains). The assumption that X_t forms a second-order Markov chain is the assumption that in (1):

$$P(x_t = 1 | x_{t-1}, x_{t-2}, x_{t-3}, \ldots) = P(x_t=1 | x_{t-1}, x_{t-2} \quad t=1,2,\ldots,n \tag{2}$$

and fitting the Markov chain involves estimating for each time period, the 4 parameters:

$$p_{hj} = P(x_t=1 | x_{t-1}=h, x_{t-2}=j) \quad t=1,2,\ldots,n; \quad h,j=0,1 \tag{3}$$

The numbers of transitions are sufficient statistics for p_{hj} so the data may be reduced to a 2 X 2 X 2 table (for each period) with entries

$$N_{ihj} = \text{Number of days with } x_t = i,\ x_{t-1} = h, x \quad t=1,2,\ldots,n; \quad i,h,j=0,1 \tag{4}$$

The obvious estimates of p_{hi} are the observed proportions:

$$\hat{p}_{hj} = N_{1hj} / N_{+hj}, \quad h,j = 0,1 \tag{5}$$

where + indicates summation over the subscript.

The log-likelihood is given by Stern and Coe (1984) as.

$$Log\ L = \sum_{h,j} N_{1hj} \log(p_{hj} + N_{0hj} \log(1-p_{hj})] \tag{6}$$

We determine the order of the chain from the given observations, S. We apply an approach introduced by Tong(1975) using Akaike's Information Criterion (Akaike,1974) as an objective procedure for the determination of the order of an ergodic Markov chain with a finite number of states.

The *Akaike Information Criterion* (AIC) is

$$AIC(q) = -2 \log L(y, \theta_q) + 2q \tag{7}$$

where q is the number of independent parameters to be estimated, and $L(y,\theta_q)$ is the likelihood. The best model is the one defined by the minimum AIC, termed the *Minimum AIC Estimate (MAICE)*. Tong(1975) gives equivalent forms of the above risk function, with the following as the most convenient for the Markov chain problem:

$$AIC(q) = {}_q\eta_L - 2(\text{degrees of freedom}) \tag{8}$$

where ${}_q\eta_L$ is -2(the log-likelihood ratio for the q-th order chain to a true order of L), see Tong(1975) for formulae, or Chin(1977) for an alternative calculation.

The loss function, AIC(q) for orders 0,1 and 2 using equation 7 were evaluated and MAICE was minimized for each growing season 14-day time period (10-21) with q equal to 1, implying a first order Markov process.

3.1.2 Precipitation Amount

In describing rainfall amounts, some authors have fitted Markov chains with many states, each representing a range of amounts (e.g. Khanal and Hamrick,1974; Haan et al,1976). Others have modeled the rainfall amounts on wet days separately. The distribution of these amounts is extremely skewed, with the smaller amounts occurring much more frequently than the larger amounts. Recall that a day was classified as wet if rainfall was at least 0.01 inches. The highest amount of rainfall in one day over the 19 years of data at Crystal Falls was 3.84 inches. This led us to use truncated forms of the functions that we consider, with a lower truncation point of 0.01, and an upper truncation point at 4.0 inches.

We let Y(t) be the amount of precipitation on day t of a given period. We assume the Y(t)'s are independent random variables with density function f(y), given for the exponential as:

(Left and Right Truncated) Exponential:

$$f(y) = \frac{(1/\lambda)\exp[-(y-t)/\lambda]}{1-\exp[-(T-t)/\lambda]} \quad 0 \le t \le y \le T < \infty, \quad \lambda > 0 \tag{9}$$

The first and second moments are given by:

$$E[Y] = \lambda + \frac{t - T\exp[-(T-t)/\lambda]}{1-\exp[-(T-t)/\lambda]} \tag{10}$$

$$E[Y^2] = 2\lambda^2 + \frac{(t^2+2\lambda t)-\exp[-(T-t)/\lambda](T^2+2\lambda}{1-\exp[-(T-t)/\lambda]} \quad (11)$$

Log likelihood for n random variables is given by:

$$\log L = -nlog\lambda-\sum^{n} y_i/\lambda+n-nlog(1-\exp[-(T-t) \quad (12)$$

The maximum likelihood estimate for λ is found by iteratively solving the following equation:

$$\hat{\lambda} = \frac{1}{2n}\sum y_i + \frac{(T-t)\exp[-(T-t)/\hat{\lambda}]}{(1-\exp[-(T-t)/\hat{\lambda})]} \quad (13)$$

3.2 MAXIMUM TEMPERATURE, MINIMUM TEMPERATURE, AND SOLAR RADIATION

Stochastic modeling of temperature and solar radiation has not received as much attention as rainfall modeling in the literature. Examples of stochastic models for weather variables are Joseph(1973) for temperature, Goh and Tan(1977) for solar radiation, and Richardson(1981) for both.

The approach used here considers maximum temperature, minimum temperature, and solar radiation to be a continuous multivariate stochastic process with the daily means and standard deviations conditioned on the wet or dry state of the day (Richardson,1981). The time series for each variable was reduced to a time series of standardized residual elements by removing periodic means and standard deviations using the following equations:

$$\chi_i(j) = \frac{\mathbf{X}_i(j) - \bar{\mathbf{X}}_i^0(j)}{\sigma_i^0(j)} \quad \text{for } Y_i = 0 \text{ (dry day} \quad (14)$$

or

$$\chi_i(j) = \frac{\mathbf{X}_i(j) - \bar{\mathbf{X}}_i^1(j)}{\sigma_i^1(j)} \quad \text{for } Y_i = 1 \text{ (wet day} \quad (15)$$

where $X_i^o(j)$-bar and $\sigma_i^o(j)$ are the mean and standard deviation for a dry day (Y_i=0), those in equation 15 refer to a wet day ($Y_i > 0$), and $\chi_i(j)$ is the residual component for variable j, for day i. These elements were analyzed to determine the time dependence (serial correlation) within each series and cross correlation between each pair of variables. Five years of data were used for the study sites. There were no solar radiation measurements for the Crystal Falls NWS. Ten years of temperature data were used for Crystal Falls and the solar radiation values from the study sites were also applied to Crystal Falls.

3.2.1 Multivariate Generating Model

The model used for generating residual series of maximum temperature, minimum temperature, and solar radiation is the weakly stationary generating process suggested by Matalas(1967). The equation is

$$\chi_i(j) = A\chi_{i-1} + B\epsilon_i(j) \quad (16)$$

where $\chi_i(j)$ and $\chi_{i-1}(j)$ are (3X1) matrices for days i and i-1 whose elements are residuals of maximum temperature (j=1), minimum temperature (j=2), and solar radiation (j=3); $\epsilon_i(j)$ is a (3X1) matrix of independent random components that are normally distributed with mean zero and unit variance; A and B are (3X3) matrices whose elements are defined such that the sequences have the desired serial correlation and cross-correlation coefficients.

The elements of the matrix A are given by

$$A = M_1 M_0^{-1} \quad (17)$$

where M_o^{-1} is the inverse of M_o. M_o is the variance-covariance matrix (lag 0 covariance matrix), is nonsingular and therefore its inverse exists. M_1 is the lag 1 covariance matrix. The matrix elements of B are given by the solution of

$$BB_T = M_0 - M_1 M_0^{-1} M_1^T \quad (18)$$

The techniques of principal component analysis may be used to solve for B in (16), applied to $M_o - M_1 M_o^{-1} M_1^T$ (Matalas,1967). Alternatively, since BB_T is symmetric, we diagonalize it and find B as P 'D, where P is an orthogal matrix of the eigenvectors, and D is the diagonal matrix with eigenvalues, of BB^T.

The matrices may be written as

$$M_0 = \begin{bmatrix} 1 & \rho_0(1,2) & \rho_0(1,3) \\ \rho_0(2,1) & 1 & \rho_0(2,3) \\ \rho_0(3,1) & \rho_0(3,2) & 1 \end{bmatrix} \quad (19)$$

$$M_1 = \begin{bmatrix} \rho_1(1) & \rho_1(1,2) & \rho_1(1,3) \\ \rho_1(2,1) & \rho_1(2) & \rho_1(2,3) \\ \rho_1(3,1) & \rho_1(3,2) & \rho_1(3) \end{bmatrix} \quad (20)$$

where $\rho_0(j,k)$ is the lag 0 cross-correlation coefficient between variables j and k, $\rho_1(j,k)$ is the cross-correlation coefficient between variables j and k with variable k lagged 1 day in relation to variable j, and $\rho_1(j)$ is the lag 1 serial correlation for variable j. Since $\rho_0(j,k) = \rho_0(k,j)$, M_0 is a symmetric matrix. However, $\rho_1(j,k)$ is not necessarily equal to $\rho_1(k,j)$, and each element in M_1 must be defined separately.

The parameters for the temperature and solar radiation model are three lag 0 cross-correlation coefficients, three lag 1 serial correlation coefficients, and six lag 1 cross correlation coefficients. The daily values of the three weather variables are found by multiplying the residuals by the standard deviation and adding the mean. The mean and standard deviations are conditioned on the wet or dry state of the day as determined by the Markov chain model and on the time period.

4.0 TESTS OF THE MODEL

4.1 Parameter Evaluation

Parameters of the precipitation model for first and second order Markov chains (P(W|W), P(W|D), P(W|WW), P(W|WD), P(W|DW), P(W|DD) and λ, for each period) were determined for Crystal Falls (19 years of data). The whole year was divided into 26 14-day periods, with period 1 starting on 1st January each year (we only use periods 10 to 21 to cover the growing season). Maximum likelihood estimates of each parameter were calculated for each period over the 19 years, and are given in Table 1 for the Markov transitions and the exponential amounts model. The exponential had the minimum AIC, compared to the gamma and Weibull functions, and so was used throughout the season.

The daily means and variances of maximum temperature, minimum temperature, and solar radiation were calculated conditional on the wet or dry states of each day (maximum and minimum temperature only for Crystal Falls) and time period. These are plotted in Figures 1-2 for the Martell's Lake site and Crystal Falls NWS.

Table 1. Markov chain transition probabilities (observed) and lambda estimates for the exponential amounts model, for the growing season only[a]

PERIOD	P(W|W)	P(W|D)	Mean Periodic Total Rain (ins)	Exponential Lambda Est.
10	0.476744	0.250000	1.11	0.120
11	0.567308	0.283951	1.57	0.140
12	0.517544	0.375000	1.88	0.155
13	0.486486	0.322581	1.51	0.140
14	0.540000	0.307229	1.58	0.145
15	0.398058	0.349693	1.53	0.150
16	0.455446	0.321212	1.69	0.160
17	0.437500	0.347059	1.71	0.160
18	0.475248	0.327273	1.78	0.165
19	0.590551	0.374101	1.76	0.130
20	0.637097	0.316901	1.79	0.135
21	0.522124	0.352941	1.16	0.950

[a] P(W|W) and P(W|D) are probability of day i being wet given day i-1 was wet and dry respectively, and estimate of lambda was calculated as sum of all rainfall in period k divided by total number of wet days.

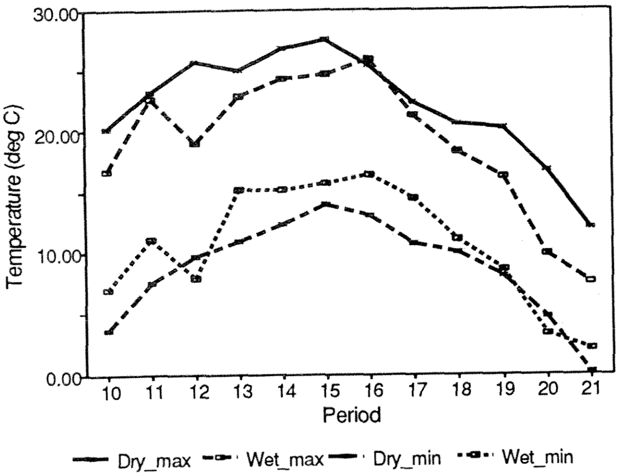

Figure 1. Average maximum and minimum temperature for wet and dry days per period for Martell's Lake Site 2.

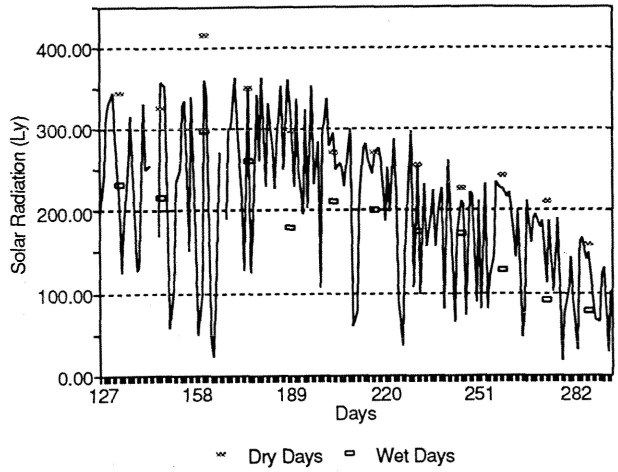

Figure 2. Average incoming solar radiation for wet and dry days per period and 1989 measurements for Martell's Lake Site 2.

Average maximum temperature is higher in general on dry days than on wet days, except when a period is unusually wet or dry. In those cases, during long wet spells, wet maximum and minimum temperatures appear to decrease further (see period 11-12). During dry spells, (e.g.Period 16) the difference is less pronounced, as wet days get warmer than dry days (which is reasonable from day to day casual observation during dry spells, when it gets very hot just before a rainstorm). Later in the growing season, the days are wetter at the study sites (after periods 18-19), and minimum temperature on wet days becomes lower than on dry days. For longer observations at Crystal Falls, average minimum temperatures are always higher for wet days than dry days. Average maximum temperatures on dry days are higher on dry days as long as temperatures are above freezing.

Standardized residual elements for each variable were calculated by time period. This resulted in a new series of residuals for each variable that should be stationary by construction, with a mean of zero and standard deviation of unity. The mean, standard deviation, skewness coefficient, kurtosis coefficients and lagged and cross correlations were computed (using the SPSSPC+ Statistical Package). These are given in Table 2 for the Martell's Lake site, as an example. Maximum and minimum temperature on the same day (lag 0) were strongly correlated. Minimum temperature and solar radiation had mostly negative cross correlation, though of small magnitude (not statistically significant, however, the sample size was very small due to a large number of missing values of solar radiation). Dependency within each variable was examined by calculating lagged serial correlations, which were all high.

The correlations in Table 2 completely define the matrices M_0 and M_1 in the multivariate generating model (equation [16]) for generating residuals of maximum, minimum temperature, and solar radiation.

4.2 Simulation of the Wet/Dry States and Amounts

The data used for estimating the parameters of the precipitation model from Crystal Falls consisted of 19 years of data. We thus, simulated 19 years of data in order to evaluate the model (in practice, many more simulations would be performed). Simulated precipitation is plotted for the first order Markov chain, using the exponential amounts model, in Figure 3. Plots of average observed and simulated transition probabilities are given in Figures 4 for P(W|D) and 5 for P(W|W). There is generally good agreement except for P(W|W). However this would improve with a larger number of simulations.

Apart from the 1st-Order transition probabilities, we test the performance of the model by comparing the observed and simulated frequencies of three and four day sequences of wet and dry days. We do this by looking at 2nd-Order and 3rd-Order transition probabilities. These are P(W|WW), P(W|WD), P(W|WWW), P(W|WWD), P(W|WDW), and P(W|WDD), and are shown in Figures 6a-d. There was, in general, very good agreement.

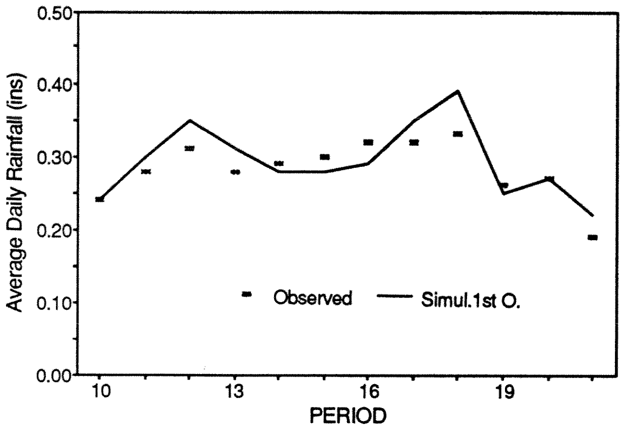

Figure 3. Observed and simulated periodic precipitation for Martell's Lake over the growing season.

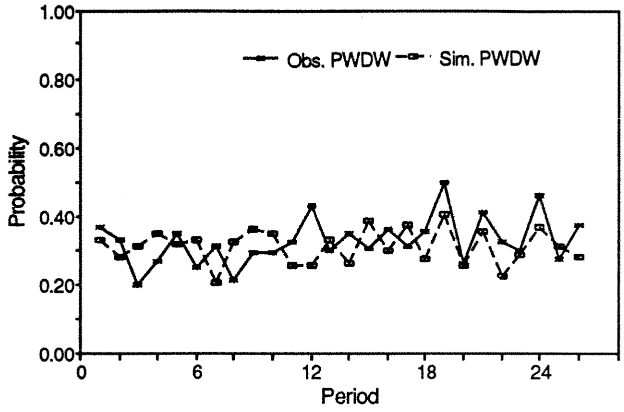

Figure 6a. Probabilities of 2nd-Order (W|DW) sequences, observed and simulated.

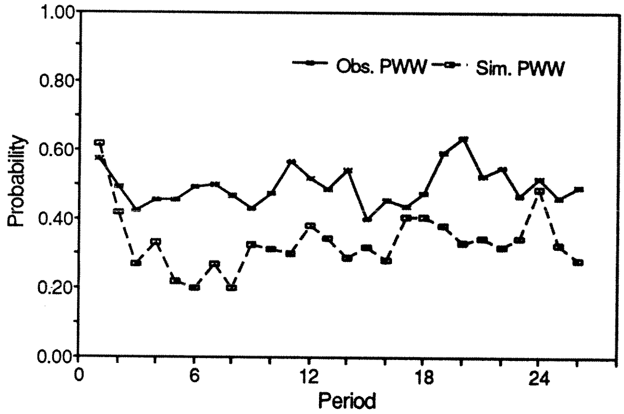

Figure 4. Average observed and simulated 1st-Order Markov transition probabilities (P(W|W)) for all year.

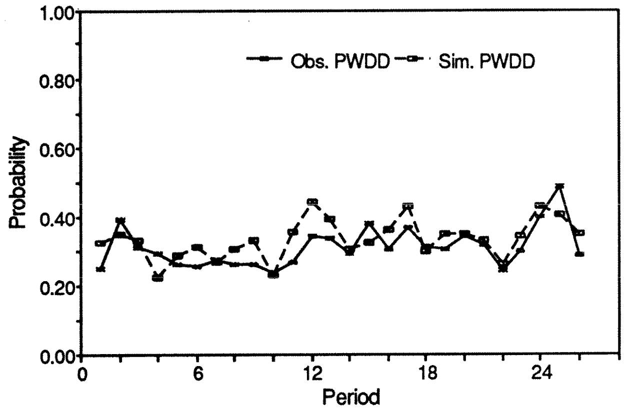

Figure 6b. Probabilities of 2nd-Order (W|DD) sequences, observed and simulated.

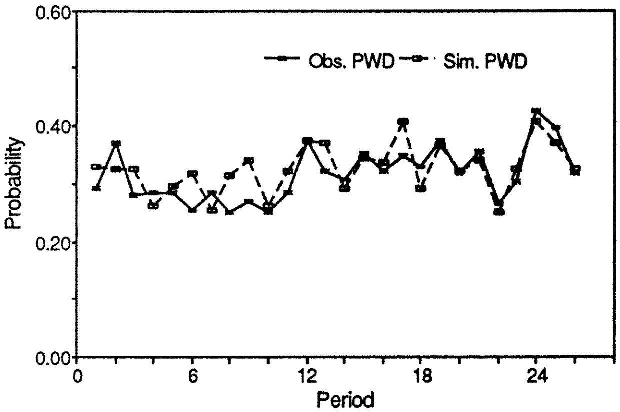

Figure 5. Average observed and simulated 1st-Order Markov transition probabilities (P(W|D)) for all year.

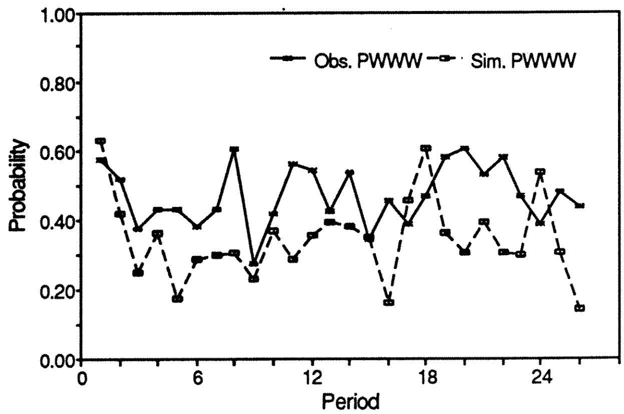

Figure 6c. Probabilities of 2nd-Order (W|WW) sequences, observed and simulated.

Table 2. Mean, standard deviation, and correlations for maximum and minimum temperature, and solar radiation residuals (over the growing season) for Martell's Lake site

	Maximum Temperature (degrees C)	Minimum Temperature (degrees C)	Solar Radiation (Langleys)
Mean Residuals	0.000	0.000	-0.007
Standard Dev.	0.977	0.977	0.966
Lag Serial Correl.	0.5511	0.4819	0.4243

	Lag Cross Correlation[b]		
Variable Pairs	$r_1(j,i)$	$r_0(i,j)$	$r_1(i,j)$
Max.T & Min.T	0.5832	0.6018	0.2563
Max.T & Solar	-0.0570	0.1007	0.0030
Min.T & Solar	0.0449	-0.0497	-0.0219

b $r_k(p,q)$ is the lag cross correlation between variable in p and variable q lagged k times

4.3 Simulation of Maximum and Minimum Temperature, and Solar Radiation

After the Markov chain-exponential model was used to generate precipitation, values of maximum and minimum temperature and solar radiation were simulated by first generating residuals of these three variables using equation (16). Then the daily values were obtained by multiplying the generated residual by the standard deviation and adding the mean, conditioned on the wet or dry status of each day. Data of temperature and solar radiation over five growing seasons were generated for one site as an example (Martell's Lake site), and these were compared with observed data. The means of all three variables for each period of the growing season compared very well with observed mean.

5.0 APPLICATIONS IN CLIMATE CHANGE STUDIES

Richardson(1981) found the correlation structure of temperature and solar radiation to be approximately the same over three sites widespread sites (Temple, Atlanta and Spokane) (see Table 3). Our sites were too similar to allow general speculation. However, if we assume that in fact the correlations are approximately constant for all locations, accommodating climate change scenarios reduces to studying precipitation processes.

Plots of the periodic transition probabilities (Figure 7 and 8) indicate that the transition probabilities do not seem to be related to the total amount of precipitation, except possibly at large amounts for P(W|W), P(W|D) follows its pattern. (These supposed relationships are likely to be very specific to the area where data was collected.) We propose regional tests of these series as follows:

i. Assume constant dependencies, then extrapolate these series for increased or decreased amounts of rainfall.

ii. Estimate the transition probabilities given the amounts for a site within the region of application.

In relating this simulation model to existing weather records, it is possible to work in monthly periods (instead of 14-day periods). Care must be taken to assess stationarity over the longer time interval. This may be particularly important since, for many locations, monthly summaries are the only available historic information.

Many ecological models, of course, do not directly utilize minimum or maximum temperature, solar radiation, or precipitation. Insteaed, summaries of this information in the form of growing degree day sums or moisture (or drought) indices may be required as input into ecological simulation models. Most such variables may be easily derived from the simulated weather conditions provided by this model, though additional site information (such as soil texture) may be needed for some particular indices.

Ecosystems respond to extremes and thus annual averages many not be sufficient for use in ecological models. Linkage of our model with ecological models would allow daily temperature and precipitation to be utilized in investigating ecological effects, even if summaries of daily variables are calculated into heat sums (for example).

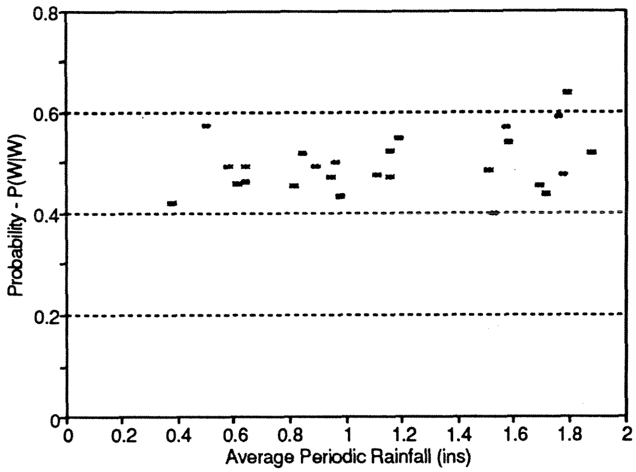

Figure 7. Periodic transition probabilities versus average total periodic rainfall (PW(W|W))

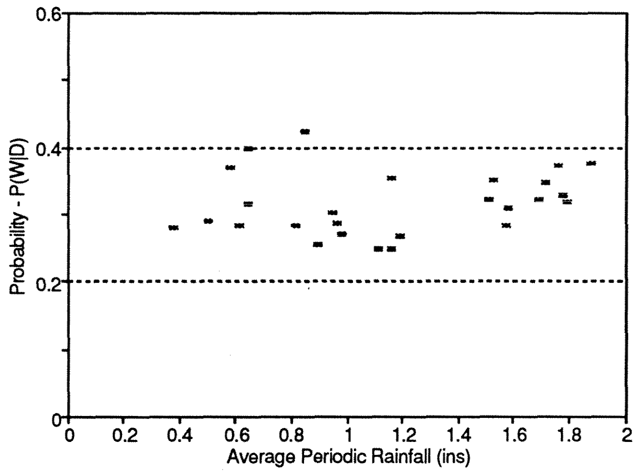

Figure 8. Periodic transition probabilities versus average total periodic rainfall (PW(W|D))

Table 3. Comparison of cross-correlations between residuals of maximum and minimum temperature, and solar radiation from Richardson(1981) with those for Martell's Lake site

Variable Pairs	Lag Cross Correlation[c] $r_1(j,i)$	$r_0(i,j)$	$r_1(i,j)$
	Temple, Texas (Richardson,1981)		
Max.T & Min.T	0.4990	0.6720	0.5770
Max.T & Solar	0.1220	0.3200	0.0900
Min.T & Solar	-0.0800	-0.1530	-0.0600
	Atlanta, Georgia (Richardson,1981)		
Max.T & Min.T	0.5370	0.6870	0.6350
Max.T & Solar	0.0760	0.2350	0.0400
Min.T & Solar	-0.1450	-0.2480	-0.1060
	Spokane, Washington (Richardson,1981)		
Max.T & Min.T	0.5590	0.7320	0.6830
Max.T & Solar	0.1080	0.1920	0.0430
Min.T & Solar	-0.0490	-0.1760	-0.0580
	Martell's Lake Site, Michigan		
Max.T & Min.T	0.5832	0.6018	0.2563
Max.T & Solar	-0.0570	0.1007	0.0030
Min.T & Solar	0.0449	-0.0497	-0.0219

[c] $r_k(p,q)$ is the lag cross correlation between variable in p and variable q lagged k times

6.0 DISCUSSION

A technique for generating daily values of precipitation, maximum temperature, minimum temperature, and solar radiation has been designed and implemented. The basic approach was to generate precipitation indepently of the other three variables, and then condition the other three variables on the wet or dry status of the day. A Markov chain of order one was used to define wet or dry status, and an exponential model was used to describe precipitation amount. A multivariate model was used for maximum temperature, minimum temperature, and solar radiation. Since the latter three variables are conditioned on wet or dry states of a day, the generation of the these states was important in this study. Comparison of simulated precipitation with observations has shown that the Markov chain-exponential model worked well.

The overall objective was to be able to use the simulator in climate related ecological studies. Ways that this can be accomplished have been explored. Other applications are in the calculation of growing degree sums and indices of moisture and drought for use in simulation models of forest tree growth and dynamics.

ACKNOWLEDGEMENTS

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FOREST LANDSCAPE CLIMATE MODELING[1]

Edwin M. Everham III, Katherine B. Wooster, and Charles A.S. Hall.[2]

The temporal and spatial patterns of climate have profound impacts on ecosystem processes. We developed a microclimate simulation model that predicts the values of insolation, temperature, relative humidity, and rainfall as a function of topography. Model predictions match closely with empirical values, with the exception of relative humidity which is consistently low, and rainfall which has not yet been validated.

Keywords: microclimate, climate modeling, simulation modeling, Luquillo Experimental Forest

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INTRODUCTION

Climate is an important factor influencing ecosystem processes. We believe that climate varies significantly over relatively small scales on complex terrains and that this variation has profound impacts on ecosystem properties. We developed a microclimate computer simulation model that predicts insolation, temperature, relative humidity, and rainfall as functions of topography. The model is integrated with a geographical information system for the Luquillo Experimental Forest (LEF). This GIS is a raster system with 30 m by 30 m grid cells holding information on elevation, slope and aspect. Our model is not intended to predict daily weather, but to simulate realistic values, that can be used to drive other models of ecosystem processes.

STUDY AREA

The Caribbean National Forest and LEF are located in the northeast corner of Puerto Rico (Figure 1) The LEF has a history of research that goes back to the 19th century. It has been managed by the US Forest Service since 1917,

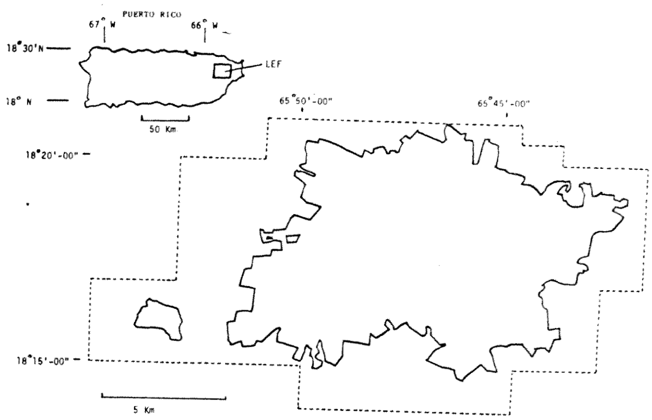

Figure 1 – Luquillo Experimental Forest

1/Presented at the Symposium on Systems Analysis in Forest Resources Conference, Charleston, SC, March 3-7, 1991.

2/Graduate student, Faculty of Environmental Science and Forestry, State Univesity of New York, College of Environmental Science and Forestry; graduate student, Graduate Program in Environmental Studies,SUNY ESF; professor,1 Faculty of EFB, SUNY ESF.

and was officially designated the LEF in 1956. It presently encompasses 11,330 hectares including four principal life zones: subtropical wet forest, lower montane wet forest, subtropical rain forest, and lower montane rain forest. More commonly the forest is viewed in terms of distinct forest ecosystems: tabanuco, colorado, dwarf, and palm (Brown et al. 1983).

The Tabanuco forest is found below 600 m and occupies approximately 70% of the area of LEF. The principal canopy species of this ecosystem is (Dacroydes excelsa Vahl). Colorado forest exists above 600 m, the average cloud condensation level, and occupies about 17% of the forest area. It derives its name from the palo colorado (Cyrilla racemiflora L.). Dwarf Forest, also called elfin or cloud forest, to indicate the short gnarled vegetation or the almost constant cloud cover, occupies approximately 2% of the LEF at ridge lines above 750 m. Palm or palm brake forest occupies 11% of the total forest area, mixed through the colorado and dwarf forest types on steeper slopes with saturated soils. The principal species in the sierra palm (Prestoea montana (Graham) Nichols) (Brown et al. 1983).

The LEF varies from 100 to 1075 m above sea level. In general as the elevation increases, temperature decreases, rainfall and soil moisture increases, community diversity (Little and Woodbury 1976) and canopy height decrease. In addition, we find significant differences in rainfall patterns depending on the region of the forest, defined by the main ridge lines (Hall et al 1990).

Burns (1988) developed GIS files of elevation, slope, and aspect on a 30 m by 30 m scale for the entire forest. This topographic information is used to drive our climate model.

MICROCLIMATE MODEL

TOPOCLIM is a computer simulation model of climate written in FORTRAN, compiled using a Lahey FORTRAN compiler, and runs on a microcomputer. It is designed to predict values of global solar radiation, temperature, relative humidity and rainfall. The relationships were developed principally from a data base compiled by Briscoe (1966) who collected climate data from ten stations at various elevations around the forest.

Solar Radiation

Solar radiation values are given as a flux density of watts per square meter based on the following equation:

GLOBAL SOLAR RADIATION = DIRECT BEAM RADIATION + DIFFUSE RADIATION + REFLECTED RADIATION

Solar radiation is calculated as a function of both slope and aspect and is modified by cloud cover and terrain feature blockage.

Direct Beam Radiation

I = Io * (SIN A' * SIN B * COS A' * COS B * COS (HR + k)

- I - radiation incident upon the surface
- Io - solar constant (1360 W/m^2)
- B - solar declination
- HR - hour angle in degrees
- A' - latitude of equivalent slope
- k - adjustment for apparent longitude of equivalent slope

The cosine law as applied by Gates (1980) calculates direct beam radiation as a function of the cosine of the angle between the direct beam and a normal to the surface. This is influenced by latitude, longitude, time of day, solar declination, slope and aspect. This value is further modified by atmospheric attenuation based on average transmissivity (0.82), stochastic generation of cloud cover, and blockage by adjacent terrain features. Average transmissivity is calculated using data for Odum and Pigeon (1970). Blockage by terrain features is determined through the integration with the GIS elevation file. For each time step, the direction and height of the sun is determined and the model searches along the line of site to the sun for any elevation grid cells that would block the direct beam.

Diffuse Radiation

SLDIF = Io * TAUDIF * (COS(SLOPE/2)**2) * AM

- SLDIF - diffuse radiation on a slope surface
- Io - solar constant
- TAUDIF - transmissivity for diffuse radiation
- SLOPE - slope angle in radians
- ALT - altitude of the sun (optical air màss factor)

Diffuse radiation is calculated assuming an isotropic sky dome and a flat horizon (Gates 1980, Liu and Jorden 1960).

Reflected Radiation

SLREF = Io * REF * TAUREF * ALT * (SIN(SLOPE/2)**2)

SLREF	- reflected radiation on a slope surface
Io	- solar constant
REF	- albedo
TAUREF	- transmissivity for reflected radiation
ALT	- altitude of the sun
SLOPE	- slope angle in radians

Reflected radiation is a function of the slope of the surface, and the albedo of the surrounding surface.

Relative Humidity

VAPPRESS = -0.474 + 1.161 * TMIN

VAPPRESS	- atmospheric water vapor pressure
TMIN	- minimum temperature

RH = 100 * VAPPRESS/SATPRESS

RH	- relative humidity
SATPRESS	- saturation water vapor pressure for given temperature

Atmospheric water vapor pressure is determined by a regression to minimum nighttime temperature (r^2 = 0.87). This water vapor level is assumed to be constant through the day. The relative humidity is then calculated as a change in saturation vapor pressure due to temperature change.

Temperature

TD(HR) = (TMAX-TMIN)*SIN(3.14*HR-(SRS+C))/(ADY+2*A))+TMIN

TN(HR) = TMIN + (TSN-TMIN) * EXP(B * BBN/ANI)

TD(HR)	- day temperature at time HR
TN(HR)	- night temperature at time HR
TMAX	- daily maximum temperature
TMIN	- daily minimum temperature
TSN	- temperature at sunset
ADY	- day length
ANI	- night length
SRS	- time of sunrise
BBN	- number of hours after sunset
A	- lag coefficient for time of maximum temperature after noon
B	- nighttime exponential decay coefficient
C	- lag coefficient for time of minimum temperature with respect to sunrise

Hourly temperature calculations are based on the work of Parton and Logan (1981), involving a modified sine curve for daytime temperatures and an exponential decay function for nighttime temperature. Maximum and minimum are calculated using a regression based on elevation.

Rainfall

NERAIN = 2.6436 * ELEV + 2728.4
NERAIN = 2.6184 * ELEV + 2144.3
SRAIN = 1.8849 * ELEV + 2654.7

NWRAIN	- yearly rainfall in mm for the NW region
NERAIN	- yearly rainfall in mm for the NE region
SRAIN	- yearly rainfall in mm for the S region
ELEV	- elevation

Rainfall is regressed to elevation and general aspect of the forest. An additional 15 weather stations around the forest had rainfall data. All discontinuous station records were normalized to the long-term records at San Juan and Fajardo. All available data were used in the regression analysis, so no validation to independent data sets was possible.

MODEL VALIDATIONS

For Cape San Juan, at 39 m above sea level, the January simulated values for radiation flux match quite closely, with an average difference of 27.3 and a maximum difference of 75.0 (Figure 2)

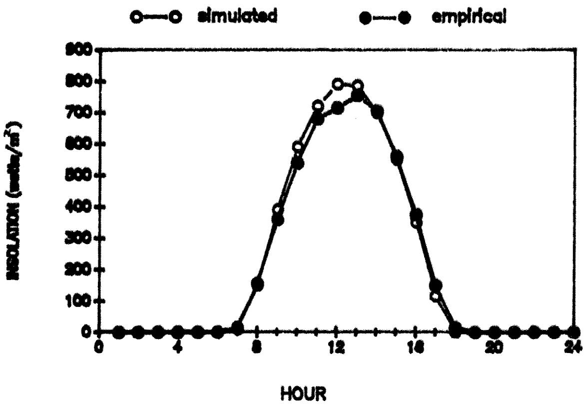

Figure 2 - Insolation for Cape San Juan January

Similar results are found for October at El Yunque, one of the highest points on the forest at 1065 m. The average error here is 39 (maximum 88) (Figure 3).

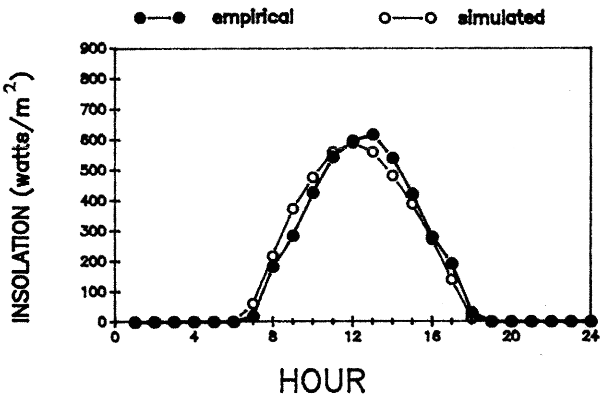

Figure 3 - Insolation for El Yunque October

The relative humidity algorithm assumes that the water vapor pressure is constant. This assumption leads to consistently low levels of relative humidity, with an average absolute error of 5.4 percent and a maximum of 16.3 percent, for Rio Blanco, at 31 m elevation (Figure 4).

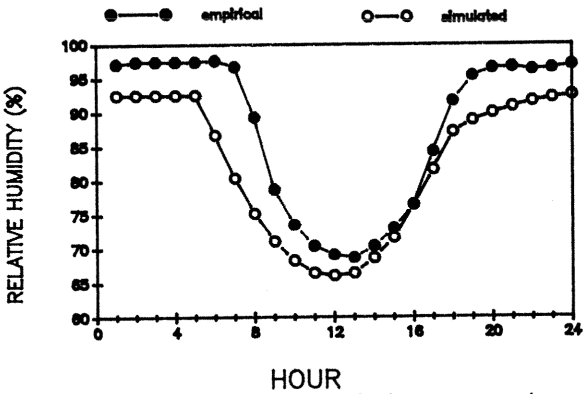

Figure 4 - Relative humidity for Rio Blanco - October

This slight daily error becomes more significant if monthly averages are calculated. This data set came from the Atomic Energy Commission irradiation study (Odum and Pigeon 1970) at 450 m elevation, and is discontinuous, thus the missing values for July and August. The average error is 8.0 percent and the maximum is 13.1 percent (Figure 5).

We reexamined Briscoe's data for daily patterns of total water vapor change and were able to adjust the relative humidity algorithm, based on average hourly changes in water vapor content. Figure 6 shows the new model

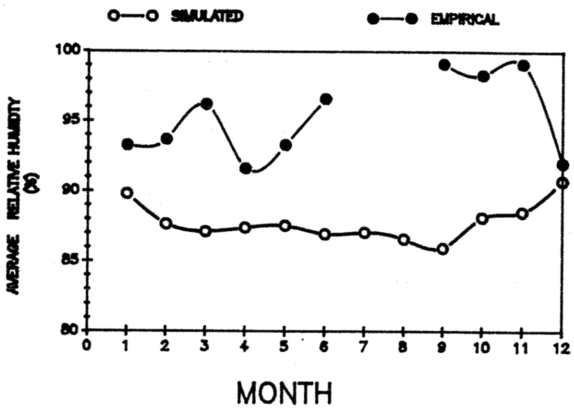

Figure 5 - Relative humidity for El Verde

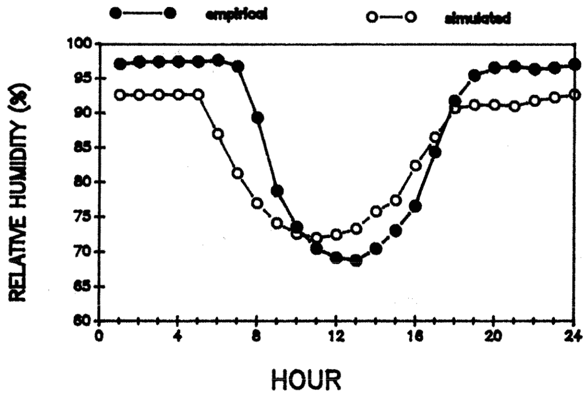

Figure 6 - Relative humidity for Rio Blanco - October. Adjusted for ocean water vapor inputs

run for Rio Blanco. The average absolute difference is now 5.2 percent and the largest difference is 15.5. This obviously does not solve the problem. We will next look a lag times correlated to elevation as the warm air masses from the ocean move up the mountain in the late morning, and attempt to quantify the evapotranspiration inputs to the atmosphere.

The temperature simulations are fairly close for this Sabana 8, at 260, m in August. The average difference here is 0.4 degrees celsius with a maximum of 1.1 degree (Figure 7).

The simulation for El Yunque in September is consistently low. and shows more error, with a maximum of 2.7 degrees difference and an average of 1.3 degrees (Figure 8).

The average monthly values for El Verde are also consistently low, but with only an average error of 0.9 degrees celsius (maximum 1.4) (Figure 9). The low temperature readings for the last two sites may be the result of aspect affects, which are not included currently in our model.

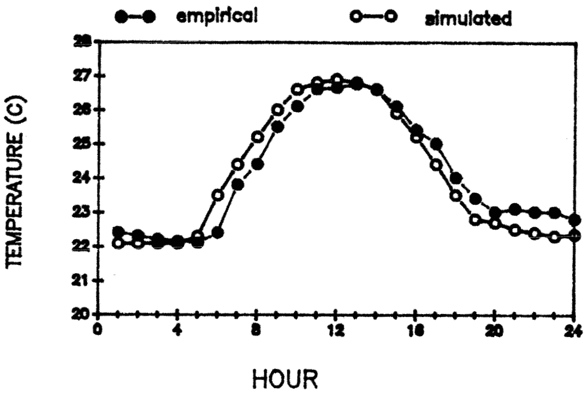

Figure 7 - Temperature for Sabana August

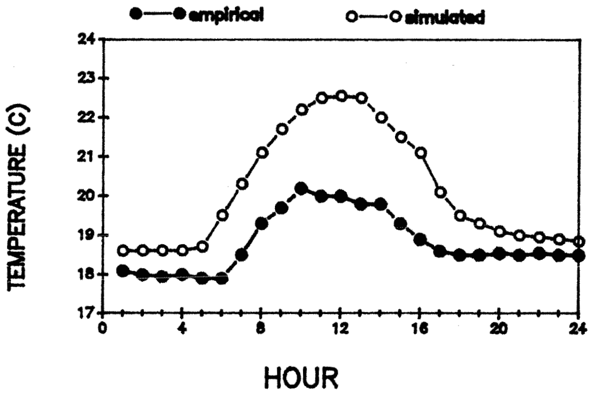

Figure 8 - Temperature for El Yunque September

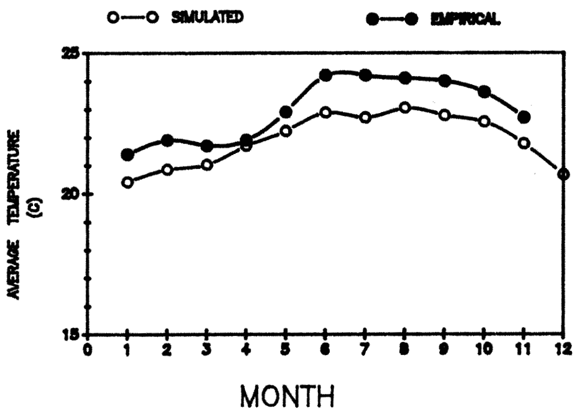

Figure 9 - Temperature for El Verde

CONCLUSIONS

Our model predicts the spatial variation of climate factors reasonably well and indicates the need to consider the affects of terrain on climate. In the future we intent to examine aspect affects on temperature, attempt to refine the relative humidity algorithm, develop gradients of these climate factors down through the canopy of each forest type, and examine the impacts of hurricane disturbance on these gradients.

We think these climate gradients can be used to explain the distribution of forest types in the Luquillo Experimental Forest and will allow us to drive models of forest hydrology, nutrient cycling, and forest growth and recovery in response to hurricane disturbance.

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ANALYSIS OF WOOD PROCUREMENT STRATEGIES:

SUPPLYING MULTIPLE MILLS FROM MULTIPLE SOURCES[1/]

D. Hubert Burger and Mark S. Jamnick[2/]

Abstract.--A linear programming wood procurement and distribution model was developed to analyze a complex wood distribution system. The model can be used to measure trade-offs between the conflicting objectives of minimizing total wood cost and maximizing profit for a woodlands division that is a profit center. The model considers mill requirements, product revenues, and harvest, transportation and wood purchasing costs.

Keywords: transportation, distribution, linear programming, trade-off analysis, profit center.

INTRODUCTION

Wood procurement and distribution decisions are crucial to the success of forest products firms. According to a 1983 estimate, these activities accounted for 55 percent of total Canadian forest management costs (Edwards 1983).

Although these decisions are important to all forest products firms, they are particularly important to large integrated firms that are often organized into mill and woodlands divisions, each of which operates as a cost or profit center. This complicates the wood procurement and distribution decisions because each division may have objectives which conflict with the objectives of other divisions. Furthermore, as the size of forest products firms increases, so does the number of sources of wood, potential harvesting systems and potential destinations and it becomes necessary to use a modeling framework to help develop cost minimizing (or profit maximizing) strategies.

This paper describes a linear programming (LP) model that was developed to analyze the wood procurement and distribution decisions for Scott Maritimes Ltd. (Scott). Although developed specifically for Scott, the model has a general structure and can be used to examine a wide variety of wood procurement and distribution decisions. The model is unique in that it includes a menu driven data editing system combined with a matrix generator, solution method, and report writer that are transparent to the user. The model uses dBASE format files so that data can be easily manipulated outside of the model.

[1/]Presented at the 1991 Symposium on Systems Analysis in Forest Resources, Charleston, SC, March 4-7, 1991.

[2/]Graduate student and Assistant Professor of Forestry, respectfully, Faculty of Forestry, University of New Brunswick, Fredericton, NB.

BACKGROUND

Scott is a forest products firm in Nova Scotia that operates a pulpmill in New Glasgow and a softwood sawmill in Parrsboro. Scott Canadian Timberlands Ltd. (Timberlands) is Scott's woodlands division and is organized into three regions. Timberlands, its three regions, and the two mills all operate as profit centres. Timberlands's profit is the sum of the profits of its regions.

Scott has several sources of wood supply. It owns 1,000,000 acres of fee land, has another 200,000 acres of provincial crown land under long-term lease, and purchases stumpage from private landowners in central and eastern Nova Scotia. Additional sources include wood purchased at roadside from independent contractors, imports from outside of the province, and chips from the Scott sawmill and 38 independent sawmills in the region.

This means that Scott has a large number of choices when deciding where to obtain its wood. Indeed, Scott has so many supply choices that it has traditionally not done any timber harvest scheduling for its own fee land. Harvest blocks were chosen based on regional decisions about what "should" be cut. Even with harvest scheduling (a system is currently being developed) there is a wide choice of blocks that may be harvested in any given period.

In addition to the supply choices, a number of different harvesting methods can be used, each with its own set of costs. The method used to harvest any given block depends on the terrain, tree size, stand density, and the availability or production capacity of each method. In many cases, more than one method can be used to harvest a given block. This increases the number of choices to be considered when making wood procurement decisions.

Timberlands is responsible for supplying all of the wood required by the Scott pulpmill and sawmill. Timberlands also supplies wood to several independent mills, either on a contractual basis or as opportunities occur.

The wood distribution system is complex (Figure 1). Timberlands supplies wood to the various mills either directly (at cost), at a fixed price, or at a variable (market) price. The price depends on the source (fee, Crown, private stumpage, or purchased), the type of wood (sawlogs, pulpwood, or chips), and mill ownership (Scott or independent).

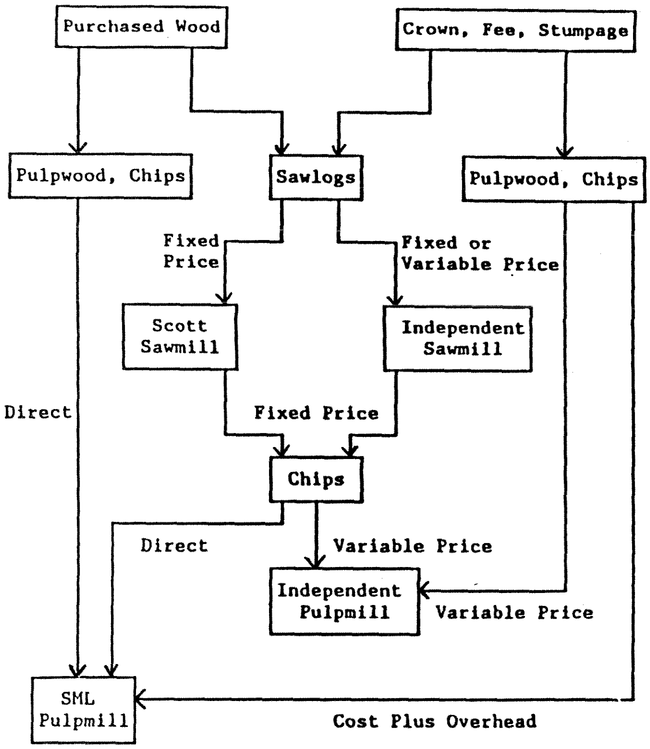

Figure 1. Schematic Of Scott Canadian Timberlands Wood Flows.

Purchased pulpwood and chips are transferred directly to Scott's pulpmill (SML) at cost. Pulpwood and chips from fee land, Crown land, or private stumpage may be sold to SML on a cost-plus-overhead basis or to an independent pulpmill at a variable price.

Sawlogs from all sources may be sold to the Scott sawmill at a fixed price, or to independent sawmills at either fixed or variable prices depending on contractual obligations. Timberlands will not sell any sawlogs without the first right to purchase sawmill chips at a fixed price. Such chips are treated as purchased wood and may be transferred directly to SML at cost or sold to an independent pulpmill at a variable price.

Timberlands's prime goal is to supply wood to SML at the lowest possible cost. However, since it is a profit center, it is also concerned with maximizing its own profit. Thus, Timberlands faces the problem of reconciling these conflicting goals.

While Timberlands may wish to maximize its own profit, it is willing to reduce its profit if it can be demonstrated that overall company profits can be increased. This may happen, for example, if it can supply pulpwood and chips to SML for less than the target average cost set each year.

PROBLEM DEFINITION

Two basic problems have been identified.

The primary problem is to identify the most cost-efficient method of obtaining wood for the Scott pulpmill (SML). This requires two types of decisions. First, given the wood supply sources that are available in any given period (usually a quarter), which sources should be selected and, where appropriate, which harvest method should be used? Second, once those sources have been selected, where should the products be shipped to meet various mill requirements?

The secondary problem is to identify where to send the wood from any particular source so that Timberlands gains the greatest benefit. This problem is a subset of the primary problem. It occurs, for example, when an additional block (harvest or purchase) becomes available.

The primary problem must be solved to meet the objectives of cost minimization for SML and profit maximization for Timberlands. The secondary problem can only be viewed from the perspective of maximizing profit (or minimizing net cost) for Timberlands.

METHODOLOGY

This problem is an extended transportation problem, with harvesting choices added to the shipping choices. The transportation algorithm (Dykstra 1984) cannot be applied in this situation, so a LP formulation is required. LP has been recognized for quite some time as being a useful technique for solving wood procurement problems (Silversides 1963, Winer and Donnelly 1963).

The challenge was to develop a model that would be completely transparent to Timberlands's staff, who have limited knowledge of LP. This means that data must be easy to handle, the mechanics of solving the problem must be hidden from the user, and useful reports must be generated automatically from the solution.

The model is a prototype constructed for one of Timberlands's regions. It was written in Turbo Pascal (Borland International 1988) and performs the following functions.

Enter and Edit Data

A menu system allows data to be entered and edited in a series of tables. Some of the data are copied directly from Scott's forest inventory database to save time and reduce errors associated with data entry. Data are actually stored in a set of dBASE files that are automatically generated by the model. This eliminates the need for the user to worry about file formats and format errors. The dBASE files can also be manipulated by more sophisticated users outside of the model.

A menu allows the user to select one of seven objective functions.

Generate the LP matrix

Once the data has been entered and an objective selected, no further input is required. A matrix generator automatically writes the objective and all of the constraints to a flat file that can be read by the LP software.

The matrix generator first creates a dBASE file containing a list of all of the variables used by the model, including decision variables representing all of the choices, and accounting variables used to track various volumes, costs and revenues. Variable names consist of two key letters that identify the type of variable followed by a number that simply represents its record number (or location) in the file. These variable names are arbitrary, so the file also records their distinguishing attributes.

The matrix generator then writes the objective and constraints by sorting through the list of variable names using the appropriate attributes, and calculating coefficients from the data files.

Solve the LP

HYPER LINDO (Shrage 1989) is used to solve the LP. It takes its input automatically from a batch file containing commands to load the input file, solve the LP, and write the solution to an output file. This eliminates the need for the user to know how to use HYPER LINDO. The solution is saved in a fixed format database file (but not dBASE) with one record for each variable.

Write Reports

The report writer reads the LINDO output file, interprets the variable names using the attributes contained in the file of variable names, performs some final calculations (totals and averages) and produces a series of reports. The reports that are available include:

- List of blocks to be harvested and the harvest method to be used in each block.
- List of product volumes produced in each block and the mills to which they should be shipped.
- List of sawmill chips shipped to each pulpmill.
- Summaries of harvest, transportation, or total costs, by product and source, for the Scott pulpmill or for Timberlands.
- Summary of revenues received by Timberlands from each mill.
- Summary of total and average wood cost for the Scott pulpmill.
- Summary of total and average revenue, wood cost and profit for Timberlands.

DATA

The model is data-intensive, but coupling the matrix generator with the data editing menus eliminates the need for the user to calculate the coefficients and manually create the LP constraints. The model has a general structure so that it can be used by a wide range of users.

Mill Information

The user must supply some general information about each mill: its type (sawmill or pulpmill), its name, and a numeric code. The model uses this information to set up a number of data files.

The minimum and maximum roundwood and chip requirements for each pulpmill must be specified by softwood (Sw) and hardwood (Hw).

The minimum and maximum softwood sawlog requirements must be specified for each sawmill by log type - tree length (TL) or random length (RL). The minimum requirement is the amount that Timberlands has agreed to supply to the mill and the maximum amount is the total capacity of the sawmill.

The prices that each sawmill will pay for sawlogs must be specified by log type (TL or RL) and source (Crown, Fee, Stumpage or Purchase).

The prices that Timberlands pays for sawmill chips from each sawmill must be specified.

The minimum and maximum amount of chips to be purchased from each sawmill must be specified. The minimum is the amount that Timberlands has agreed to purchase from the sawmill and the maximum is total amount that the sawmill can produce.

Harvesting Information

Each harvest method must be defined. A harvest method usually refers to a particular equipment combination. An example of a harvest method is: manual felling, skidding of full trees, and mechanical delimbing at roadside. Each method has a number of components, one for each product produced. Current products include: Sw TL and RL sawlogs; Sw TL and RL pulpwood; Hw RL pulpwood; and Sw and Hw chips. Components for the example harvest method would be Sw TL sawlogs, Sw TL pulpwood, and Hw RL pulpwood.

The total production capacity must be specified for each method. This is the total amount of wood that can be processed by each method for the period being studied.

Each product component in each method has its own fixed cost, which must be specified. Each component may also have a variable cost. Timberlands uses variable costs for mechanical felling or mechanical delimbing operations, where cost depends on the tree size and density of the block. The presence of a variable cost must be indicated for each component. Variable costs are supplied separately. If a component has a variable cost, then the model will use the code supplied by the user in the Forest Inventory Information section below to determine the appropriate variable cost.

Utilization factors are specified for each product component. For example, if a chipping component will recover 110 percent of the indicated inventory volume, then a utilization factor of 1.10 is specified.

Components from different harvest methods can be combined into a harvest option. For example, one harvest option may use the Sw TL sawlog and Sw TL pulpwood components from a manual felling and skidding operation in conjunction with the Hw chip component of a chipping operation. The use of harvesting options provides complete flexibility in designing harvest operations. All harvest options must be defined by their constituent components.

Stumpage Rates

Stumpage rates are specified by product (Sw or Hw; sawlogs, pulpwood, or chips) for each source (Crown, Freehold, Stumpage or Purchase). Stumpage rates can be specified individually for each stumpage block and purchase block. Stumpage rates for purchase blocks are actually the purchase prices.

Transportation Information

The distance from each compartment to each mill and the distance from each sawmill to each pulpmill must be specified.

Trucking rates must be specified and may have fixed and variable components. The fixed component is used for truck loading and unloading and the variable component is applied to the distance travelled. Scott has two sets of rates - one for sawmill chips which travel exclusively on paved roads, and another for all other products which travel on a mixture of bush and paved roads.

Forest Inventory Information

This information is required for each block, including wood purchased at roadside. The basic information is copied directly from Scott's forest inventory database and includes: block and compartment identification numbers; ownership or source (Crown, Fee, Stumpage or Purchase); and total volume of softwood sawlogs, softwood pulpwood, and hardwood pulpwood in the block.

The user must add the following items to the basic information for each block: one or two harvest option numbers; the codes for mechanical harvesting and delimbing, where appropriate; and the maximum proportion of the block to be harvested.

The user may optionally specify if the block must be harvested, for example, if it is being carried over from a previous period.

Miscellaneous

Timberlands's allowable markup for wood sold to SML must be specified by source (Crown, Fee, Stumpage or Purchase). The markup is used to cover overhead costs for any wood that is not transferred directly to SML at cost.

In addition, a minimum and maximum harvest level for each source, a minimum profit level for Timberlands, and a target average wood cost for SML may be specified.

STRUCTURE OF THE LINEAR PROGRAM

Objectives

A common objective for a mill is to minimize total wood cost. However, this can cause problems in a LP model because one way to achieve minimum total wood cost is by simply reducing the total volume of wood harvested or purchased. This objective therefore tends to produce solutions that just satisfy minimum volume requirements.

A more appropriate objective is to minimize average wood cost, which is simply the ratio of total cost to total volume:

$$\text{MIN} \left[\frac{\text{Actual Total Cost}}{\text{Total Volume}} \right] \qquad (1)$$

This objective allows solutions with higher total costs and total volumes as long as the ratio remains unchanged, thus avoiding the problems associated with minimizing total cost.

However, Total Volume is a variable whose value depends on the outcome of the model, so this objective function violates the assumption of linearity required in LP. When average cost is defined this way, it cannot be used in an LP model.

The solution to this problem involves using a target for average wood cost for the mill. Let T equal the target average cost, for example in

$/tonne. Since T is a constant, it can be subtracted from the objective function in (1). This operation performs a simple translation without changing its slope.

$$\text{MIN} \left[\frac{\text{Actual Total Cost}}{\text{Total Volume}} - T \right] \qquad (2)$$

Multiplying the expression in (2) by Actual Total Volume gives:

$$\text{MIN [Actual Total Cost - (T)(Total Volume)]} \qquad (3)$$

Multiplication changes the slope of the objective function and Actual Average Cost is lost as a component, but now it is a linear function and can be used in an LP model.

The second term in (3) can be called the Target Total Cost. For any objective function Z, MIN (Z) equals MAX (-Z), so (3) becomes:

$$\text{MAX (Target Total Cost - Actual Total Cost)} \qquad (4)$$

The objective in (4) causes an LP model to maximize the difference between Target Total Cost and Actual Total Cost. Focussing on the difference between these two Total Costs equalizes and effectively removes the impact of Actual Total Volume. This has the same effect as an objective to minimize average cost. Thus, the objective in (4), which is linear, can replace the objective in (1), which is non-linear, even though the two objectives produce different objective function values.

The objective function value for (4) represents the total amount of money saved compared with the Target Total Cost. Actual average cost can be calculated from the solution by dividing Actual Total Cost by Total Volume, both of which can be calculated by the model.

The objective in (4) will also attempt to ensure that Actual Total Cost is less than Target Total Cost. This objective will produce a positive difference when Target is greater than Actual and a negative difference when Target is less than Actual, so maximizing will naturally move the optimal solution toward a positive difference. A negative difference will still be obtained if the target average cost (the constant T) is set too low, but this does not change the overall effect of minimizing average cost.

This approach to minimizing average cost is used for one of the objectives in the Scott model, which includes the following objectives:

- Minimize SML's total wood cost
- Minimize SML's average wood cost
- Maximize Timberlands's profit
- Maximize Crown harvest
- Minimize Crown harvest
- Maximize Freehold harvest
- Minimize Freehold harvest

The first three objectives are the most important. The last four objectives are available for testing the impact on wood costs of harvest requirements by source.

Constraints

The matrix generator automatically writes the selected objective and all of the constraints that form the basic model:

Objective

subject to:

$$\sum_h (B_{ih}) \le b_i \quad \text{or} \quad \sum_h (B_{ih}) = b_i \quad \text{for each block } i \qquad (1)$$

$$\sum_j (V_{phij}) - Y_{phi} \cdot B_{ih} = 0 \quad \text{for each product } p\text{, harvest option } h\text{, and block } i \qquad (2)$$

$$\sum_p \sum_i \sum_j (V_{phij}) \le Q_k \quad \text{for each harvest method } k \qquad (3)$$

$$\sum_h \sum_i (V_{phij}) + \sum_m (SC_{mj}) \ge N_{pjn} \qquad (4)$$

and

$$\sum_h \sum_i (V_{phij}) + \sum_m (SC_{mj}) \le N_{pjx} \qquad (5)$$

for each mill j and product p (or group of products p for a pulpmill)

$$SC_{mj} \ge X_{mn} \quad \text{for each sawmill } m \text{ where } j = SML \qquad (6)$$

$$\sum_j (SC_{mj}) \le X_{mx} \quad \text{for each sawmill } m \qquad (7)$$

$$\sum_p \sum_h \sum_i \sum_j (V_{phij}) \ge H_{sn} \qquad (8)$$

and

$$\sum_p \sum_h \sum_i \sum_j (V_{phij}) \le H_{sx} \quad \text{for each source } s \qquad (9)$$

where:

B_{ih} is the proportion of harvest block i harvested using harvest option h (purchase blocks are treated as being harvest blocks)

b_i is the proportion of the block that is available.

V_{phij} is the volume of product p harvested using option h in block i and shipped to mill j.

Y_{phi} is the total yield of product p produced by harvest option h in block i.

Q_k is the capacity of harvest method k, and k is determined from the specific product component of harvest option h.

SC_{mj} is the volume of softwood chips shipped from sawmill m to pulpmill j.

N_{pjn} is the minimum and N_{pjx} is the maximum mill requirement for product p and mill j.

X_{mn} as the minimum amount of chips to be shipped from each sawmill m to SML.

X_{mx} is the maximum chip production capacity for sawmill m.
H_{sn} is the minimum and H_{sx} is the maximum amount to be harvested from source s, where s is an attribute of block i.

Constraint set (1) states that the total amount of a block that is harvested must be less than bi, or equal to bi if the block must be harvested. If the entire block can be harvested, then bi = 1.

Constraint set (2) provides the link between the block proportions and the volumes shipped. If a block is harvested, then all of the products from the block must be shipped. This prevents cutting particular products from a block because it is close to a particular type of mill.

Constraint set (3) states that the total volume harvested using a specific harvest method must be less than the total production capacity for that method.

Constraint sets (4) and (5) set the minimum and maximum mill requirements.

Constraint set (6) sets the minimum amount of chips to be shipped from each sawmill to SML.

Constraint set (7) sets the maximum amount of chips that can be shipped from each sawmill.

Constraint sets (8) and (9) set the maximum harvest level by source.

A number of additional rows calculate values for accounting variables that are used in generating the reports. These variables include: volumes received by each mill by product and source; total volume harvested or purchased by source; harvest costs and transportation costs by product and source; total wood costs for SML and for Timberlands; and revenues for Timberlands.

The matrix generator automatically adds optional constraints to the basic model depending on which objective was selected. These constraints are:

$$\sum_p \sum_s (T \cdot M_{psj}) - SMLCOST \geq 0 \quad \text{where } j = \text{SML only} \qquad (10)$$

$$TREV - TCOST \geq Y \qquad (11)$$

Constraint (10) ensures that the actual average wood cost for SML is less than T, the target average cost. It is used when the primary problem is being solved and the objective is other than minimizing total or average wood cost for SML. Since the actual average cost depends on total volume, which is variable, the constraint is phrased in terms of total costs.

Constraint (11) ensures that Timberlands's profit is greater than some target amount. It is used when the primary problem is being solved and the objective is other than maximizing Timberlands's profit.

For a problem consisting of 10 mills and 80 blocks, a matrix is generated with approximately 2800 to 3200 variables and 1200 to 1400 constraints, depending on the number of harvest blocks that have a second harvest option.

APPLICATION OF THE MODEL

The model can be used to solve the two basic problems previously described. The LP solution indicates the wood sources to select, which harvest systems to use in each harvest block, and where to ship all of the volumes to meet the selected objective. The reports give detailed information on harvest, transportation, and total costs by product and source.

It is expected that significant cost savings will be realized by using this model compared with the current manual method. In a study using mixed integer programming to plan harvest and transportation activities, Walker and Preiss (1988) found that delivered wood costs could be reduced by $1 to $4 per cubic meter, compared with manual methods.

The problem of reconciling the two objectives of minimizing SML total wood cost and maximizing Timberlands's profit can be handled by setting one of them as the objective and using the other as a con- straint. For example, cost minimization can be the objective subject to a minimum profit level. Different profit levels can then be tested for their effect on total cost. The user can choose the solution that is most acceptable.

The other major use of the model is as a simulation tool to test the impact of a variety of factors on any objective.

The model can determine the impact of varying the minimum volume of logs supplied to, or the minimum volume of chips purchased from, any particular sawmill. This could indicate the desirability of continuing to do business with that sawmill. The results could be used to negotiate new amounts for log supply agreements and for chip purchase agreements.

The impact of changes in any of the costs or prices can be evaluated. This could again be used when negotiating with sawmills. It can also be used to evaluate the impact of increases in the cost of trucking or harvesting.

The effect of maximum or minimum harvest requirements by source can be determined (for example, giving up the Crown lease, or setting a ceiling on Purchase wood). This helps to identify which sources can provide the cheapest wood.

The change in wood cost caused by increasing the production capacity for a harvest method could assist in making equipment buying decisions. If the annual cost of increasing the capacity is less than the savings in total annual wood cost, then the equipment is worth buying.

This model is a prototype intended for use by Timberlands in each of its regions. Since each region is only concerned with wood sources and mills within its boundaries, opportunities may be missed to reduce costs or increase revenues by shipping wood across regional boundaries. The model could therefore be used in Timberlands's main office to evaluate the effect of regional boundaries and to realize further cost savings.

SUMMARY

A linear programming model was developed to examine wood procurement strategies for Scott Maritimes Ltd. The model allows company staff to enter and edit data, generate an LP matrix, solve the problem, and generate reports, without requiring any knowledge of LP. The model allows analysis of the trade-offs between SML's total wood cost and Timberlands's profit. The model can also be used as a simulation tool to analyze the impact of changing any of the inputs on costs and revenues.

This model is a tool for analyzing short-term wood procurement strategies. Using it to minimize wood cost in the short-term will always produce solutions that harvest the cheapest and closest wood. It has no mechanism for dealing with long-term wood cost. Further research is required to link this kind of short-term planning with harvest scheduling in order to minimize wood costs over the long term.solutions that harvest the cheapest and closest wood. It has no mechanism for dealing with longterm wood cost. Further research is required to link this kind of short-term planning with harvest scheduling in order to minimize wood costs over the long term.

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MULTI-LEVEL HARVEST PLANNING AND LOG MERCHANDISING USING GOAL-PROGRAMMING[1/]

Andre Laroze & Brian Greber[2/]

Abstract.--A multi-level planning model was developed to help define harvest plans intended to maximize a company's net present income, based on the factors that control the generation and merchandising of the logs obtained from harvesting forest stands. The solution-method proposed considers a hierarchical structure based on 3 decision levels: **Strategic:** Strategic plans define an indicative harvesting plan for the next 5 years, based on the actual state of the available stands, the forecasted demands for the different markets and a 2 rotation period lookahead at harvest potentials. **Tactical:** Tactical plans define a more detailed harvesting schedule, based on the plan proposed in the strategic level for the first 2 years of the planning horizon. The tactical plan will permit a more precise evaluation of the activities and investments required to harvest during this period (e.g., stand acquisition, road construction and machinery selection). **Operational:** Operational plans define the current season's (summer or winter) stand cutting sequence and the merchandising guidelines for those stands. The decision levels are formulated using a sequential goal-programming model.

INTRODUCTION

For many Chilean forest companies, Monterey pine (Pinus radiata, D. Don) log exports constitute a significant end-use for harvested trees. For these companies, the production management policy is characterized by harvesting stands to obtain logs for export markets and allocating residual supplies to domestic sawmills' and pulpmills' demands. Thus, their problem of harvest planning and log allocation consists of defining a "production plan" that will maximize the company's present net income, considering the different factors that control the yield and the merchandising of the logs produced.

For Forestal Chile S.A., a Chilean industrial private forest owner, markets are characterized by their log-specifications: a typical market requires 3 to 5 different types of logs (defined by their length, minimum end-diameter and quality) that are subjected to overall production restrictions such as volumetric proportions and minimum mean end-diameter of all logs produced. Value paid per volume unit and measurement rules will vary by markets. Also the yield and revenue a stand can generate for a given market will vary through time (depending basically on its height-diameter distribution). Production cost varies from stand to stand in relation to their accessibility (i.e., road types), distance to the markets (i.e., mills or ports), and terrain conditions.

The inherent complexity related to the definition of an efficient production-plan makes a log production-and-allocation (LPA) model very helpful to orient the optimal use of available mature stands in a dynamic planning process. Such a model should help define strategic goals (e.g., the cutting budget), tactical requirements (e.g., stand acquisition and road construction) and operational activities (e.g., specify stand harvest sequencing). It also must be able to handle the complexity of a continuously evolving land ownership and allow for changing markets.

Forestal Chile recognized a need to have its LPA model resemble, to some extent, the decision-making process being used at present. The reasons were (a) to incorporate professional expertise of end-users into solutions proposed by the model, and (b) to provide a smooth transition in the decision-making process in order to ensure that the model will be accepted by end-users. It was also recognized that for real-life applications the LPA model will require a decision support system (DSS) in order to give end-users high

[1/]This paper is based on a project developed for Forestal Chile S.A., in 1988, by Andre Laroze (former Head of Forestal Chile's Systems Department) and Peter Backhouse (Associate Professor, Department of Industrial Engineering, University of Concepcion, Chile).

[2/]The authors are Graduate Research Assistant and Assistant Professor, Department of Forest Resources, Oregon State University.

flexibility to define and analyze different scenarios. For this company such DSS will have to be integrated with existing software available on a multi-station network (i.e., geographic information system, growth and yield simulator, and harvesting-cost system); thus, imposing a model designed to be solved by microcomputer-based software.

Subjected to these considerations, a LPA model suitable for medium-run and short-run analyses was developed for Forestal Chile. The model is based on a hierarchical approach where each level is defined in a goal-programming formulation. Its purpose is to aid in defining production plans that lead to maximizing the company's net present income, considering different aspects related to stand harvesting and log trading.

DECISION-MAKING PROCESS

At present, Forestal Chile's harvesting plans are the result of non-systemized operative analyses made every year based on the actual state of available stands, expected demands and prices, and personal judgments of those evaluating different harvesting options. The decision-making process can be represented by the following procedures:

Collection of Basic Information

The basic information used in defining annual harvest plans includes:

a. Estimated values for demand levels and prices obtained from forecast analyses made every year for all potential markets.

b. Data describing the actual state of available mature stands. The data are retrieved from a GIS and consist of:

Yield variables: Stand area and stand attributes (e.g., age, dominant height, basal area, and stems per hectare). These attributes determine a stand's yield for each market at any specified time. Stand parameters are projected through time with a growth and yield model.

Harvest cost variables: Topography, accessibility and location of available stands. A specially designed system estimates the harvesting cost for a specific stand based on these variables. A stand's accessibility is determined by its limitations for transporting logs: If only bare-land roads access the stand, log transportation is restricted to spring and summer (summer accessibility); winter accessibility requires the existence of a pavement or rubble road accessing the stand to permit transportation of logs during the rainy season (fall and winter).

Strategic Planning: Definition of Cutting Budget

Based on the preceding information, the net present value for each stand is estimated considering different markets and harvest periods. Then the cutting budget is established using a trial-and-error process, where allowable cuts consider not only the aggregate harvest levels, but also the allocation of logs to the various markets at different periods. The goal is to optimize the company's net present income for a 5 year moving horizon (predicted demands and prices are not considered sufficiently reliable for longer projections).

Defining the cutting budget is considered strategic, and the senior manager and his staff get directly involved in this decision-making stage: They consider several different scenarios, and priorities for supplying different markets are defined. Priorities are a function of (a) the degree of interest in servicing minimum captive markets by providing for at least some level of demand, (b) emphasis for capitalizing on favorable short term demands, and (c) the expected behavior of specified markets with respect to future demands and prices.

Tactical Planning: Definition of Capital Investments

To meet the cutting budget for any harvest plan investments will be required to provide productive infrastructure. For Forestal Chile, these investments typically consist of (a) upgrading roads to enable the transport of logs from the stands to their destination during the winter season (bare ground roads converted to rubble roads), and (b) stand acquisition to support cut levels higher than those realizable with current company lands. For the harvesting contractors, these investments correspond to machinery acquisition for efficient harvesting and log transportation. (To stimulate efficiency, the company assists its contractors with machinery-investment credits subjected to harvesting contracts and achievement of technical requirements.)

Both Forestal Chile and the contractors thus require a precise definition of the stands to be harvested over at least the next two years. So at this stage of decision-making a two year harvest plan is drafted along with a capital investment plan. This implies a detailed review of the original cutting budget by the Production Division for the first two years of the planning horizon: a time interval considered reliable with respect to estimated demands and actual state of the company's land-ownership. The objective is to provide an adjusted harvesting plan that minimizes investment risks (in practice this means to minimize investments).

Operational Planning: Definition of a Harvesting Schedule

Near the beginning of the next harvesting season (summer or winter), the Harvest Department receives a list of monthly orders for shipments of logs to export markets. The list specifies each vessel and their expected arrival/departure times and the volume to be carried to a specific market.

The shipments list plus the information of stands selected to be cut in that season in the harvesting plan are used by the Harvest Department to prepare an operational harvesting schedule. The schedule defines the area of each stand that will be allocated to each market on a monthly basis. Inventory analysis is also considered.

Information related to the volume that a stand will produce to a given market and the shipments' characteristics are both stochastic. This implies that actual production data must be traced with a harvesting control system. Near the end of each month, this system provides reports that are used to revise the harvest schedule and a new plan is defined.

A similar procedure is applied with respect to monthly orders received for domestic sawmills and pulpmills.

This operational harvesting schedule constitutes the reference basis for planning the activities required to actually realize the harvesting and log allocation process.

Decision-Making Efficiency:

The efficiency of this decision-making process relies on factors related to "professional expertise and skills" and "common sense". Furthermore, this process can only consider a limited number of alternatives, a restricted planning horizon, and a small degree of detail.

In order to expand the scope of decision-making and to provide integration between decision-making levels, a mathematical programming based LPA model was developed. This model is described in the following section.

MODEL DESCRIPTION

In order to assist the decision procedure related to harvest planning and log allocation a solution method was designed that considers a hierarchical scheme based on 3 decision levels currently recognized in the company.

Strategic Planning

The primary objective of strategic planning is to define the cutting budget that specifies the outputs that the company is able to supply to each specified market over the planning horizon. Due to the high uncertainty implicit in forecasting demand levels in a long time horizon, market analysis is only considered for a 5 year interval with two harvesting seasons per year: summer and winter. The need for segregating summer and winter harvest seasons is determined by stands' accessibility (a major factor to be considered when defining harvesting schedules).

For a longer planning horizon (2 rotations) a different model, called OFERTA, is used to define non-decreasing long-term yield sustainability. OFERTA defines the available stands to be harvested during the next 5 years.

Strategic plans give an "indicative" cutting budget that defines the area of each "aggregated-stand" that should be cut for the specified markets within each season. This cutting budget permits estimation of the required investments for road construction and other production infrastructure.

To reduce the number of decision-variables and constraints, and to orient solutions proposed by the model, stands are grouped into "stand aggregation units". These aggregated-stands are established using stratification criteria such as: age, site index and accessibility. The area assigned to each aggregated-stand corresponds to the sum of the individual stands within it. The volume per product type and net present value considered for each unit area of an aggregated-stand is a weighted average of the respective stand values. The weighting factor corresponds to the relative area of each stand in relation to the aggregated-stand area.

Strategic plans are designed to be revised in the following situations: (a) at the end of each year, (b) when there are significant stand additions or losses, and (c) when structural changes occur in market demands and/or prices.

Tactical Planning

The purpose of tactical planning is to define, with greater detail than in the strategic level, the harvest outline for the first 2 years of the planning horizon and the required capital investments over the same period. In this stage, the cutting budget proposed by the strategic level is revised for the first 4 seasons in relation to: (a) individual stands selected to be harvested in this sub-horizon, (b) actual output levels, and (c) harvest-timing within the sub-horizon in order to meet spatial-distribution externalities that were not considered in the strategic analysis.

In this hierarchical level, aggregated-stands that were proposed to be harvested by the strategic plan are segregated into their original stands. Nevertheless, it may be convenient to maintain certain stands integrated in re-defined aggregated-stands due to associated externalities (e.g., small stands and common road construction costs).

The harvest schedule defined by tactical plans will permit a more precise analysis of activities and investments required to perform the production program (e.g., stand acquisition, road implementation, machinery selection, and contractor engagement). The reduction of the problem size at this stage allows consideration of two kinds of demands per market and season: certain demand (already contracted volumes) and uncertain demand (based on forecasting analysis).

Tactical planning is considered to be re-evaluated periodically near to the end of each season in order to analyze the effect of the current period harvest on the future. Also, by definition, tactical plans shall be re-defined each time strategic plans are modified.

Operational Planning

The objective of an operational plan is to define the harvest schedule for the current season of the planning horizon. Based on the cutting budget suggested by tactical plans, a more precise schedule and allocation can be defined as the result of being able to segregate the season's markets demand into 6 monthly periods.

For defining operational plans it is assumed that (a) demand levels per market are real, (b) required stands are available and ready for harvesting and (c) required productive infrastructure is available (e.g., roads and machinery).

The operational plans consist of schedules that define the sequence and hectares of each stand that will be harvested for each market. This information represents the basic data required by the other kinds of operational-models related to machinery allocation and transportation.

Operational plans should be revised at the end of each month, in order to maintain updated data that will determine the harvesting schedule for the remainder of the current season.

Practical Considerations

To meet log specifications for a particular market, considering on-site bucking, harvesting crews must concentrate on producing logs for only one market at a specific time: For this reason a given area is allocated to produce for only one market. In addition to capitalizing on harvesters' expertise to maximize resource utilization (i.e., optimal bucking subject to market constraints), this helps to control the achievement of production requirements using a harvesting-control system.

The company trades its logs in several markets but, due to common features and in order to simplify the problem, only 5 generic markets are considered for all decision levels: 3 export markets (namely Japan, Korea and China), domestic sawmills, and domestic pulpmills.

MODEL FORMULATION

Strategic and Tactical Levels

Strategic and tactical decisions levels are characterized by a common goal-programming model. The formulation of such model is given next:

Objective function:

Maximize $\Sigma_i^N \Sigma_j^5 \Sigma_t^T NPV_{ijt} * X_{ijt} - \Sigma_j^5 \Sigma_t^T PV_{jt}^- * Y_{jt}^- - \Sigma_j^5 \Sigma_t^T PV_{jt}^+ * Y_{jt}^+ - \Sigma_t^T PC_t^+ * H_t^+$

Subject to:

Export markets' demand: $\forall_t$

$\Sigma_i^N V_{ijt(1)} * X_{ijt} + Y_{jt}^- - Y_{jt}^+ = D_{jt}$ *[j = 1, 2, 3]*

Domestic sawmills' demand: $\forall_t$

$\Sigma_i^N V_{i4t(2)} * X_{i4t} + \Sigma_i^N \Sigma_j^3 V_{ijt(2)} * X_{ijt} + \Sigma_j^3 K_{j(2)} * Y_{jt}^- + Y_{4t}^- - Y_{4t}^+ = D_{4t}$

Domestic pulpmills' demand: $\forall_t$

$\Sigma_i^N V_{i5t(3)} * X_{i5t} + \Sigma_i^N \Sigma_j^4 V_{ijt(3)} * X_{ijt} + \Sigma_j^4 K_{j(3)} * Y_{jt}^- + Y_{5t}^- - Y_{5t}^+ = D_{5t}$

Budget constraints: $\forall_t$

$\Sigma_i^N \Sigma_j^5 C_{ijt} * X_{ijt} + H_t^- - H_t^+ = M_t$

Area constraints: $\forall_t$

$\Sigma_i^N \Sigma_t^T X_{ijt} + R_i = A_i$

Operational Level

For operational planning the following model was defined:

Objective function:

Maximize $\Sigma_i^N \Sigma_j^5 \Sigma_t^T NPV_{ijt} * X_{ijt} - \Sigma_j^5 \Sigma_t^T PI_{jt} * I_{jt}$

Subject to:

Export demands: $\forall_t$

$\Sigma_i^N V_{ijt(1)} * X_{ijt} + I_{jt-1} - I_{jt} = D_{jt}$ *[j = 1, 2, 3]*

Domestic demands: $\forall_t$

$\Sigma_i^N V_{ijt(k)} * X_{ijt} + \Sigma_i^N \Sigma_h^{k+1} V_{iht(k)} * X_{iht} + I_{jt-1} - I_{jt} = D_{jt}$ *[j = 4, 5; k = 2, 3]*

Inventory capacity: $\forall_t$

$\Sigma_j^5 I_{jt} \le S_t$

Area constraints: $\forall_t$

$\Sigma_i^N \Sigma_t^T X_{ijt} + R_i = A_i$

Note: *Σ_n^N stands for $\sum_{n=1}^{N}$*

Nomenclature:

Sub-index

i : Stands. (i = 1, ..., N) *[N: Depends on decision level]*

j : Markets. (j = 1, ..., 5) *[1: Japan; 2: Korea; 3: China; 4: Sawmills; 5: Pulpmills]*

t : Periods. (t = 1, ..., T) *[Strategic: T = 10; Tactical: T = 4; Operational: T = 6]*

(1) : Export-logs.

(2) : Sawmill-logs.

(3) : Pulp-logs.

Decision variables

X_{ijt} : Harvested area. *[ha]*

R_i : Remaining area. *[ha]*

Y_{jt}^- : Supply deficit. *[m^3]*

Y_{jt}^+ : Supply surplus. *[m^3]*

H_t^- : Budget surplus. *[$]*

H_t^+ : Budget deficit. *[$]*

I_{jt} : Inventory. *[m^3]*

Penalty coefficients

PI_{jt} : Inventory. *[$/$m^3$]*

PV^-_{jt} : Supply deficit. *[$/m^3$]*

PV^+_{jt} : Supply surplus. *[$/m^3$]*

PC^+_t : Budget deficit.

Technical coefficients

$V_{ijt(k)}$: Volume. *[m^3/ha]*

$K_{j(k)}$: Volumetric proportion.

C_{ijt} : Production cost. *[$/ha]*

NPV_{ijt} : Net present value. *[$/ha]*

Resource vectors

A_i : Stand area. *[ha]*

D_{jt} : Demand. *[m^3]*

S_t : Inventory capacity. *[m^3]*

M_t : Budget availability. *[$]*

Volume Estimation

$$V_{ijt(k)} = f_{jk}(ns_{it},hd_{it},ba_{it};\underset{\sim}{b}_{j(k)})$$

Where:

ns_{it} : Number of stems. *[/ha]*

hd_{it} : Dominant height. *[m]*

ba_{it} : Basal area. *[m^2/ha]*

$f_{jk}(\cdot)$: Function used to estimate the volume of export-logs, saw-logs, and pulp-logs that will be obtained under optimal bucking for a specific market.

$\underset{\sim}{b}_{j(k)}$: Vector of parameters.

$$[V_{i4t(1)} = V_{i5t(1)} = V_{i5t(2)} = 0]$$

The parameters $\underset{\sim}{b}_{j(k)}$ were estimated using multivariate regression analysis based on data collected by simulating on-site optimal bucking for different market specifications in a sample of 150 stands.

Revenue Estimation

$$R_{ijt} = \Sigma^3_k \, p_{jt(k)} * V_{ijt(k)}$$

Where:

$p_{jt(k)}$: Price per log type at the market (mills or port). *[$/m^3$]*

R_{ijt} : Total revenue. *[$/ha]*

Cost Estimation

$$C_{ijt} = g(h_{i(q)},d_{ij(r)},a_{it},w_t)$$

Where:

C_{ijt} : Production cost. *[$/ha]*

$h_{i(q)}$: Stand's proportion allocated to harvest system "q".

$$[\Sigma^Q_q \, h_{i(q)} = 1 \quad \forall_i]$$

Examples of harvest systems:

q = 1 : skidder, steep slope, and short logging distance.
q = Q : skyline, multi-span, and long logging distance.

$d_{ij(r)}$: Distance per road type "r". [km]

[r = 1 : pavement; r = 2 : rubble; r = 3 : bare land]

a_{it} : Accessibility.

[a_{it} = 0 : summer accessibility; a_{it} = 1 : winter accessibility]

w_t : Season.

[w_t = 0 : summer; w_t = 1 : winter]

$g(\cdot)$: Function used to estimate production cost for specific stands.

NPV Estimation

$$NPV_{ijt} = (R_{ijt} - C_{ijt})/adr_t$$

Where:

adr_t : Accumulated discount rate.

NPV_{ijt} : Net present value. *[$/ha]*

Penalty Coefficients

The minimum values recommended for the penalty coefficients are indicated below:

PI_{jt} : Inventory cost. *[$/m^3$]*

PV^-_{jt} : Cost of external supply. *[$/m^3$]*

PV^+_{jt} : Production cost. *[$/m^3$]*

PC^+_t : Cost of money based on discount rate.

<u>Quantity-Guided Process</u>

The linkage between hierarchical levels is based on a quantity-guided process. The strategic level indicates what stands are candidates to be harvested during the tactical planning horizon. It also indicates the volume that should be produced for the different markets from such stands (but penalty coefficients for volume deviations are re-defined in the tactical analysis).

Finally, the budget for production costs is also provided from the strategic level jointly with its associated penalty cost.

The tactical level, using the information received from the strategic level and more detailed spatial information (related to location and accessibility of segregated stands, and road habilitation projects), re-defines the production plan. The revised plan provides the information required by the operational level: stands that can be harvested in the current season and expected volume to be produced for each market.

Stand Aggregation Criteria

The recommended stand aggregation criteria are described below:

Volumetric structure: Stands that will belong to an aggregated-stand should have similar volumetric parameters with respect to their most likely destiny. In practical terms, stands should be homogeneous in relation to age, site index and previous management.

Location: Stands composing the same aggregated-stand should have a similar distance to their most probable destination. It is also convenient for them to share a common main access road.

Accessibility: It is a basic requirement that aggregated-stands are comprised of stands having the same kind of accessibility (summer or winter).

Externalities: When deciding aggregated-stands composition it is convenient to have in mind certain externalities that will influence the practical aspects of harvesting operations (e.g., joining stands of small size that are close to each other and/or gathering stands that will be cut at the same time). [However, in tactical and operational levels it may be convenient to decompose some stands into sub-stands depending on factors that can affect harvesting (e.g., terrain slope).]

Aggregated-stand technical coefficients must correspond to a weighted average of the respective coefficients of its conforming stands: the weighting factor corresponds to the relative area of each stand. This weighting procedure is required to guarantee that solutions will remain feasible when stands are considered separately.

PERFORMED TESTS

Several tests were carried-out to evaluate logic, robustness and consistency of the solutions proposed by the model. Additionally, some tests were done to estimate solution-time and numeric accuracy.

To test the model's logic a set of stands with highly differentiated characteristics related to age and site index (accounting for different present volume and growth rate by market), distance to markets and slope (implying different production costs), and accessibility (accounting for cutting seasons and road implementation) was defined. Several scenarios, related to different market-period demands, were considered for such set of stands. Solutions given by the model were compared to expected solutions based on logical criteria: tests were specially designed to be able to evaluate solutions' quality for problems of reduced size (10 stands, 5 markets and 4 periods).

The same set of stands and scenarios used to test the model's logic was used to test the robustness of the solutions proposed by the model. In this case, the objective was to evaluate the penalty costs required to obtain pre-specified solutions (different than the "natural" solutions). The parametric approach used for defining the penalty coefficients permitted examination of the effect of such coefficients in the solutions obtained, and simultaneously determine how management of penalty costs can improve solutions' robustness: reducing the variability induced by small changes in demand levels.

To test solutions' consistency (feasibility and optimality), the set of stands described above was "segregated": Each original stand was treated as an aggregated-stand and decomposed into 3 to 5 stands, simulating a disaggregation process. Using this information a complete multi-level decision-making process was conducted for 3 representative scenarios. Solutions obtained by this procedure permitted testing of feasibility at the different decisions levels. To evaluate sub-optimality such solutions were compared to the respective solutions obtained using a monolithic approach (i.e., a single-level single-run model). This analysis was repeated 3 times: The parameters corresponding to the original aggregated-stands were the same in all cases, but they were decomposed into stands with different degrees of homogeneity (high, medium, and low similarity within the aggregated-stands).

To test solution-time and numeric accuracy several sets consisting of 25 stands with "randomly" generated characteristics were used. Different demand scenarios, related to 5 markets and 10 periods, were considered for each set of stands. The corresponding problem size was fixed at 1250 variables and 85 constraints for all runs.

Test results indicate that the model performs adequately in terms of solution-time and numeric accuracy: no significant rounding errors were detected and solution-time using a 386 micro-computer did not exceed 5 minutes for the most complex problems: stands of very similar characteristics, under a unitary supply/demand ratio, and considering high penalty costs for deviations in all constraints. Solutions proposed were logical with respect to log production and allocation: some apparently "illogical" allocations turn out to be very "clever" when studied in detail. Penalty coefficients allow solutions to be oriented as desired, but this is a double-edged feature: values poorly defined will induce inefficient solutions. Feasibility at disaggregation is conditioned by the weighting of individual stands' technical coefficients: relative area was found to be an appropriate factor. Sub-optimal levels of solutions based on aggregated-stands depend directly upon the internal homogeneity of these in relation to the main stratification criteria: a higher homogeneity leads to a smaller sub-optimality.

COMMENTS

Several attributes of the model made it particularly well suited to the needs of Forestal Chile. These are summarized in the following sections, as are some shortcomings.

Hierarchical Planning

The hierarchical planning structure mirrored the general decision-making process in its composition of different decision levels: each requiring different degrees of detail for its analyses and each subject to different degrees of uncertainty.

The hierarchical approach also permitted a significant reduction of the problem size, enabling it to be solved by a micro-computer.

Goal-Programming

Goal-programming permits a differentiated weighting of the constraints considered in the model. This important feature is basic to define priorities in supplying outputs to specific markets or time periods.

Penalty coefficients allow "expert knowledge" to orient solutions the model will propose. It is considered very convenient to be able to guide solutions for them to be "logical" (according to standard forestry criteria) and "robust" (in the sense of stable solutions in the presence of non-significant variation in some parameters).

Goal-programming also simplifies sensitivity analyses in that a mathematically feasible solution will always be obtained by the model (although some of these solutions may not be realistic).

Constraint Formulation

Markets and number of periods considered for each planning level are suggested for practical reasons, and can be changed without affecting the model's structure. The structure defined for constraints permits one to easily expand the problem size in terms of new markets (e.g., pulp-log exports), more periods (e.g., a period 11 in strategic level for considering long term continuity), and different species (e.g., Eucalyptus).

One practical concern with respect to the formulation is that no extreme limits are considered for supply deficits or surplus, and a maximum bound is not considered for harvesting costs exceeding available budgets. These parameters were not included because unreasonable bounds could be detected in the solution and problem specifications adjusted appropriately.

Another practical concern is that no lower bound is considered for the remaining area of stands that will not be harvested entirely. Controling for this would require use of integer programming, which substantially increases solution-time, without significant gains: the expected number of stands allocated to be partially harvested is low, and they will occur only in the last period.

Stand Aggregation

The main objectives of using aggregated-stands are (a) to reduce the problem size (it would not be possible to solve the strategic problem in a micro-computer without considering stand aggregation), and (b) to guide solutions proposed by the model (definition of aggregated-stands allows incorporation of users' experience in order to achieve specific objectives).

However, it shall be realized that stand aggregation implicitly generates sub-optimal solutions, and eventually infeasible solutions at lower hierarchical levels. To reduce sub-optimality efficient aggregation criteria must be used and appropriate training of users is required. To avoid infeasibility aggregated-stand technical coefficients must be determined based on a correct weighting of the original stand coefficients.

Implementation

A primary concern related to the model's structure was the need for it to be easily implementable and accepted by end-users. These aspects were successfully achieved. The model's final version resembles and improves the decision-making process presently being used: acceptance was straightforward.[3/] The DSS required to use the model in real-life applications will not require additional hardware nor software acquisition by the company. Moreover, the information used by the model can be directly obtained from existing technical information systems.

[3/]The model's structure presented corresponds to the final version. It evolved based on early test results and end-users contributions.

MANAGING OPERATIONS IN PINE FOREST INDUSTRIES [1/]

Andrés Weintraub [2/]
Ramiro Morales
Jorge Serón
Rafael Epstein
Pier Traverso

Abstract.-- We present two applications of administrative, quantitative and computational techniques to support short term decisions in forest management of pine plantations in Chile. The first corresponds to a successful implementation of daily scheduling of truck trips. The second to determining short term timber cutting schedules. Linear Programming with 0-1 variables, simulation and heuristics techniques are used in the implementations.

Keywords : Management of Forestry Firms, Modelling, Algorithms.

THE TRUCK SCHEDULING SYSTEM

Description of the Problem

Daily timber hauling by truck from production sites to different destinations (plants, ports, sawnmills) is a mayor decision process, as it constitutes about 45% of total timber production costs.

At each origin, different timber products (defined by length and diameter) which have been previously stocked or are processed during the day must be transported. At each demand point the amount required daily of each product is defined, allowing for some fluctuations of up to 5% from this target.

Hauling is carried out by contracted trucks. In a typical operation, there are about 15 origins, 10 destinations and a fleet of 40 to 100 trucks is used. Trucks are divided by type and class. Type reflects mainly to load capacity and class to engine characteristics, which indicate the possibility to travel with load in certain roads. Truck owners are paid through a formula based on the number of cubic meters-Kilometer (m^3-Km) hauled. What is required is an efficient hauling schedule, which will make best use of the trucks and the loading-unloading equipment.

1/ Presented at the Symposium on Systems Analysis in Forest Resources Charleston, S.C., March 3-7, 1991.

2/ Professor of Industrial Engineering, University of Chile, Santiago; Professor of Forest Mangement, University of Chile, Santiago; Manager of Operations, Forestal Arauco; Assistant Professor of Industrial Engineering, University of Chile, Santiago; Manager of Transportation, Forestal Arauco.

The Assignment System

The objetive is to develop a truck and loading unloading schedule to minimize the total cost of the system while satisfying timber supply and demand constraints. This implies minimizing idle time and length of trips. Since in the long run truck owners must cover their costs, minimizing total costs of the transportation system is usually a better objetive than minimizing actual daily transportation incurred by the forest firm (payments to truck owners).

As a first step, an administrative ordering was required (in some firms it was carried out jointly with the implementation of the computarized system). The basic restructuring implied changing the original system, in which there was no schedule and trucks were loaded on a first come first served basis, which led to long queues and underutilization of equipment, to a programmed schedule, where trucks had to follow precise instructions on where and when to load and unload. A daily schedule was first devised manually.

Since scheduling these trips is a complex combinatorial problem, a computerized system was installed to improve the daily schedules. The system is based on simulation and heuristic techniques and is described next.

The Truck Scheduling Process

The scheduling program is carried out through a simulation. As inputs we consider: the amount of each product available in each origin (loader), the trucks of different types and classes available, the loading, unloading and travelling times, cost parameters, which include operation and utilization of trucks. Other considerations are also included, such as defining a lunch break, having drivers start and end their schedule close to their home town, assigning priority to some products, fixing specific origins or destinations to some trucks, etc.

The simulation replicates how the trucks and the timber move along the day, given heuristically designed scheduling rules. Thus, the simulation starts at say 6:30 in the morning, assigning the first trucks. The assignment rules are based on the following criteria.

i) Fulfilling demands has highest priority. In addition, demand must be satisfied regularly along the day (e.g. 4 trucks arriving each hour).

ii) Supply at origins. If some products arenot moving fast enough from an origin, a truck should be sent there.

iii) For administrative reasons, total income in a month should be similar for all trucks of the same type and class. This implies assigning the most profitable daily schedules to specific truck owners.

The heuristic rules, which are not described here in detail, (see Weintraub, et al, 1990) assign to each truck after unloading its next destination in an optimal way. In order to avoid near sighted decisions the scheduling looks ahead one hour, and schedules firmly the decisions of the simulation for the first 15 or 30 minutes. This is carried on, in a moving horizon form through the end of the day.

Description of the Algorithm

We show the main aspects of the simulation through an example. In Figure 1, let the time of simulation be TPO. Between TPO and (TPO + 1) trucks 1 an 2 arrive to destination D, truck 3 to E and trucks 4 and 5 to F. (exact arrival times are indicated in the time axis (T1 for truck 1, and so on). After truck 1 unloads, the alternatives for the next trip are: load in B and unload in E or load in C and unload in F. A similar analysis can be made for the other trucks.

The simulator will assign simultaneously the 5 trucks so as to minimize total costs while satisfying all constraints of the system. (as described above)). However, only decisions corresponding to the first half hour (TPO, TPO + 0.5) are actually implemented. This corresponds to trucks 1 and 2, while the decisions for trucks 3,4,5 are discarded. The next simulation interval is (TPO + 0.5, TPO + 1.5). New trucks which arrive to their destinations in the interval (TPO + 1.0, TPO + 1.5) are added to trucks 3,4 and 5 for the next assignment.

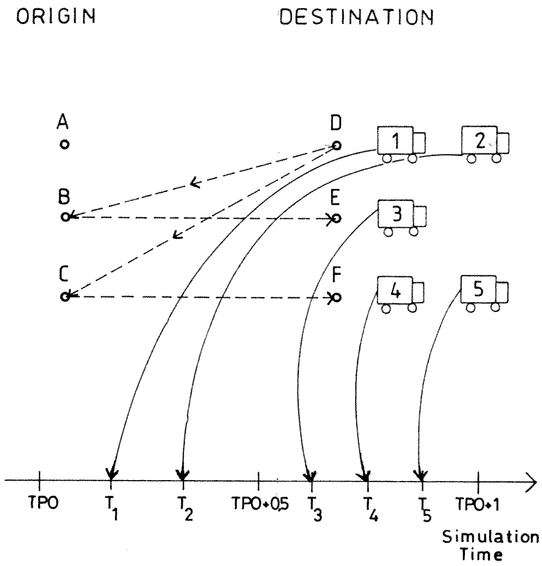

Figure 1

Implementation

The system is written in Fortran for use in personal computers. It requires 640 Kb RAM and it functions better with a hard disc with 2 or 3 Mb of memory. An information system in dBase IV is used to input data daily, in an efficiente and user friendly way. At present, the simulation process has a capacity to handle 150 trucks, 30 origins, 20 destinations, 20 types of products, 6 types of trucks, 15 classes of trucks, 4 "home" nodes where trucks spend the night. These dimensions are enough to handle current problems, but can be easily increased.

The computer time requirements are moderate. Using a PC/AT with math coprocessor, the larger problems require about 20 minutes. The software generates daily schedules for each truck: (For example, start at 7:32 AM in origin C, after loading leave at 7:50 to destination 4, arrive at 8:57. Unload, etc.) and each loading and unloading machine (For example, 6:45 load truck #62, 7:05 load truck #5, etc.). It also generates global statistics for analysis. Schedules are given the day before to truck drivers and machine operators. At this moment there is only communication between machine operators and the operation center. In case of failures, the operations center redistributes the work manually.

Results obtained

The system has been implemented in 5 firms, and is in the process of being implemented in 3 additional ones.

Improvements due to the implementation of new administrative rules and the simulation process ranged from 20% to 35%. This improvement could be measured in different forms: reduction of the number of trucks required, increase of production hauled with the same number of trucks, reduced number of hours of the daily schedule. In addition, the truck drivers and machine operators experienced a significant improvement in the lenght and quality of their working hours. As queuing time was reduced typically from an average of over 4 hours a day to less than 30 minutes, they could do the same hauling in less time. So their working hours were significantly reduced and better structured.

In any schedule planning the first use of the system is to determine truck requirements, given the amount of timber to be moved, as the simulation only introduces into the system the trucks that are needed. In one firm for example, the simulation runs showed that 40% of the trucks that were used at that moment were superfluous, and in time the fleet was reduced in that amount.

THE SHORT TERM TIMBER CUTTING SCHEDULE

Description of the Problem

Forest firms must satisfy different types of requirements. Typically, these are to supply pulp plants, sawnmills and export logs of a given quality.

In this case decision making concerns short term (3 months) assignment of: i)stands to be harvested, among those already mature and accessible, ii) the type of machinery to be used (towers or skidders, according basically to steepness of the slopes to be intervened) iii) volume to be cut, in what period, to what specifications (length, diameter) and (iv) where to ship the timber.

The main cost elements to consider are: value of standing timber (oportunity cost), transportation costs, equipment operation costs (cutting, loading, unloading), set up costs (obtaining access and preparing sites for operations). Requirements of different products in demand centers are defined by length, minimum diameter of individual logs as well as average log diameter, which determine log cutting patterns. Typically, the longest pieces are assigned for export by ship, at given dates. Each importing country has specific requirements of length and diameters. Shorter pieces are sent to sawnmills and the rest is used for the pulp plant. A typical log cutting pattern may be in 5 pieces.

12.10 m. in length, 20 inches minimum diameter, 32 inches average diameter.

8.10 m. in length, 20 inches minimum diameter, 28 inches average diameter

4.10 m. in length, 20 inches minimum diameter, 26 inches average diameter

4.10 m. in length, 20 inches minimum diameter, 24 inches average diameter

4.10 m. in length, 16 inches minimum diameter, (for pulp)

The multiple product requirement leads to many cutting patterns, and these should be defined so as make best use of the timber, since thicker logs for export get best prices and logs assigned to the pulp plant the lowest.

The Mathematical Model

The model typically optimizes over a 3 month horizon, in a rolling horizon approach, and is to be run every week. The first four periods correspond to weeks and the last two to a month each.

The problem can be expressed as a 0-1 mixed LP. The main decision variables are related to:

i) Decisions on what stands to interviene and in which period to start. This implies set up costs and lead to integer variables. If the stand is to harvested with skidders, how many should be used in each period. If towers are used, when should they be installed. This also leads to integer variables. (Once a tower is installed, it normally is used in that place until the whole are it can reach is harvested).

ii) Management activities for stands, including cutting patterns for logs.

iii) Volume of each product sent from a given stand to a destination (port, plants, sawnmills) in each period.

The main constraints (in each period) are:

i) Stands are available for harvesting (through skidders or tower) if access and set-up work has been done.

ii) Consistency between production and available harvesting machinery in each stand.

iii) Consistency between production and available timber; for each type of product and cutting patterns.

iv) Consistency between production in each stand and timber transported from it.

v) Consistency between timber transported to and demand at destinations, for each type of product.

vi) Consistency between timber hauled and trucks available.

vii) Constraints reflecting diameter requirements for different export shipments and sawmnills.

viii) Additional constraints reflecting a) harvesting policies, e.g. once production is started in a stand, a minimum area must be harvested. b)Policies in use of equipment and trucks. c) Policies on global production and financial considerations.

Implementation of the model

The implementation presents three main difficulties.

i) The presence of 0-1 integer variables.

These are derived from decisions in setting up areas to harvest and installing towers. Since their number is too high to run with a mixed integer LP package, a heuristic approach is used to obtain from the continuous LP solution a good integer one.

ii) The size of the model.

Given the high number of products that are defined (typically over 100) and hauled to different destinations, a typical problem could have over 10,000 constraints and 100,000 variables. These dimensions are reduced substantially (to about 1,400 constraints and 11,000 variables) through careful deletion of variables that are unlikely to appear in a solution and some aggregation procedures.

iii) Finding appropiate cutting patterns.

These patterns must be defined according to the products required. Again, to obtain a good mix of options, an unmaneageably large number of patterns would be required. By interacting with expert users and the use of heuristics, a relatively small but adequate number of cutting patterns is defined.

For cases where this reduction of cutting patterns is not sufficient to reduce the size of the model, a column generation approach has been proposed. In this case, the master program, would be the model described, and a subproblem based on Dynamic Programming would generate desirable cutting patterns to add to the master program.

The system is implemented for personal computers (PC) type 386, and can be divided into four parts:

1) Data input: Timber volumes are derived from supply simulation models, already in use in each firm. A Data Base Package (e.g. dBase IV) or Spread Sheet (e.g. Lotus 1-2-3) is used.

2) LP input: A Fortran program is used to develop data in MPS format.

3) The model is run using LINDO 386.

4) Reports. A report writer translates results of the LP into reports at managerial and operational level.

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AN EXPERT SYSTEM FOR MODELING FOREST GROWTH IN THE SOUTH[1/]

Lawrence R. Gering[2/]

Abstract.--Growth and yield research results for southern U.S. forest types have accumulated over the past half century into a collection of several hundred publications. Wide technology gaps may exist between this valuable knowledge base and the large group of potential users. An expert system may provide a means of bridging this gap. The research reported here describes the on-going development of such a system.

Keywords: Research, yield, knowledge base, technology gap

INTRODUCTION

There are over 182 million acres of forest in the South classified as timberland suitable and available for growing crops of trees. Timber productions are the region's most valuable cash crop and rates of tree growth in the South are the envy of the rest of the Nation (USDA, 1988). However, in many cases, this forest land base is being pressured by competing land uses and increased demands for lumber, paper, fuel, and other wood-fiber products. It is obvious that the South's forests must be managed with ever-increasing intelligence and awareness of the current and projected situation of the resource.

The U.S. Forest Service identified "Southern Forest Productivity" as a priority research program and has recognized the urgent need for accelerated research focused on protecting and increasing the productivity of southern forests. This program identifies eight major research categories needed to provide knowledge for the intelligent management of forest resources. Two closely related categories are "quantitative studies" and "decision analysis". Included within the general outlines of each of these are the development and use of mathematical models, computer programs, and expert systems to analyze and predict forest characteristics (Loftus et al., 1988).

While research efforts in these categories are considered critical, the importance of technology transfer has also been identified as a major part of the research program. It is important to transfer technology to users, concurrent with its development. Only in this manner can research meet the potential for improving Southern forest productivity (Loftus et al., 1988).

One objective of this study was to collect, review and document mathematical models currently available for predicting growth of forest stands in the South. A second objective was to develop a microcomputer-based expert system that will select an appropriate growth model for a user-specified set of conditions.

BACKGROUND

In 1987, the International Union of Forestry Research Organizations (IUFRO) sponsored the Forest Growth Modeling and Prediction Conference in Minneapolis, Minnesota. This conference provided a forum for the dissemination and discussion of more than 150 research papers. Topics included all types of tree and forest growth modeling methodology, including theory and evaluation of models, incorporation of silvicultural treatments, regeneration, mortality, and many environmental perturbations. The conference demonstrated that there has been progress and increasing interest in forest growth modeling in recent years (Ek et al., 1988).

A forest growth model may be defined as a mathematical function, or system of functions, used to relate actual growth rates to measured

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1/Presented at the Systems Analysis in Forest Resources Symposium, Charleston, SC March 3-7, 1991.

2/Assistant Professor of Forestry, PO Box 10138, Louisiana Tech University, Ruston, LA 71272.

tree, stand and site variables (Bruce and Wensel, 1988). Growth and yield research results for southern U.S. forest types have accumulated over the past half century into a collection of several hundred publications (Alig et al., 1984). Hepp (1988) noted that wide technology gaps exist between this valuable knowledge base and a large group of potential users. He stated that there has been little evidence that consulting, State and Extension foresters, who manage vast non-industrial forests, are making effective use of contemprary growth and yield prediction technology.

One reason for the lack of effective use of appropriate models by foresters is simply the great number of models from which to choose. At one time, users new the model builder and were able to directly learn about the model's application. Currently, an immense body of scientific and technical information is available but this knowledge is fragmented, unwieldly and time-consuming to evaluate. The demand for useful knowledge to solve specific problems has overloaded the ability of our present methods for creating, storing, retrieving, and disseminating such knowledge(Coulson and Saunders, 1987). In other words, there is a critical need for the potential user to converse with an expert in order to select an appropriate model (figure 1). Stark (1987) observed, however, that most experts are scarce and in high demand; their knowledge is often valuable and rare. Thus, expert systems can provide a more accessible and consistent source of expertise.

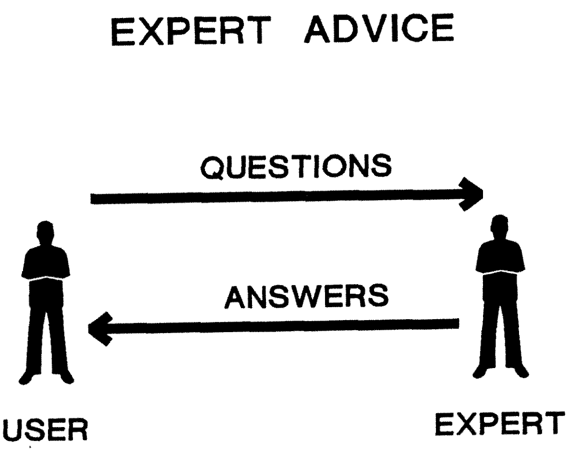

Figure 1.--Representation of model user talking with an expert in order to select appropriate model.

Expert systems are computer systems that advise on or help solve real-world problems which would normally require a human expert's interpretation. Such systems, combining computer software and desktop microcomputers, work through problems using a model of expert human reasoning. They are designed to reach the same conclusions that a human expert would be expected to reach if faced with a comparable problem (Weiss and Kulikowski, 1984).

Feigenbaum (1984) stated that an expert system is a computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution. Expert systems are based on knowledge which is acquired from experts in a specific domain. This domain knowledge (such as characteristics of forest growth models) is stored in the knowledge base of the system (figure 2). The knowledge is applied and processed using a set of inference procedures which controls the reasoning of the expert system (Duda and Gaschnig, 1981).

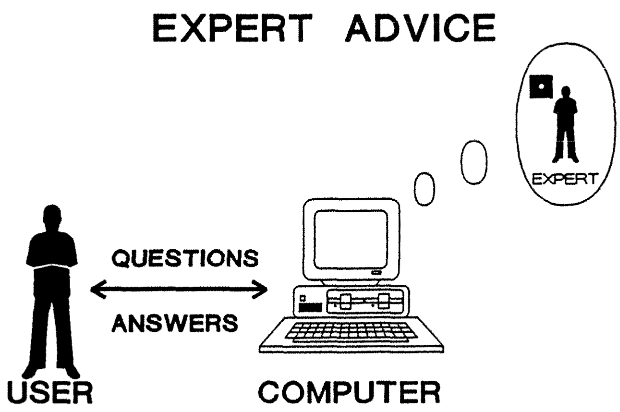

Figure2.--Representation of an expert system in which model user accesses expert advice stored in computerized knowledge base.

In general, expert systems are designed to be easy to use. Such a system interacts with the human user in English and can often be used after only a few minutes of instruction. Additionally, expert systems are unique in their ability to "explain" their line of reasoning or justify conclusions reached. Thus, such systems will allow usable knowledge to disseminate or transfer to users (Stark, 1987).

STATUS OF PROJECT

The initial portion of the project is nearing completion. We have identified many models which will be included in the knowledge base of the expert system. These publications document the development, validation and application of mathematical models used to evaluate growth of forests in the South. The models can be viewed as the data for this project. Representative examples include:

Bailey,R.; Dell,T. 1973. Quantifying diameter distributions with the Weibull function. Forest Science 19(2):97-104.

Borders,B.; Bailey,R. 1986. Fusiform rust prediction models for site-prepared slash and loblolly pine plantations in the Southeast. Southern Journal of Applied Forestry 10(3):145-151.

Burk,T.; Burkhart,H. 1984. Diameter distributions and yields of natural stands of loblolly pine. Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources, Publication No. FWS-1-84. 46pp.

Clutter,J.L. 1963. Compatible growth and yield models for loblolly pine. Forest Science 9:354-371.

Newberry,J.; Pienaar,L. 1978. Dominant height growth models and site index curves for site-prepared slash pine plantations in the lower coastal plain of Georgia and north Florida. University of Georgia, School of Forest Resources, Plantation Management Research Cooperative Research Paper 4: 47pp.

Schumacher,F.X. 1939. A new growth curve and its application to timber-yield studies. Journal of Forestry 37:819-820.

It is apparent that the growth and yield research to be used in this project comes from a variety of sources. Tracking down suitable models from refereed publications is relatively simple. Greater difficulty is encountered when attempting to locate models documented in university publications or in published proceedings from meetings and conferences. Often, these have limited circulation except among participants of the particular meeting.

The current phase of the project involves reviewing each model and creating common or universal variables. For example, when modeling basal area, abbreviations such as B, BA or BASAL are commonly encountered. It is important (and somewhat tedious) to re-write these models so that a common set of abbreviations are used.

FUTURE WORK

Once all models have been identified, documented and assigned universal variable abbreviations, the expert system can be created. The purpose of such a system is to take unorganized data (the models and accompanying documentation) and structure them in a form that can serve as a knowledge base. The expert system will be developed using a commercially-available shell such as VP-Expert; this is a rule-based package that can be implemented on a PC.

The expert system will interact with a human user (in English) and will access both the knowledge base of growth models as well as a set of internal inference procedutes. Once the system has selected a model, it will be able to justify its choice using terminology a forester can understand. It will also be possible to create such a system in a form so that it can exchange data with computerized spreadsheet, database and text files. This will allow the user to learn about the development of the model directly from the creators. It will also be possible to process inventory data from spreadsheets so predicted growth values can be determined. The transfer of knowledge from one representation to another may be transparent to the human user. However, the user will be able to request justification prior to acceptance of the predicted values.

CONCLUSION

Harold Burkhart, Thomas M. Brooks Professor of Forest Biometrics at Virginia Polytechnic Institute and State University,(1990) stated that forest growth and yield modeling methodology has advanced significantly in recent years, but that the future promises even more rapid advancement. He also noted that progress in growth and yield modeling centers around three key elements of data collection, analytical techniques, and computing technology. I believe it is appropriate to add a fourth element that must also be considered - dissemination or transfer of knowledge about the model to users.

There are a great number of models available for use. Some are general in form and can be applied to a variety of data sources. Others were designed for very specific sets of conditions and might require extensive modification if they were to be used in a differing situation. However, if a potential user is unaware of these existing models, the result could be duplicated effort in creating a new model. Or, perhaps as costly, the user could try to use a model that did not fit his needs as closely as a less known model. Hopefully, the creation of a large knowledge base of information pertaining to growth and yield modeling, together with an expert system, will allow users to become aware of existing models that will fulfill their needs.

ACKNOWLEDGMENTS

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MAXIMIZING THE DIAMETER CLASS DIVERSITY OF UNEVEN-AGED NORTHERN HARDWOOD STANDS[1]

J. H. Gove, D. S. Solomon, S. E. Fairweather, and G. P. Patil[2]

Abstract. Two mathematical programming formulations are presented which allow the determination of diameter distributions that maximize the diameter class diversity in uneven-aged northern hardwood stands. Distributions generated from these models were found to be comparable from a management standpoint and could be incorporated into existing linear programming models as alternative management scenarios. The models presented here provide an initial framework for quantitatively addressing the requirements of NFMA with respect to consideration of ecological diversity in the planning process.

Keywords: Intrinsic diversity ordering; nonlinear programming; diversity profiles.

INTRODUCTION

The National Forest Management Act (NFMA) final rule (Federal Register 47(190), 1982) requires that diversity be considered in formulating management alternatives in the national forest planning process. NFMA specifically states that "Forest planning shall provide for diversity of plant and animal communities and tree species consistent with the overall multiple-use objectives of the planning area." In addition, it calls for the quantitative evaluation of diversity in both past and present conditions so that the impact of proposed management practices on diversity may be evaluated. The NFMA is vague as to how such quantifications of diversity are to be handled, however. Presumably, the drafters of NFMA saw this as an area open for future research.

In this paper we present a quantitative method which has been found to be useful for comparison of diversity in forest communities (Swindel *et al.* 1987). In addition, we use this method as a basis for a model which lays the groundwork for incorporating diversity considerations into the planning process. The model considers one aspect of community diversity, which itself may be envisioned as a multidimensional quantity including species, genetic and structural components among others, and which together define what has been termed the "variety of life in an area" (Salwasser 1989). Specifically, the model determines the diameter distribution which maximizes diameter class diversity in an uneven-aged northern hardwoods stand under certain constraints. It addresses only the horizontal aspect of structural diversity and does not explicitly consider the other components.

The diameter distributions presented in this paper are not meant to be used as practical stocking guides by the manager or policy maker interested in diversity considerations. Rather, this paper is methodological in intent, providing the model formulations necessary to produce such guides on the desired forest stands. The methodology is developed using growth and economic information which allows comparison with other similarly constructed stocking guides found in the literature such as physical- and investment-efficient distributions (Adams and Ek 1974, Adams 1976). Therefore, the growth and economic components, and thus the resulting distributions, may have little or nothing in common with the actual conditions of other communities in the northern hardwoods forest type.

AVERAGE SPECIES RARITY, DIVERSITY, AND DIVERSITY ORDERING

In this section we discuss the concept of community diversity as average species rarity, first put forth by Patil and Taillie (1979). Throughout this discussion we speak in terms of a conceptual community, C, which is composed of s species. However, it is important to realize that "species" is simply a conve-

[1] Presented at the 1991 Symposium on Systems Analysis in Forest Resources, Charleston, South Carolina, March 3–7.

[2] Research Forester and Project Leader, respectively, Forest Service, U. S. Department of Agriculture, Durham, NH; Assistant Professor of Forest Resources Management and Professor of Statistics, respectively, The Pennsylvania State University, University Park, PA

nient label for the categories into which we aggregate individuals, and that the names or labels of the individuals themselves are of no consequence. In addition, in this discussion we define abundances in terms of numbers of individuals (by species). That is, in an s-species community, the absolute abundances are given as $N_1, N_2, \ldots, N_s$ such that $\sum_{i=1}^{s} N_i = N$, the total number of individuals. Just as "species" is used generically for some method of categorization, other measures of abundance could also be used; these include biomass, board foot or cubic foot volume, basal area, or any other mensurational quantity. Patil and Taillie (1979) summarize this concept quite succinctly

> For the diversity-related conceptualization, what constitutes the total or unit quantity is not of particular interest. What the actual categories are is not of any consequence either. The important concern is about the nature and the degree of apportionment being more diverse or less diverse... (p. 4)

With the above thoughts in mind, we find that the absolute abundances and total number of individuals in a community are quantities of little use in diversity considerations; the apportionment, or relative distribution of individuals and the number of species are of primary interest. The relative abundance vector for a community is given by $\underline{\pi} = (\pi_1, \ldots, \pi_s)$, where $\pi_i = N_i/N$; therefore, $\sum_{i=1}^{s} \pi_i = 1$. The total number of species in the community, s, is called the *species richness*; the conceptual community may therefore be written as $C(s, \underline{\pi})$, or simply $C(\underline{\pi})$ since s is implied in the dimension of $\underline{\pi}$. Now consider a community such that all species have the same relative abundance; that is, $\pi_i = 1/s = \pi_E$ for all i, so that s alone determines the abundance vector. Such a community is denoted $C_E(s)$ and is termed the *completely even community*.

Diversity is defined here as average community rarity. The rarity of species i is a quantitative measure associated with that species and is denoted $R(i; \underline{\pi})$, or simply $R(\pi_i)$. Patil and Taillie (1979, 1982) discuss two types of rarity measures: *rank-type* and *dichotomous-type*. The dichotomous-type rarity measure derived by them is used here; it is given by

$$R_\beta(\pi_i) = \frac{\left(1 - \pi_i^\beta\right)}{\beta}, \quad -\infty < \beta < \infty. \tag{1}$$

Rarity is a species property while diversity is a property of the community. To determine community diversity, rarity is considered a measurable random variable and diversity is given as its expectation, $\mathrm{E}[R(\pi_i)]$. Therefore, using the dichotomous rarity index we find that the diversity for community $C(s, \underline{\pi})$ is

$$\Delta_\beta(\underline{\pi}) = \sum_{i=1}^{s} \pi_i R_\beta(\pi_i) = \frac{\left(1 - \sum_{i=1}^{s} \pi_i^{\beta+1}\right)}{\beta}, \quad \beta \geq -1. \tag{2}$$

The restriction on the parameter β is required in order that $\Delta_\beta(\underline{\pi})$ have certain desirable properties (see Patil and Taillie (1979, 1982) for more discussion). Note that the normal limiting definition is used at $\beta = 0$ for both $R_\beta(\pi_i)$ and $\Delta_\beta(\underline{\pi})$.

The use of $\Delta_\beta(\underline{\pi})$ as the diversity measure has two important consequences. First, three of the common ecological diversity indices are special cases of $\Delta_\beta(\underline{\pi})$. When $\beta = -1$, $\Delta_{-1}(\underline{\pi})$ is the species count; at $\beta = 0$, $\Delta_0(\underline{\pi})$ is the Shannon index; and at $\beta = 1$, $\Delta_1(\underline{\pi})$ is the Simpson index. This ties the $\Delta_\beta(\underline{\pi})$ definition of diversity in with much of the ecological literature on diversity both past and present.

The second important consequence of using $\Delta_\beta(\underline{\pi})$ is that if β is allowed to vary while $\underline{\pi}$ is held fixed, a plot of $\Delta_\beta(\underline{\pi})$ by β yields a diversity profile. Figure 1 presents diversity profiles for a hypothetical community with $\underline{\pi} = (.1, .5, .1, .05, .25)$ and the completely even community $C_E(5)$. The diversity profiles present a way of ordering the diversity of different communities. In general, if $C(s, \underline{\pi}')$ and $C(s, \underline{\pi}'')$ are two different communities, and $\Delta_\beta(\underline{\pi}') \geq \Delta_\beta(\underline{\pi}'')$ for all β, then community $C(s, \underline{\pi}')$ is *intrinsically more diverse* than community $C(s, \underline{\pi}'')$ (Swindel *et al.* 1987). Therefore, in Figure 1, the completely even community is intrinsically more diverse than the other community with abundance vector given above.

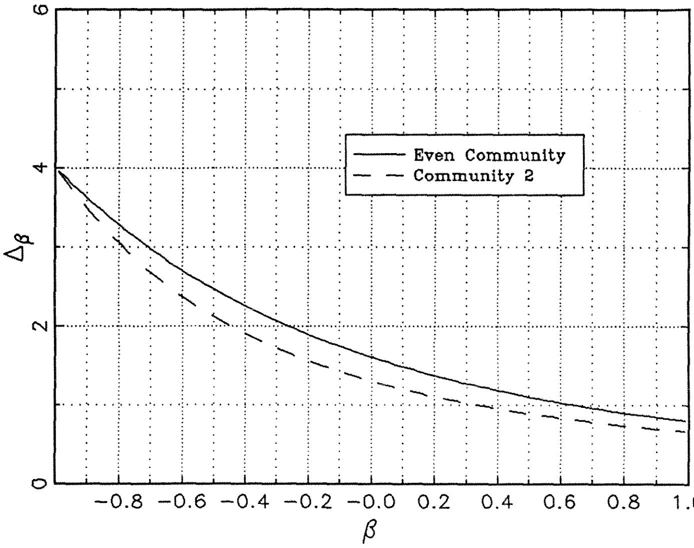

Figure 1. $\Delta_\beta(\underline{\pi})$ profiles for two hypothetical 5-species communities.

Any number of diversity profiles may be plotted against one another. The risk of comparing too many communities in one plot is that they may grade into each other at one or more points, and it may be difficult to determine whether they intersect or not, depending upon the resolution of the graph. If two profiles intersect, then they are not intrinsically comparable in terms of diversity. However, some statement still may be able to be made about diversity using the profiles. Note in Figure 1 that when β is small (close to -1), $\Delta_\beta(\underline{\pi})$ is more sensitive to rare species than when β is large (close to $+1$). This can easily be seen by noting that $\Delta_{-1}(\underline{\pi})$ yields the species count index in which all species, irrespective of the associated community abundance vector, receive the same weight. However, Simpson's index ($\Delta_1(\underline{\pi})$) is very insensitive to rare species. Therefore, β may be interpreted as a "sensitivity" parameter. For example, in a mature, even-aged, mixed Appalacian hardwood forest, the forester may be very sensitive to the occasional "high-value" species (e.g. black walnut) in this community. The forester might choose $\beta = -1$ to measure diversity in this case. The red-eyed vireo, however, who sees an unbroken canopy of choice mature oak habitat for nesting and foraging, would be more interested in measuring diversity at larger β since abundance of what it considers "high-value" species is of primary importance.

The possible intersection of $\Delta_\beta(\underline{\pi})$ profiles and their interpretation brings up an important point. Different diversity *indices* may order communities in an inconsistent manner (Patil and Taillie 1979, 1982, Swindel *et al.* 1987). For example, if two profiles cross between $\beta = 0$ and $\beta = 1$, then the species count and Shannon indices would order the two communities in the opposite sense to Simpson's index. Therefore, the diversity profiles given by $\Delta_\beta(\underline{\pi})$ yield a method for catching such disparities and associated possible incorrect interpretations which may go unrecognized if indices alone are used.

MAXIMIZING DIVERSITY

In the previous section it was noted that for any given vector of relative abundances $\underline{\pi}$, a diversity profile could be generated by allowing β to vary in (2). In this section we view $\Delta_\beta(\underline{\pi})$ in the opposite sense: we hold β fixed and allow $\underline{\pi}$ to vary subject to the constraints that $\beta \geq -1$ and $\sum_{i=1}^{s} \pi_i = 1$. When this is done a *diversity surface* is generated at β.

Figure 2 presents a triangular chart of a three species ($s = 3$) community. Each of the three axes of the chart are scaled such that $0 \leq \pi_i \leq 1, i = 1, \ldots, 3$. This type of a chart is useful for envisioning the diversity surface since it automatically incorporates the constraint $\sum_{i=1}^{s} \pi_i = 1$. The contours plotted on the interior of the chart represent the level curves of the $\Delta_\beta(\underline{\pi})$ diversity surface when $\beta = 1$. Any corner point on the chart represents a single species community, edges are two species communities, and interior points are three species communities. The chart clearly shows for $\beta = 1$ that the $\Delta_\beta(\underline{\pi})$ diversity surface reaches its maximum at the center—the completely even community.

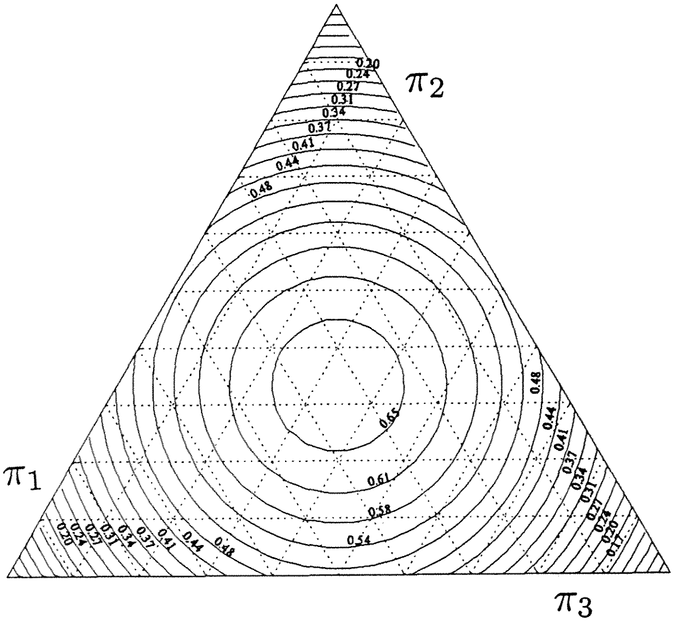

Figure 2. $\Delta_\beta(\underline{\pi})$ diversity surface at $\beta = 1$ for all 3-species communities.

A similar chart is shown in Figure 3 for the $\Delta_\beta(\underline{\pi})$ surface at $\beta = 2$. Note the slight difference in the shape of the diversity surface level curves when compared with Figure 2. In Figure 3 the curves are less circular and are beginning to become somewhat "triangular" in shape. Indeed, if the $\Delta_\beta(\underline{\pi})$ surface is plotted as $\beta \to \infty$, the level curves become more and more triangular. The maximum again is clearly seen to occur at the completely even community when $\beta = 2$.

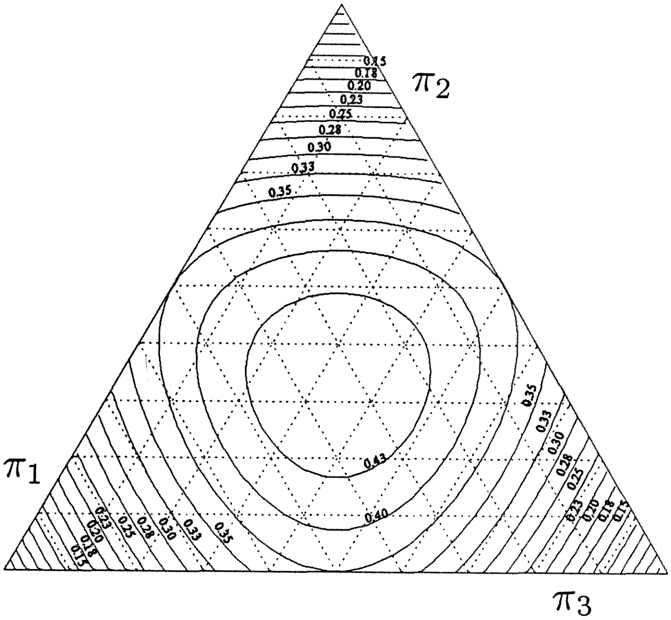

Figure 3. $\Delta_\beta(\underline{\pi})$ diversity surface at $\beta = 2$ for all 3-species communities.

The result that the completely even community maximizes diversity for a given number of species s is well known (Patil and Taillie 1979, 1982, Pielou 1974, Solomon 1979). In general, the problem may be formulated for $\Delta_\beta(\underline{\pi})$ as

$$\begin{aligned} &\underset{\{\underline{\pi}\}}{\text{Max}} \ \Delta_\beta(\underline{\pi}) \\ &\text{St}: \sum_{i=1}^{s} \pi_i = \underline{\pi}'\underline{1} = 1. \end{aligned} \tag{3}$$

It is straightforward to show that the solution to (3) is $C_E(s)$. This is an interesting finding because it allows the introduction of an alternative objective function into model (3). We find that maximizing (3) is the same as the following problem

$$\begin{aligned} &\underset{\{\underline{\pi}\}}{\text{Min}} \ \sum_{i=1}^{s} |\pi_E - \pi_i| \\ &\text{St}: \sum_{i=1}^{s} \pi_i = \underline{\pi}'\underline{1} = 1. \end{aligned} \tag{4}$$

The diversity surface for this formulation is presented in Figure 4. Note the difference in the shape of the level curves in this surface when compared to Figures 2 and 3; the level curves for (4) are hexagonal. This surface is minimized at the completely even community, implying that diversity is at its maximum.

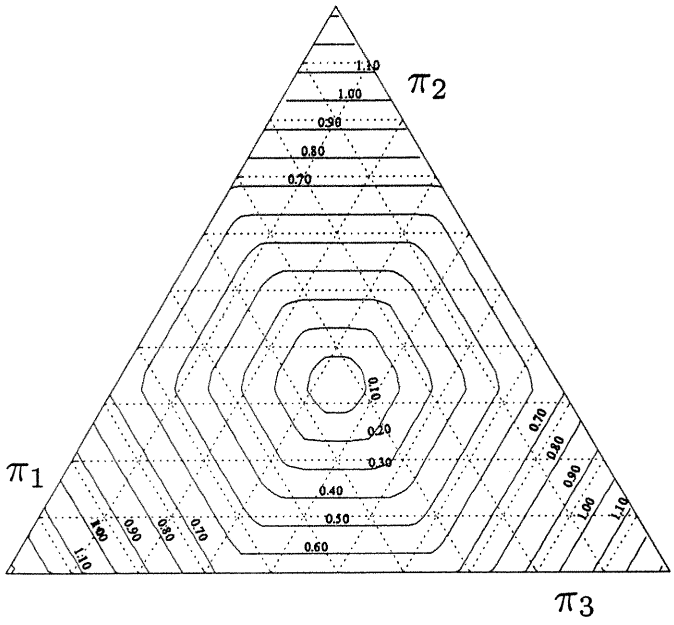

Figure 4. Model (4) diversity surface for all 3-species communities. (Note that the surface is actually piecewise linear.)

MAXIMIZING DIAMETER CLASS DIVERSITY

Model Formulation

In this section we consider an uneven-aged northern hardwoods stand and pose the question: Given certain stocking, economic, and biological growth constraints, what is the diameter distribution which maximizes diameter class diversity? Based on the results of the last section, the non-technical answer is that it is the diameter distribution which is most nearly even. However, the result will not be a completely even diameter distribution if the constraints impose any true restriction on the diversity surface.

Under the current scenario, notice that "species" has now become synonomous with *diameter class*; therefore, s is now the number of diameter classes which is held constant here. Relative abundances composing $\underline{\pi}$ are determined in the classical sense, in terms of number of trees per acre. Therefore, the quantitative measure of "number of individuals" remains the same as in the previous discussion.

We adopt as a mathematical programming model structure, the basic Adams and Ek (1974) paradigm which has been used in numerous studies in recent years (see Gove and Fairweather (1991) for a literature review). Two general model formulations are presented—both are solved as nonlinear programs. The concepts discussed in the previous section may be extended to $s > 3$ in these two models to maximize diameter class diversity. The first formulation in equation set (5) maximizes the diameter class diversity using the objective function from (4); this is termed Model I.

$$\underset{\{\underline{\pi}\}}{\text{Min}} \sum_{i=1}^{s} |\pi_E - \pi_i| \tag{5}$$

$$\begin{aligned}
\text{St}: & \sum_{i=1}^{s} \pi_i = \underline{\pi}'\underline{1} = 1 \\
& N_i(t) - N_i(t-1) \geq 0, \quad i = 1, \ldots, s+1 \\
& 0 < \pi_i \leq 1 \\
& BPA = PSL \\
& LEV = ESL
\end{aligned}$$

$s =$ The number of diameter classes ("species"); $s = 9$ in this study. The diameter class width used was 2 inches, with a minimum diameter of 6 inches.

$N_i(t-1) =$ The number of trees in diameter class i in the optimal stand at the *beginning* of the 5-year growth period.

$N_i(t) =$ The number of trees in diameter class i in the optimal stand at the *end* of the 5-year growth period given the growth dynamics predicted by the growth model.

$BPA =$ The total basal area per acre in the optimal stand (taken at the midpoint of the 2-inch diameter classes).

$LEV =$ The land expectation value for the optimal stand computed at 3 percent alternative rate of return. The individual tree values used in the computation of LEV are Martin's (1982) fair site (site index 55) values.

$PSL =$ Some physical stocking level of basal area per acre.

$ESL =$ Some economic stocking level in present value dollars per acre.

Model II maximizes $\Delta_\beta(\underline{\pi})$ with the added constraint that β must be fixed; the rest of the model is the same as Model I. The complete formulation is given in equation set (6)

$$\underset{\{\underline{\pi}\}}{\text{Max}} \ \Delta_\beta(\underline{\pi}) \tag{6}$$

$$\begin{aligned}
\text{St}: & \sum_{i=1}^{s} \pi_i = \underline{\pi}'\underline{1} = 1 \\
& N_i(t) - N_i(t-1) \geq 0, \quad i = 1, \ldots, s+1 \\
& 0 < \pi_i \leq 1 \\
& BPA = PSL \\
& LEV = ESL \\
& \beta = b,
\end{aligned}$$

where β may be fixed at any value b such that $-1 \leq b < \infty$.

The growth dynamics for both formulations are modeled with a simple set of nonlinear whole-stand diameter class growth equations, first presented by Adams and Ek (1974). Therefore, the diameter distribution recovered in the optimal stand is for the entire community composed of all species with minimum diameters greater than 6 inches—no individual species distributions are available.

The physical stocking constraint on basal area and the economic constraint on LEV are what keep the solution from either model feasible from a biological perspective. If both of these are set simply to be positive, Model I will lead to a degenerate solution; Model II may find a feasible solution with nonzero $\underline{\pi}$, however, the stand basal area and trees per acre will effectively be zero. Therefore, the growth constraints alone do little to determine a biologically reasonable solution. In addition, if only one of these two constraints is used and it is restricted between lower and upper bounds (e.g. $BPA_L \leq BPA \leq BPA_U$), both models always seem to find a solution at the lower bound.

Other constraints may be added to either formulation. Volume, weight and value growth constaints are just three examples which could either be added or substituted into either model. In addition, a probability density or mass function may be used to model the $\underline{\pi}$ in a similar manner to Martin's (1982) use of the two-parameter Weibull distribution, though the findings of Bare and Opalach (1988) should be considered before so doing.

Model Results

Models I and II were optimized using the generalized reduced gradient program GRG2 (Lasdon and Waren, 1986). Solutions were found at several different economic and physical stocking combinations; all solutions presented satisfied the Kuhn-Tucker stationary conditions.

Table 1 presents solutions to Model I with *LEV* constrained only to be positive, but with stand basal area set at several different stocking levels. Note that the diameter distributions in Table 1 are not completely even; this is a consequence of the constraints on growth and basal area which are all binding in both model formulations. A plot of the $\Delta_\beta(\underline{\pi})$ profiles for these three communities is shown in Figure 5. The distribution at 60 ft^2 is the most diverse community according to the intrinsic diversity ordering of the $\Delta_\beta(\underline{\pi})$ profiles. In addition, the evenness criterion correctly orders each community with respect to diversity in this example.

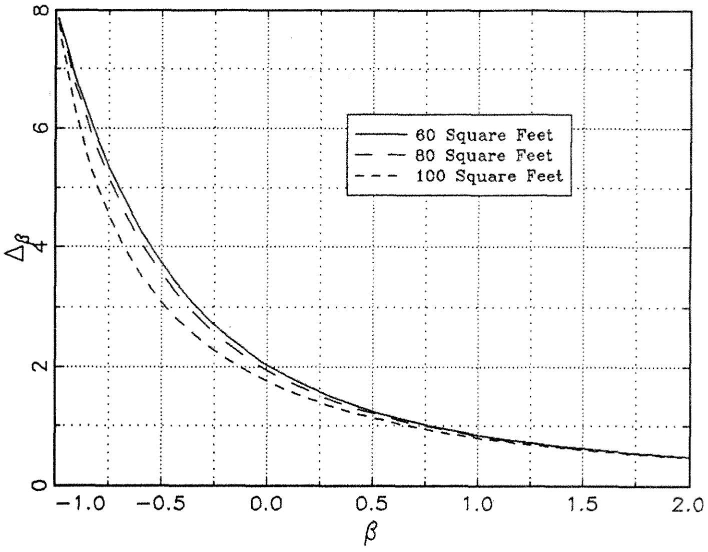

Figure 5. $\Delta_\beta(\underline{\pi})$ profiles of maximum diversity diameter distributions for Model I at different basal area stocking levels.

The most striking aspect of the distributions in Table 1 is that *LEV* is zero for all solutions. The reason for this is that *LEV* and evenness work against each other in these formulations. In order to even-out a distribution (i.e. maximize diversity), as many trees as possible are put into the larger diameter classes. This happens in accordance with satisfying the growth and *BPA* constraints until *LEV* reaches its lower bound of zero. However, trees in the sawtimber size classes ($\geq$ 12 inches) contribute substantially more to holding costs in the calculation of *LEV*; therefore, few trees are needed in these classes to drive *LEV* to zero. Thus the positive constraint on *LEV* is a mechanism which works against evening-out the dis-

Table 1. Maximum diversity diameter distributions for Model I at different basal area stocking levels.

Diameter Class	Basal Area Per Acre 60 ft^2	80 ft^2	120 ft^2	Value Per Tree[a]
	Trees Per Acre			
6"	18.44	30.03	64.63	0.11
8"	13.66	21.90	45.62	0.30
10"	10.67	16.86	34.16	0.54
12"	8.63	13.47	25.02	3.83
14"	7.16	11.05	20.08	6.15
16"	6.05	9.25	16.35	8.61
18"	5.20	7.87	4.80	11.23
20"	4.52	3.01	0.11	14.66
22"	1.47	0.56	0.04	17.79
Total *TPA*	75.80	114.00	210.81	
LEV \$/Acre	0.00	0.00	0.00	
Evenness[b]	0.467401	0.554299	0.718561	

[a]The tree values used are from Martin's (1982) fair site guides; values for 24" and 26" trees used by Martin were \$21.19 and \$24.97 respectively.
[b]Evenness is defined as $\sum_{i=1}^{s} |\pi_E - \pi_i|$.

Table 2. Maximum diversity diameter distributions with 80 ft^2 of basal area per acre for Model II at different β.

Diameter Class	β 0.01	1.0	10.0	100.0
	Trees Per Acre			
6"	30.53	29.99	30.03	34.78
8"	22.26	21.87	21.90	25.29
10"	17.13	16.84	16.86	18.51
12"	13.69	13.45	13.47	10.29
14"	11.22	11.04	11.05	8.47
16"	7.66	9.24	9.25	7.11
18"	6.53	7.86	7.87	6.06
20"	3.03	2.66	3.01	5.24
22"	2.01	0.89	0.56	1.91
Total *TPA*	114.06	113.84	114.00	117.66
LEV \$/Acre	0.00	0.00	0.00	0.00
Evenness	0.577137	0.554539	0.554299	0.669038

tribution at optimality. Indeed, if *LEV* were left unconstrained, it would be driven negative in the optimal solution, resulting in a more diverse community than the 60 ft^2 solution in Table 1. Such a result may be reasonable if financial considerations are of no concern to the manager.

Maximizing Model II is not as straightforward as minimizing Model I. The reason for this was pointed out earlier: inasmuch as different diversity surfaces are generated at each β, $\Delta_\beta(\underline{\pi})$ should be optimized several times, each at a different level of β to allow for comparison of the resulting distributions. Table 2 presents the results of this process for four different levels of β at 80 ft^2 of basal area per acre. All of the constraints (with the exception of β) have remained the same in each of these solutions; therefore, the solution space has not changed—the only difference contributing to the slightly different results is the shape of the diversity surface at each β. This phenomenon may be envisioned quite readily by imagining one or two simple linear constraints in Figures 2–4. Note that, depending upon how the constraints are arranged in these figures, the optimal solution may be slightly different in each case. This same reasoning applies to the results in Table 2.†

The results in Table 2 show a range of only four trees per acre difference between the resulting stands; therefore, from both a biological and practical perspective, there is no difference between the resulting distributions at different β. Technically, the value of the evenness statistic might be used to judge which of these distributions is in fact the most diverse at the 80 ft^2 level. However, the evenness criterion is only a one-dimensional statistic and has not been shown to order communities consistently for a given s as have the $\Delta_\beta(\underline{\pi})$ profiles. Indeed, a plot of the four $\Delta_\beta(\underline{\pi})$ profiles (not shown) reveals that they are not intrinsically comparable since the profiles cross. In this case, it seems reasonable to pick the community at $\beta = 10$ since it has the smallest evenness and is the solution to Model I (see Table 1). Given the practical considerations, nothing is compromised in this decision.

One further cautionary note is in order when optimizing Model II. If β is set equal to -1, the diversity surface generated by $\Delta_\beta(\underline{\pi})$ is a constant at $s - 1$ for *all* $\underline{\pi}$ as noted earlier. In this case, the only factors restricting the solution are the constraints, and any point which satisfies the constraints within the feasible solution space may be chosen as a solution. Thus Model II should never be optimized at $\beta = -1$ as solution vectors having little relation to the results of Model I may result. In addition, if β is left unconstrained in Model II, the same result occurs since $\beta \to -1$ in this case.

The results of adding a *LEV* constraint different from zero to Model I are shown in Table 3. The first distribution constrains *LEV* to be \$100 per acre while allowing *BPA* to go free. The other two distributions constrain both *LEV* and *BPA*. Comparing the 60 ft^2 and 80 ft^2 distributions in Tables 1 and 3 clearly shows that the affect of the *LEV* constraint is to add more trees to the smaller diameter classes, while removing trees from the larger sawtimber classes. This causes a decrease in the holding costs, allowing *LEV* to increase over the distributions in Table 1. It also decreases the evenness statistic and therefore the diversity as expected. This illustrates the interplay between evenness and *LEV* alluded to above.

CONCLUDING REMARKS

The models presented provide a framework for quantitatively considering diversity as part of natural resource mathematical programming models. Diversity here is considered the objective to be maximized in both model formulations. However, there is no reason why it could not be reinterpreted into constraint form if some other objective was desired. The limiting factor in these formulations is the nonlinearity of the $\Delta_\beta(\underline{\pi})$ function, requiring solution techniques which necessarily fall

† Special care was taken in all of the solutions to use the smallest convergence tolerences possible while still meeting the Kuhn-Tucker stationary conditions. This insures that the solutions do not differ because of sensitivity to the convergence tolerance magnitude.

Table 3. Effects of constraining *LEV* on maximum diversity diameter distributions for Model I.

Diameter Class	Basal Area Per Acre		
	50.7^{a} ft^2	60 ft^2	80 ft^2
		Trees Per Acre	
6"	26.78	25.56	42.38
8"	19.79	18.84	30.72
10"	15.42	14.64	23.53
12"	11.34	11.80	18.71
14"	9.40	9.75	15.28
16"	4.98	8.22	4.64
18"	2.25	5.06	3.62
20"	0.07	0.15	1.93
22"	0.03	0.00	0.00
Total *TPA*	90.06	94.02	140.81
LEV $/Acre	100.00	60.00	80.00
Evenness	0.739646	0.618121	0.749250

[a]The *BPA* constraint was free in this distribution.

within the realm of nonlinear programming. Biologically and mathematically such nonlinearity makes sense, however, it excludes the explicit use of such functions in large linear programming models such as those used in national forest planning. Diameter distributions produced by solving (5) could, however, be incorporated into linear programming models in the form of alternative management scenarios.

The solutions of Models I and II suggest that both models will give approximately the same answers. However, because of the nature of the diversity surfaces generated in these models and the uncertainty of diversity ordering based on a single index like evenness alone, it is recommended that both models be solved, as was done in the previous section. In addition, $\Delta_\beta(\underline{\pi})$ profiles should *always* be plotted when comparing models for diversity ordering. Other profiles are available and may also be useful. For example, in comparing the distributions of Table 2, the $\Delta_\beta(\underline{\pi})$ profiles plot very close to each other, and it is difficult to determine if and where they cross. In this case the right *tail-sum* profiles of the relative abundance vector were extremely helpful (see Patil and Taillie 1979).

In each of the tables presented the absolute abundance vectors are given because this measure is necessary for management. It is therefore possible to incorrectly interpret the results of these tables by trying to judge evenness based merely on the diameter distributions alone, while not taking into account the respective total trees per acre. In addition, the "species richness" was held constant for each distribution to facilitate comparison. If new distributions were generated with different numbers of diameter classes, this would also enter into the subsequent evaluation of diversity ordering. It should be remembered that the relative abundances and species richness are the keys for evaluating diversity.

Models I and II were kept relatively simple in order to introduce the concept of maximizing diversity and related diversity ordering. For example, $\underline{\pi}$ is treated as a deterministic vector in both models. Actually, because of the stochastic nature of the underlying growth equations, $\underline{\pi}$ is a random vector with unknown sampling distribution (Gove and Fairweather, 1991). In addition, we only treated the whole stand diameter distribution in this paper. Extensions of these two models are readily apparent, with future work involving species and structural components as well as possible inclusion of nontimber-related constraints (e.g. wildlife habitat).

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DETERMINING FOREST MANAGEMENT REGIMES VIA PSEUDODATA ANALYSIS[1]

Terry P. Harrison[2] and Richard D. Twark[2]

Abstract.—*Pseudodata analysis* is broadly defined as the use of models (rather than empirical observation) to collect data. Most frequently, this pseudodata is used to develop a simpler, or reduced form of the original model. The goal is to capture a significant portion of the model's performance with a much smaller set of equations and variables.

Here we describe our work on the development of a generalized procedure for determining near optimal forest management strategies based on a particular growth and yield model. The key result is to determine the number, timing, and intensity of harvest as a function of exogenous parameters (site index, discount rate, pulpwood and sawtimber prices). We do this by first developing a set of pseudodata from the growth and yield model. This data represents the optimal harvest regimes for various combinations of the exogenous variables, requiring the solution of thousands of individual optimization problems. Least squares is used to create the reduced form model from the pseudodata. Based on the performance of our regression, we conclude that pseudodata analysis is a viable method for developing forest management strategies from underlying growth and yield models.

KEYWORDS: Optimization, regression, forest growth and yield

Introduction

Determining the optimal number, timing, and intensity of harvests is a major theme of forest management. Through the spatial and temporal manipulation of the forest, one heavily influences both the financial and ecological outputs. For example, timber production, wildlife habitat (and indirectly, wildlife populations), aesthetics, and recreation are key forest outputs that are directly affected by stand characteristics.

A prerequisite to making wise management choices is the ability to predict the response of the forest to various cutting and cultural practices. For example, one of the most widely used methods of developing forest management plans is to enumerate a collection of possible management strategies, predict the response of the forest under each of the strategies, and then choose a subset of the strategies to optimize one (or several) management objective(s), possibly subject to various types constraints. With this approach, the final outcome is heavily dependent on the underlying growth and yield model.

We develop a new and non-traditional approach to determining forest management regimes based on the idea of *pseudodata analysis*. Pseudodata are not obtained in the traditional sense via empirical observation. Rather, the pseudodata is the output of some other model. For our analysis, the pseudodata is the *optimal* (or near optimal) number, timing and intensity of harvests (endogenous

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[2] Associate Professor of Management Science, Penn State University, University Park, PA 16802

variables) for a given set of values for site index, discount rate, pulpwood price and sawtimber price (exogenous variables). With this collection of data, we determine a regression equation that predicts the optimal value of the endogenous variables as a function of the exogenous variables so as to maximize the net present value of the stand.

The use of a pseudodata model offers the following features:

1. provides an opportunity to view the performance of the underlying growth and yield model when used to drive an optimization;
2. permits a better understanding of the management implications of using a particular growth and yield model;
3. facilitates investigation of the relative effects of external (exogenous) variables such as site index, discount rate, and stumpage prices on optimal strategies;
4. provides management guidelines that are easy to develop and use.

Data Generation

All yield data in this study were generated from the old field loblolly plantation growth and yield simulator of the YieldPLUS system (Hepp [1987]). YieldPLUS in an integrated software package which provides the ability to interactively simulate the growth and yield of a number of different stand types. It also includes a collection of financial analysis options.

The loblolly plantation simulator is based on the results of a number of different authors. The survival and Weibull distribution estimating equations (unthinned stand) and diameter class/height relationships are from Smalley and Bailey [1974]. The site index curves are from Smalley and Bower [1971]. The cubic foot volume estimates are from Smalley and Bower [1968]; while board foot and topwood volume are from Burkhart, Parker, Strub, and Oderwald [1972]. Taper equations and weight estimates are from Bailey, Grider, Rheney, and Pienaar [1985]. Basal area growth after thinning is based on Burkhart and Sprinz [1984]. Survival after thinning is taken from Lemin and Burkhart [1983]. The stand table projection is developed from Clutter and Jones [1980].

The pseudodata were obtained by placing a mesh over the space of endogenous and exogenous variables (see Table 1). For a fixed combination of exogenous variables, the set of values of the endogenous variables that resulted in the highest net present value was selected. This resulted in 2240 optimal management regimes (observations) over a wide variety of stand and economic conditions, representing approximately 16 million individual simulations.

Model Development

As an aid to the process of model development, we performed a series of preliminary analyses to evaluate the extent to which the numerical data and some initial relationships seemed "reasonable" or agreed with our *a priori* expectations. Exploratory data analysis involving descriptive statistics, boxplots, scatter diagrams, and simple correlation coefficients were used. Boxplots provided a quick visual picture of the range, first and third quartiles, and median value for each variable, while scatter diagrams were useful to assess potential linear and nonlinear associations between selected variables.

The use of pseudodata does not permit the usual tests of statistical significance such as the F-test or Student t test for individual regression coefficients. However, measures such as R^2 and least squares residuals do provide a measure of how well the models performed. Here we view least squares purely as a numerical method for obtaining a best estimate (according to a particular metric) for the individual model parameters.

Because of the simplicity and ease of interpretation of parameters for linear models, our initial efforts focused on simple linear and then multiple linear correlation and regression analyses for net present value. Tables 2-5 show the resulting R^2 values. Rather than directly include the number of harvests as an endogenous variable, we developed a separate model for each value of number of harvests (1–4).

For these simple linear models, discount rate ranked highest among the four exogenous variables in explaining the variation in net present value. The proportion of variation in $NPVmax$ explained by discount rate alone ranged from 42% for the one harvest model to 56% for the four harvest model.

We investigated the extent to which multiple linear relationships could be used to explain $NPVmax$ using the four exogenous variables. While the linear relationships were relatively strong, (R^2's around 70% to 80%) other preliminary analyses suggested that substantial nonlinear effects were also present.

We tried various log-linear models with limited success. However, since we had so few exogenous variables, our belief was that a complete second order model would better capture the curvature and interaction which was present in some of the earlier analyses.

The complete second order model (Mendenhall and Sincich [1989]) consists of an endogenous variable expressed as a quadratic function of 4 exogenous variables, resulting in a total of 14 independent variables (all one and two way combinations of the four exogenous variables).

Therefore the model for the i^{th} endogenous variable is given by:

$$\begin{aligned} Y_i = &\beta_0 + \beta_1 SI + \beta_2 R + \beta_3 PP + \beta_4 SP + \beta_5 SI^2 + \beta_6 R^2 + \\ &\beta_7 PP^2 + \beta_8 SP^2 + \beta_9 SI \times R + \beta_{10} SI \times PP + \\ &\beta_{11} SI \times SP + \beta_{12} R \times PP + \beta_{13} R \times SP + \\ &\beta_{14} PP \times SP + \epsilon \end{aligned}$$

where ϵ is the usual error term, the β_i's are estimated using ordinary least squares, and *SI*, *R*, *PP* and *SP* are site index, discount rate, pulpwood price and sawtimber price, respectively.

We used the RSREG procedure of SAS (SAS Institute [1985]) to fit the quadratic response surface for each of the endogenous variables (harvest ages and residual basal area after thinning) for one harvest, two harvest three harvest and four harvest models. The output of RSREG provides not only the traditional statistical output of ordinary multiple linear regression software, but also indicates how much of each effect (i.e., linear, quadratic, and cross-product) and each factor contributes to the overall fit of the model.

The resulting models performed very well in predicting both *NPVmax* and *NPVmin*, with R^2s ranging from 0.946 to 0.985 (Table 7). Figure 1 contains a representative plot of predicted versus actual net present value for the four harvest model. Harvest ages and residual basal areas were not as well described. It appears that the timing of intermediate harvests in a multi-harvest regime is less sensitive to the exogenous parameters than the final harvest. For example, the R^2s for predicting harvest ages 1–4 in a four harvest regime were 0.612, 0.493, 0.724, and 0.754 respectively. This pattern also existed for the two and three harvest models. The residual basal area model exhibited similar results. Figures 2 and 3 show representative plots of predicted versus actual harvest age and residual basal area.

There was a wider variation between *NPVmax* and *NPVmin* as site index increased. This seems reasonable in that a low site stand will be relatively less sensitive to harvesting strategy with respect to net present value. The response surface appears to be rather flat, indicating that a deviation from the optimal regime does not severely penalize the resulting net present value. As expected, the *NPVmax* models are strongly correlated positively with site index and strongly correlated negatively with discount rate.

The mean values for harvest age and residual basal are for each of the second order models is contained in Table 6. Rotation length varied from 26 years with the one harvest model to 36 years in the four harvest model. Residual basal area for all harvests were in the 60–70 ft.^{2} range.

Conclusions

We have applied the general framework of pseudodata analysis to the issue of developing a simple model of directly determining *optimal* harvesting strategies with respect to maximizing net present value. All pseudodata were derived from the old field loblolly pine plantation model in the YieldPLUS system (Hepp [1987]). The endogenous variables (present net worth, harvest ages and residual basal area) were modeled as a function four exogenous variables (site index, discount rate, pulpwood price and sawtimber price).

We found the complete second order approach to provide the best model. The ability to capture cross product and second order effects was clearly critical. Additional work is needed to validate this pseudodata method on other growth and yield models, and potentially to other models of stand outputs.

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Table 1. Values for Optimization Variables

Variable	*Type*	*Minimum Value*	*Maximum Value*	*Increment*
Site Index	Exogenous	40	70	5
Discount Rate	Exogenous	1%	7%	2%
Pulpwood Price	Exogenous	$10	$40	$10
Sawtimber Price	Exogenous	$100	$200	$25
Number of Harvests	Endogenous	1	4	1
Harvest Age 1	Endogenous	15 years	40 years	5 years
Harvest Age 2	Endogenous	20 years	40 years	5 years
Harvest Age 3	Endogenous	25 years	40 years	5 years
Harvest Age 4	Endogenous	30 years	40 years	5 years
Residual Basal Area 1	Endogenous	40 $ft.^2$	90 $ft.^2$	10 $ft.^2$
Residual Basal Area 2	Endogenous	40 $ft.^2$	90 $ft.^2$	10 $ft.^2$
Residual Basal Area 3	Endogenous	40 $ft.^2$	90 $ft.^2$	10 $ft.^2$

Table 2. R^2—One Harvest Model

Endogenous Variable	*Site Index*	*Discount Rate*	*Sawtimber Price*	*Pulpwood Price*
NPVmax	0.256	0.423	0.003	0.114
NPVmin	0.317	0.271	0.005	0.109
NPVdif	0.107	0.474	0.001	0.077
Harvest Age 1	0.038	0.231	0.034	0.411

Table 3. R^2**—Two Harvest Model**

Endogenous Variable	*Site Index*	*Discount Rate*	*Sawtimber Price*	*Pulpwood Price*
NPVmax	0.218	0.547	0.029	0.028
NPVmin	0.250	0.338	0.005	0.134
NPVdif	0.092	0.529	0.059	0.012
Harvest Age 1	0.019	0.096	0.062	0.203
Harvest Age 2	0.088	0.561	0.045	0.078
Residual Basal Area 1	0.305	0.130	0.023	0.001

Table 4. R^2**—Three Harvest Model**

Endogenous Variable	*Site Index*	*Discount Rate*	*Sawtimber Price*	*Pulpwood Price*
NPVmax	0.215	0.553	0.035	0.024
NPVmin	0.253	0.351	0.005	0.142
NPVdif	0.077	0.513	0.077	0.030
Harvest Age 1	0.033	0.082	0.068	0.203
Harvest Age 2	0.007	0.408	0.016	0.096
Harvest Age 3	0.097	0.589	0.018	0.050
Residual Basal Area 1	0.294	0.243	0.006	0.001
Residual Basal Area 2	0.095	0.558	0.003	0.002

Table 5. R^2**—Four Harvest Model**

Endogenous Variable	*Site Index*	*Discount Rate*	*Sawtimber Price*	*Pulpwood Price*
NPVmax	0.213	0.558	0.038	0.022
NPVmin	0.295	0.379	0.009	0.103
NPVdif	0.035	0.556	0.090	0.304
Harvest Age 1	0.050	0.063	0.079	0.230
Harvest Age 2	0.004	0.307	0.004	0.062
Harvest Age 3	0.025	0.603	0.006	0.031
Harvest Age 4	0.046	0.634	0.003	0.022
Residual Basal Area 1	0.257	0.252	0.006	0.003
Residual Basal Area 2	0.023	0.495	0.026	0.064
Residual Basal Area 3	0.010	0.790	0.004	0.001

Table 6. **Mean Values—Complete Second Order Models**

Endogenous Variable	*Harvests* 4	3	2	1
Harvest Age 1 (years)	16.3	16.4	16.4	26.2
Harvest Age 2 (years)	25.0	27.2	30.9	
Harvest Age 3 (years)	31.0	33.9		
Harvest Age 4 (years)	36.2			
Residual Basal Area 1 ($ft.^2$)	62.7	63.6	62.4	
Residual Basal Area 2 ($ft.^2$)	70.9	64.4		
Residual Basal Area 3 ($ft.^2$)	58.6			

Table 7. **R^2—Complete Second Order Models**

Endogenous Variable	*Harvests* 4	3	2	1
NPVmax	.985	.983	.982	.976
NPVmin	.974	.959	.950	.946
Harvest Age 1	.612	.544	.558	.830
Harvest Age 2	.493	.606	.824	
Harvest Age 3	.724	.794		
Harvest Age 4	.754			
Residual Basal Area 1	.755	.763	.712	
Residual Basal Area 2	.656	.741		
Residual Basal Area 3	.897			

Figure 1. NPVmax—Four Harvest Model

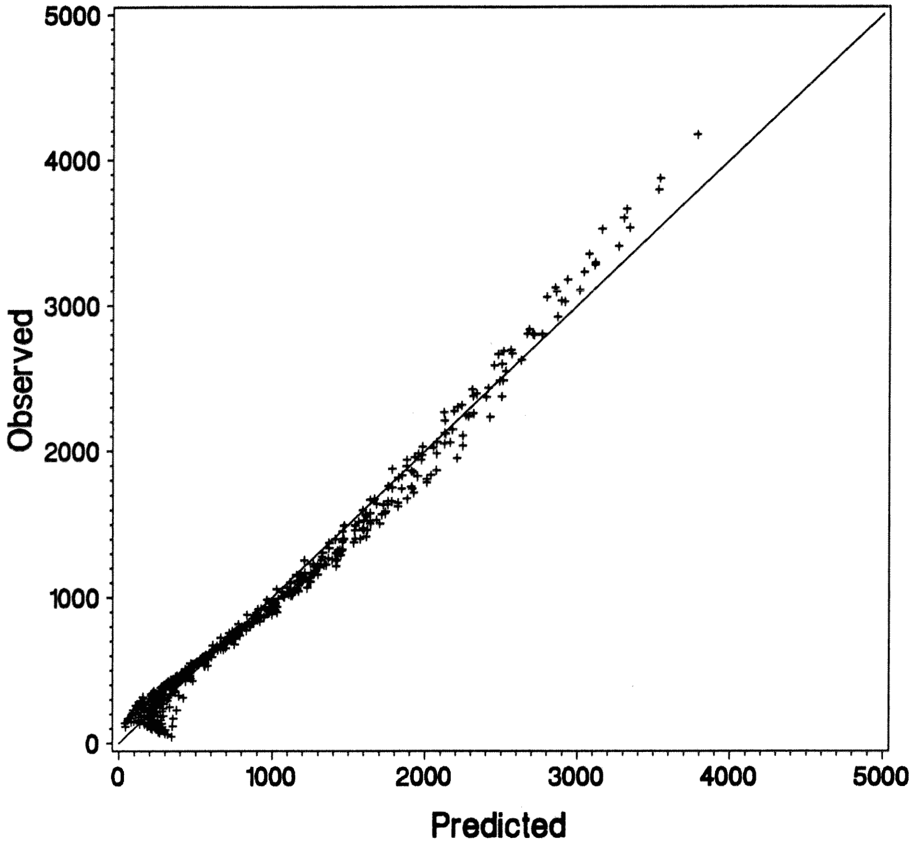


Figure 2. Harvest Age 1—One Harvest Model

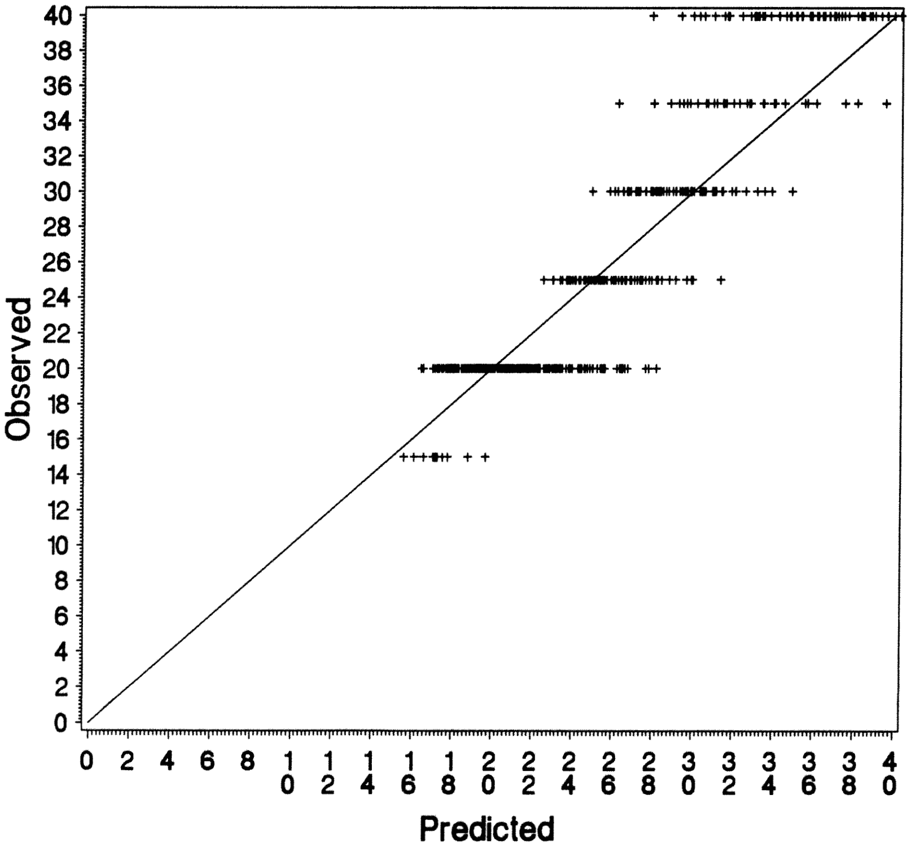
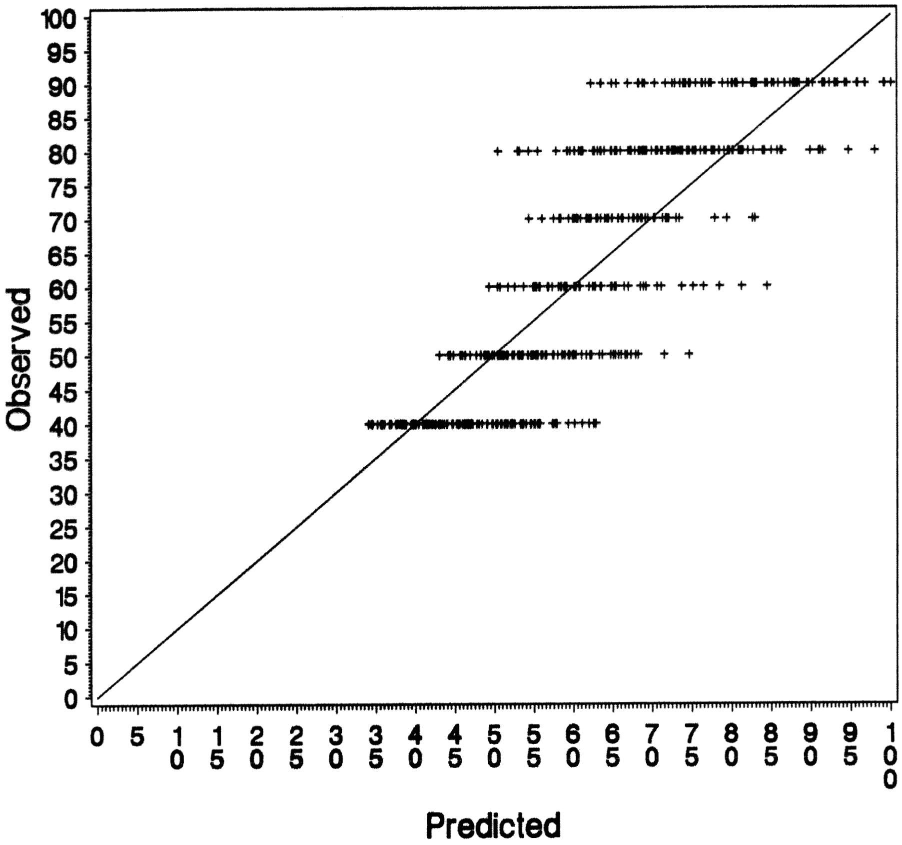


Figure 3. Residual Basal Area 1—Two Harvest Model



SOME ASPECTS OF HIERARCHICAL PRODUCTION PLANNING IN FOREST MANAGEMENT [1]

Eldon A. Gunn [2]

Abstract. This paper reviews the notion of hierarchical planning processes (HPP) and attempts to relate these to the process of forest management planning. The well known forest harvest scheduling models are discussed as the tactical modelling component of the HPP. Questions of the use of these models in the face of uncertainty are discussed.

Keywords: forest management, harvest scheduling, linear programming, stochastic programming, planning, uncertainty

INTRODUCTION

In this paper, we want to examine forest management as a hierarchically structured planning process and try to develop some consequences of this viewpoint. We begin in section 2 by examining Anthony's hierarchy of strategic, tactical and operational planning and attempt to relate these to the process of forest management planning. Briefly, we shall see that strategic planning involves the decisions as to what resources to provide to the enterprise under consideration, that tactical planning involves plans to make the most effective use of these resources over a sufficiently long time horizon to take into account the major dynamic factors and that operational planning involves planning for the many detailed operational issues that make the system function. This hierarchy of problems involves different levels of detail, certainty and level of management involved in the decision process.

Following our discussion of hierarchical planning, we proceed to examine this planning structure in the context of forest management. We attempt to categorize forest management in terms of strategic, tactical and operational control models. In this categorization, we will see that the the well known harvest scheduling models are tactical models.

We then proceed to a more comprehensive discussion of these tactical level models. We focus on two questions. The first is that of model structure with an emphasis on the harvest linkage constraints. The second is the role of uncertainty and its implications for model formulation and usage. Finally we close by outlining a family of integrated models that can quite naturally form the basis of a hierarchical planning system.

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[1] Presented at the Symposium on Systems Analysis in Forest Resources, Charleston, SC, March 3-7, 1991.

[2] Professor, Department of Industrial Engineering, Technical University of Nova Scotia, PO Box 1000, Halifax, Nova Scotia, Canada, B3J 2X4.

HIERARCHICALLY STRUCTURED PLANNING PROBLEMS

In 1965, Robert N.Anthony (see Silver and Peterson) suggested a framework for the analysis of the decision making process. In spite of the fact that all real systems are ongoing with no clear demarcation of either time period, time horizon, decision maker or problem, Anthony showed that categorizing decisions into three categories was a useful tool for understanding the process of decision making and implementation. These categories were strategic planning, tactical planning and operational control. Briefly we can differentiate these categories as follows:

- Strategic Decisions: Defining the role and nature of the enterprise and the resources that the enterprise will have available to it.
- Tactical Planning: Making the most effective use of the resources available to the enterprise
- Operational Control: Detailed scheduling of weekly and shift level activities to make the system function.

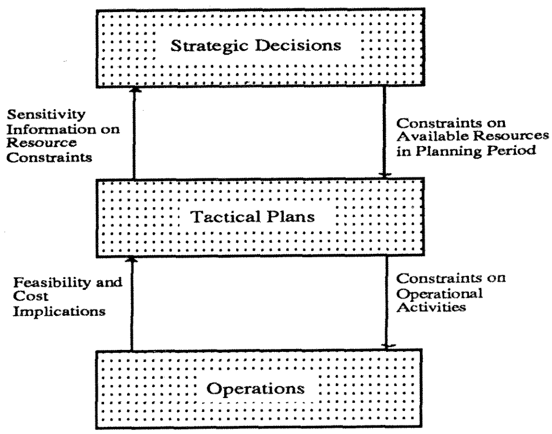

Figure 1. Feedback process of Decision Hierarchy

Moreover, the decisions taken at one hierarchical level act as constraints on the lower level decisions. In turn the information from the lower levels of the process feedback information to the upper level decision processes. This information feedforward/ feedback is illustrated in Figure 1.

Anthony's main observation is that decision problems at each of these level differ in time horizon, management level involved in the decision process, source and detail of information and the uncertainty and risk associated with the decision outcome. Table 1. indicates the characteristics appropriate to each type of decision problem. A key observation is that at all levels, decision making is a dynamic process with information and plans constantly changing. However, information feedforward and feedback enables most organizations to function effectively. Resource availability developed with the long term viewpoint of the strategic level feeds forward capacity information to the tactical decision process. Thus annual budgets and plans can be developed without explicit concern as to capacity change. However the process of tactical planning often leads to insight as to the effect of availability of additional resources and this feedsback to the strategic planning process.

Table 1. Characteristics of Decision Problems in Hierarchy

Characteristics	Strategic Planning	Tactical Planning	Operational Control
Objective	Resource	Resource acquisition	Execution utilization
Time Horizon	Long	Middle	Short
Level of Management	Top	Middle	Low
Scope	Broad	Medium	Narrow
Source of Information	External &Internal	External &Internal	Internal
Level of Detail	Highly Aggregate	Moderately Aggregate	Very Detailed
Degree of Uncertainty	High	Moderate	Low
Degree of Risk	High	Moderate	Low

Similarly the results of a tactical plan provide constraints on short term operating decisions that guarantee that the resources of the firm will be used efficiently. This means, that within these constraints, operating management can focus on the short term, detailed issues of scheduling without destroying longer term performance. Conversely, problems of feasibility of short term operational control provide feedback to the tactical planning process.

HIERARCHICALLY STRUCTURED PLANNING SYSTEMS

The concept of hierarchical planning systems arises from the thought that if we can indeed structure a hierarchy of decisions as discussed above and if management of enterprises is itself organized hierarchically, then it may well logically follow that the planning process should be organized in a hierarchical fashion. The result has been the development of what has come to be known as a hierarchical planning process. Some of the history of this approach to planning is discussed in Hax and Candea. A number of implemented examples are given in Bradley, Hax and Magnanti.

There are four main aspects of hierarchical planning that we wish to emphasize. These involve i) the use of separate models for each hierarchical level, ii) the rolling planning horizon implementation of model solutions, iii) the role of hierarchical planning in coping with uncertainty and iv) the mirroring of corporate organizational structure.

Separate Models: The first concept of hierarchical planning is that of using separate models for each hierarchical level. Instead of trying to develop one large model encompassing all aspects of an enterprise, separate models (or separate decision processes) are used at each level. Normally upper level models will be based on aggregate data, particularly for time periods far removed from the current decision point. The upper level models will be used to provide appropriate constraints for the lower level, shorter term model. Detailed information is required only for the short term decision problems for which it is likely to be more accurate.

Rolling Planning Horizon Implementation: The second key concept is implementation via a rolling planning horizon. The strategic model may develop a capacity plan but only the immediate decisions of that plan are explicitly implemented. Before implementing later phases, we will develop an updated plan. For a one year tactical model, the solution of the model may be implemented in terms of immediate commitments for one month. Before implementation of the second month the tactical model will be run again with updated information. Similarly, the lower level operational model may be for several weeks and this model will be updated and re-run every week. The overall result is that planning is no longer thought of static "once-for-all-time" concept but as a dynamic ongoing activity.

Recognition of Uncertainty: Implicit in the hierarchical approach is a recognition that the planning environment is uncertain and that the most uncertain data is detailed information for time periods far removed from the current period. The use of an aggregate tactical level model, enables the process to provides broad guidance to policies that attempt to optimize the performance of the enterprise over time while leaving detailed decisions to be made when more accurate information is available as to data and system state.

Mirroring of Organizational Structure: One advantage of a hierarchical approach is that each model will be aimed at a specific level of management. Management at one level see model results which do not include the details that are, for the most part, inappropriate at their level. Furthermore, the constraints provided to the model from the upper level models correspond closely to the type of constraints that management normally experience on their own decisions. Dempster et al. have observed that there is again a chicken and egg situation here. They comment that "hierarchical organizations, as well as hierarchical planning systems are a response to the nature of the problem being solved and to the need to reduce complexity and respond to uncertainty.

We might comment that, even in organizations that do not use extensive formal models for planning, many of the principles of hierarchical planning can be observed in practice. Volman, et al. (Chpt. 15) in their Ethan Allan case study illustrate this quite clearly. We might also comment that it is not necessary that the models involved be optimization models. Gunn and Rutherford provide an example where the lower level decision is facilitated by a detailed simulation model. The key point is that lower level decisions constantly respond to an updated system state within the context of policy constraints from upper level decisions.

A HIERARCHY OF FOREST PLANNING

Since this is a paper about forestry planning models, we turn to the question of what lessons we can learn from the experience of hierarchical planning. We first point out that many of the negative reactions that forest analysts have experienced with regard to modelling are very similar to the experience in the manufacturing industries. It is just this type of response that led to the development of hierarchical planning systems.

In the development of an hierarchical approach to forest management, we will try to address three issues. The first is the identification of appropriate levels and the decision problems that need to be addressed at each level. The second is discussion of the aggregation at each level and the information feedforward/feedback. The third will be the treatment of uncertainty. For the purposes of this paper we will focus on the tactical level. There are two reasons for this. Firstly we shall argue that the major modelling efforts, embodied in such packages as FORPLAN, TimberRAM etc. have been aimed at tactical planning. Secondly, tactical models are often used at the strategic decision level as simulation devices. Furthermore, the operational level tends to be highly specialized to the local environment so that the types of models appropriate at this level are not completely clear.

Strategic Level

The role of the strategic level is to decide on the resources available to the enterprise . The first question to address is what is the enterprise? In many situations there are actually two levels here. Much of the forest land is owned by governments and is either operated directly by government or on long term lease with policy regulation on harvest and management. On the other hand, production capacity decisions in wood using industries are usually a private enterprise decision.

Our framework will be that of a firm that owns its own land outright or holds it under long term lease. The major strategic decisions appear to be of two types. The first is how much land to operate for forestry purposes. The second is the production capacity of the various segments of the enterprise. These would include the number, type and capacity of sawmills, pulpmills, and facilities requiring wood fiber. Associated with these decisions are others that affect the cost and/or yield of the enterprise. These would include investments in harvesting systems, transport systems, and processing machinery. Strategic decisions could also include long term contracts since these can be regarded as a resource to be exploited. At the governmental level, there is yet another type of strategic decision. This is the decision as to the regulatory environment in terms of environmental, wildlife and other ecological effects.

It should be emphasized that strategic decisions are normally what Simon has called "nonprogrammed" (Bradley et al., 1977) The decisions are multi-criteria and involve substantial risk and uncertainty. Decisions are not made purely on "economic" terms. In many cases they involve an expression of will on how the enterprise wishes to define itself. Interestingly, the Swedish approach to forest involves just such a strategic approach (see Hägglund). Few models have evolved that address the strategic problems of forestry. Some models are being used to examine capacity issues (see Vertinsky et. al. as well as several papers at this symposium), but this is somewhat different from capacity modelling in other industries (Luss, 1982). In general we see evidence of tactical models being used to simulate the effects of strategic alternatives.

Tactical Level

Forestry presents an interesting case in that some of the tactical problems are of such long term that they almost beg to be treated as a strategic. For example, we have the harvest scheduling problem addressed by the linear programming packages such as FORPLAN, MUSYC, and TimberRAM. In spite of its very long time horizon, the nature of the problem is clearly tactical; namely how to schedule harvesting and silvicultural activities for an existing land base over time. No resources are being created for the enterprise. We will return to examine these models and ask how appropriate they are for this tactical planning task.

Tactical problems in industrial forestry have at least three aspects. The first is guaranteeing the long term supply of the wood consuming industry while maximizing expected profits. This supply problem requires an attention to not only the gross timber harvest at any point in time but its division into appropriate timber classes (softwood and hardwood; veneer logs, sawlogs, pulpwood). The second involves stand level harvesting issues. These involve developing a plan for harvesting and silviculture treatments specific to the site capabilities and species of the various stands in a district or some smaller management region. Issues, such as adjacency and/or road building, may also need to be considered. The third is the problem of annual aggregate wood logistics. At this stage growth is not an issue. The problem is to decide where to harvest and on the allocation of the harvested timber types to mills so as to maximize profit (gross revenues minus harvesting transportation and other procurement costs). Issues of available work force and machinery as well as mill production schedules, seasonality in markets and management of finished product inventory may well enter here. The outcome of the annual aggregate plan is usually an annual or longer term budget.

It should be noted that much of the current usage of FORPLAN and other such packages have been for tactical problems with significant constraints not mentioned above. These have often included stringent definitions of sustainability as well as specific concerns as to wildlife habitat and preservation of ecological niches. It is important to recognize that these constraints constitute strategic decisions of the forest enterprise or of the larger society within which the enterprise exists. Tactical level models do not have normative capability for these strategic decisions. What tactical level models do provide is the ability to evaluate (simulate) the consequences of these decisions in terms of the tactical level objectives. There is a need however to be careful as to what tactical level consequence is being simulated. Often this simulation is carried out with stand level models over a relatively small timbersheds (100-1000 acres). This may mean that the sustainability constraints (non-declining yield) are too restrictive and that more realistic constraints (over a much larger land base) should be used. Furthermore the impact of constraints on wildlife habitat and preservation of unique ecological features may appear to be more severe than they would in the larger picture. On the other hand, the combined effects of these types of constraints over a number of different timbersheds may have quite severe consequences to the feasibility and economics of total timber supply.

Operational Level

The line dividing tactical from operational decisions is never precise. The easiest distinction is that operational decisions are those that are implemented whereas tactical decisions constitute plans within which these actions are taken. The role of operational planning is making sure the system functions effectively within the tactical framework. Within forestry, operational decisions typically constitute the weekly and shorter term decisions. One operational decision is deciding to implement, possibly with modifications, the next period (month) of the relevant tactical plan. The remaining decisions are the details of how to do this. These are project management and scheduling decisions. They would include scheduling cutting crews and machines to stands, maintenance scheduling, truck allocation and scheduling, mill production schedules and specification of wood mix, sawing optimization and others. The primary goals are feasibility and cost minimization. One point to raise is that there needs to be some mechanism to verify that tactical plans can in fact be implemented operationally.

Operational level decision making is usually highly specific to the particular enterprise. A great deal of Operations Research work has been addressed to these types of issues in many different types of industry. This work is extensively used in the forest industry, but very little of it has been published[3] .

MODELLING FOR TACTICAL PLANNING

A number of issues have appeared in the literature dealing with what we are categorizing as tactical models. A fundamental question involves the modelling approach. There are three that might be considered. The first is the development of harvest policies based upon the economics inherent in the Faustmann formula. Although this has obvious advantages in terms of modelling simplicity, as a method of developing tactical plans it suffers from fundamental flaws (Tait(1988), Gunn(1988), Gunn and Rai(1987)). The primary flaw is that no account is taken of the current state of the forest nor of the capacity to use the wood produced as a result of the harvest process. A second approach involves the use of linear programming models such as FORPLAN, MUSYC, and others. This shall be the main focus of our discussion below. Thirdly, there are a number of simulation based models such as FORMAN (see Jamnick, 1990 for a discussion) which have been used as analysis tools for tactical planning. We do not plan to deal with these here, but it should be noted that simulation models can play an important role in tactical planning (Silver and Peterson, page 558-559). Gunn and Rutherford(1990) give an example in the mining industry where a simulation model is used to operationalize a tactical plan developed via a linear programming model.

We now turn to examine the linear programming approach. Before this discussion let us outline a somewhat abstract version of these LP problems. We will state the model as:

$$\text{Maximize} \sum_{t=1}^{T} e^{-rt} \sum_{z=1}^{Z} R_{zt}(x_z,h_z)$$

Subject to :

$$x_z = G_z(h_z), \qquad z=1,Z \qquad (1)$$

$$(x_z,h_z) \in \mathbf{F}_z, \qquad z=1,Z \qquad (2)$$

$$\sum_{z=1}^{Z} H_{zt}(x_z,h_z) \in \mathbf{H}_t \qquad t=1,T \qquad (3)$$

where :

T is the time horizon, the number of time periods.
Z is the number of management zones .

h_z is a vector of decision variables indicating harvest policy on zone z. Usually h_z will have dimensions depending on the number of time periods and age classes.
x_z is a vector of state variables of timber amounts over time on zone z. Usually x_z will have dimensions depending on the number of time periods and age classes.

$R_{zt}(x_z,h_z)$ is a function giving expected revenue in period t, zone z for the decision process h_z and the state process x_z
$G_z(h_z)$ is a function relating the state process for region z to the choice of the harvest process h_z
$H_{zt}(h_z)$ is a function giving the wood volumes from zone z generated in period t by using harvest policy h_z.

$\mathbf{F}_z$ is the set of feasible harvest, state processes for region z
$\mathbf{H}_t$ is the set of feasible timber harvest volumes for period t

This structure portrays the forest harvest scheduling problem as involving harvest decisions over a number of independent zones z=1,Z. The objective is to maximize discounted net present value of revenues with the only linkage being the Harvest Constraints (3). Without this linkage, then the solution to this model would correspond to Faustman like harvest policies on each zone.

There are a number of questions that are often raised with regard to these models. We argue that much of the confusion is a result of not considering the particular tactical planning role. These questions include i) model type, ii) stand vs. region based models, iii) time horizon and time divisions, iv) flow constraints and v) attitude to uncertainty.

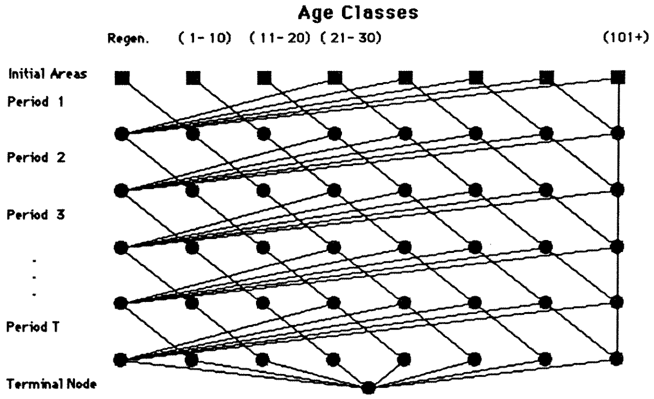

Figure 1 Model III Network Representation

Model Type

This refers to the modelling of the growth harvest process on each zone (equations 2,3 above) Three dominant models of the growth/harvest process have emerged. The first two, referred to as Model I and Model II, were first discussed by Johnson and Scheurman (1977). Model I consists of enumerating a number of possible schedules for a given land unit with the decision variables consisting of an assignment (or partial assignment) of the land unit to the harvest schedule. Model II consists of specifying a network of possibilities where each arc corresponds to the assignment of the land unit to a particular treatment/harvest strategy only until the next regeneration process. Although equivalent flexibility in harvest schedules can be represented with a much smaller number of decision variables using a Model II representation, Model II requires a more

[3] witness the comments of Ralph Colberg, Mead Coated Board at this symposium.

extensive constraint structure than the equivalent Model I. The third model, which we will refer to as Model III, involves another type of network structure (see Figure 1) developed simultaneously by Garcia (1984), Reed and Errico (1986) and Gunn and Rai (see Rai, 1984) where nodes correspond to age class and time period and the arcs are of two types. Harvest arcs lead from a given age class in in period to the 0 (regeneration) age class in the next period. Growth arcs lead to the next age class in the next period. Fundamental to Model III is the assumption that the length of a time period is equal to the width of an age class.

Stand Based versus Region Based Models

The question here is what do we mean by the "regions" in our LP model. Jamnick et.al. (1990) have recently explored the accuracy of stand based versus region based models. For stand based models, the forest is represented on a stand basis. A stand is usually thought of a unit of land with a homogenous mix of species, age class and homogenous growing conditions (soil, drainage, etc). Stands are the natural unit for the forest treatments since, only with the knowledge of the details of stand composition and site conditions is it possible to forecast response. On the other hand, it requires an enormous number of stands to represent the landholdings of any large scale forest enterprise. Another option is to aggregate landholdings on some basis, usually geography, ownership, covertype, site type and try to predict the growth and silviculture response of this aggregate. Jamnick et. al. have shown that this may well underestimate the performance achievable with a stand based model. However, for overall enterprise planning, even a region based representation leads to large models and this may be the only feasible alternative.

Time Horizon and Time Divisions

The proper choice of the time horizon T and time divisions t is a question which often arises in these models. Long horizons are required to ensure long term feasibility of the wood supply and to properly take into account future costs imposed by current decisions. Small time divisions are useful to properly account for growth and the overall wood supply dynamics. However, long time horizons and small time divisions imply enormous models. Compromises inevitably have to be made. As we will discuss, there are in fact different levels of tactical models that should be used and different time horizons and time divisions are appropriate for these different models.

Flow Constraints

The nature of the harvest flow constraints (3) is worthy of some discussion. In Ware and Clutter (1971), it was made clear that without some version of these constraints, the harvest becomes extremely erratic and incompatible with the normal operation of a wood processing industry. Two types of constraints are often used. One of these is even flow where the requirement is that the harvest volume in period t should be equal to (within a tolerance) the harvest in period t-1. A second type, commonly used within FORPLAN, is non-declining yield where the constraints (3) require that the harvest in year t is greater than in year t-1. Both of these have the difficulty that harvest is itself a multi-dimensional quantity. There are issues of commodity classes of the timber produced, for example veneer logs, sawlogs, pulpwood. Also, it is not clear how best to measure harvest, by volume, by area harvested, by revenue. It would appear that both the even flow and non-declining yield constraints are not very suitable for tactical models. First, they have little meaning in terms of the operation of an enterprise. Second, they are known to produce unstable and paradoxical effects when implemented in a rolling planning framework (see Daugherty[4] and Pickens et al.) Barros and Weintraub (1982) and Gunn and Rai(1987) have discussed situations where, there are issues of substitution and complementary production. Sawlogs can be substituted for pulpwood. Also, sawlogs, when processed, result in chips which can serve as inputs to the pulpmill. In both cases, we see the use of capacity based constraints as flow constraints. The Gunn and Rai formulation of this model is reproduced in Appendix 1 to illustrate this type of modelling. These capacity oriented constraints appear better suited for many tactical planning implementations.

Uncertainty

The LP models do not explicitly account for uncertainty. There are however a number of implicit ways of doing so. Discount rates higher that nominal interest are often used as one means (see Bussey, 1980). Many modellers will downgrade growth estimates as a hedge against catastrophic events such as fire or budworm. Finally, using the model in a rolling horizon framework amounts to a way of taking advantage of the recourse possibilities to uncertain events. In other industries, notably the electric power industry, one often sees the use of a reserve margin on system demand used as a mechanism for dealing with uncertainty. However, unless the harvest flow constraints are similar to the capacity based constraints of Gunn and Rai (1987) and Barros and Weintraub (1982), reserve margins on system demand constraints are not possible.

STRUCTURING A FAMILY OF TACTICAL MODELS

In fact, we can identify three types of tactical level problems in forest planing; long range tactical, medium term tactical and annual aggregate planning. We comment on each of these problems and indicate the relevant aspects of modelling.

Long Range Tactical

This problem is that of ensuring long term enterprise wood supply while maximizing forest net revenues. In particular, the focus should be on the various types of timber requirements (veneer logs , sawlogs, pulpwood) and how these requirements can be satisfied from the total landholdings of the enterprise. Landholdings are differentiated by management district (geographical zone), forest cover and possibly by ownership distinctions. In the situations that we have in mind, sustainability of harvest is in terms of the long term ability to supply industry requirements, although there will be a need to consider other issues such as workforce stability within each district.

For this type of problem, a region-based model with capacity based flow constraints and a very long time horizon appears to be necessary. By specifying reserve margins on capacity in the wood using industry, we can increase the probability of being able to meet requirements. Since the models are not stand specific, most of the arguments for Model I formulations would not apply. This would argue for use of Model II or III.

Medium Term Tactical

The long range tactical models can, based on highly aggregate forest information and uncertain information on price, market, growth and technology, develop an optimal plan in terms of forest harvesting by zone that is long term feasible for industry capacity. However, since it is not stand specific, it is not possible to interpret this solution on terms of stand treatments. The medium term problem is to decide on these stand level decisions for the stands within a zone.

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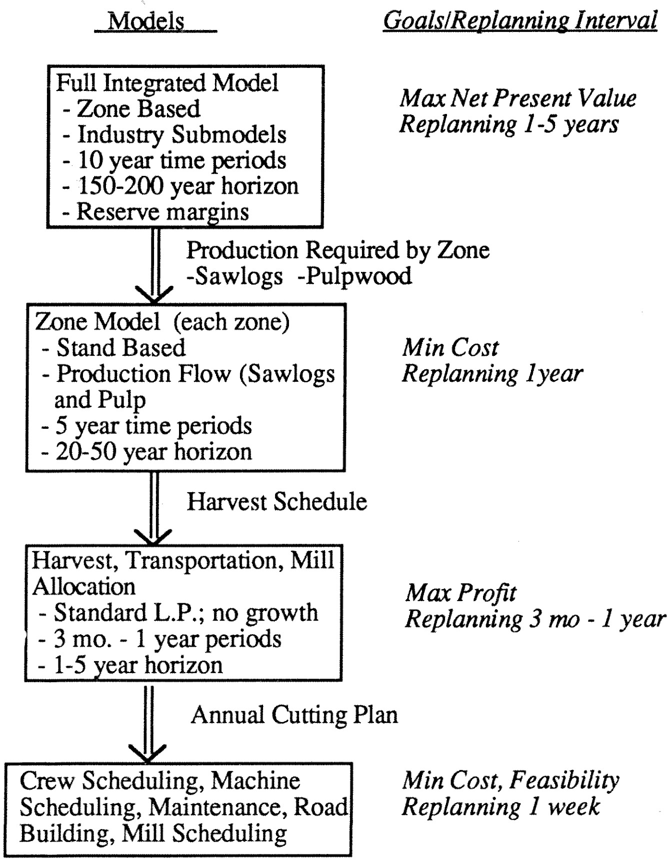
[4] P.J.Daugherty, Dynamic Inconsistency in Forest Planning, at this symposium.

Clearly this model should be stand based. Because the upper level model gives a rough idea of harvest and silviculture policy, it may be reasonable to use a Model I based formulation because of the flexibility it allows. This model does not need to be as long term as that discussed above since issues of long term feasibility have been dealt with there. However, it would seem wise to use shorter periods to facilitate implementation. Harvest flow constraints can be simplified to requiring that the volume of each type of wood produced correspond to that calculated in the long term model for each model period.

Short Term Tactical

The output of the medium term plan will give a harvest and treatment plan for each stand. However, this plan is still not detailed enough for annual planning. We need to be able to specify for the coming year (perhaps broken down to smaller time periods) which stands to cut and how to allocate the wood products to the mills operated by the enterprise and/or its customers so as to maximize its profits. Constraints, such as available workforce and machinery, enter into the model as do mill prices, harvest costs, and transportation costs. These models may be single period models or multi period models covering up to five or more years with quarterly or monthly periods. The key distinction is that it is not necessary to account for growth in these models. These are quite standard LP models. A single period model of this type was described by Gunn (1975)

Figure 2. Outline of Example Hierarchical Structure



Overall Structure

Given the above considerations, the outcome is a structure somewhat like that shown in Figure 2. This figure indicates the goal and nature of each tactical level, the replanning interval and information linkage to the lower level problem in the hierarchy. It is worthwhile noting the similarities between the structure presented here and that discussed by Morales and Weintraub.[5] There are two points to note about this structure. First, it is oriented to implementation with each model leading to an immediate decision. For example the long term tactical decision is how much to plan to cut from each zone over the next 10 years. The medium term decision is the amount of harvest and silviculture treatment on each stand of the zone in the next 5 years. The short term decision is how much to harvest from each stand in the zone over the next year and how to market the resulting timber . The operational decisions include where to send the cutting crews next week. The second point to note is that long term decisions do not depend on detailed information in periods far from the current decision point. Problems increase in detail but decrease in planning horizon as we proceed down the decision hierarchy.

HIERARCHICAL PLANNING AND UNCERTAINTY

As indicated above, a hierarchical planning framework has computational advantages and advantages in terms of mirroring the structure of decision and implementation. We want to now briefly address its role in coping with uncertainty. The viewpoint that we adopt below is oriented to what we have termed the long term integrated model. However the notion is general. The framework that we choose is that of stochastic programming. The problem that we consider can be written, again abstractly, as:

$$\text{Max } \{ R_0(x_0, h_0) + e^{-r} E_\xi G_1(x_1);\ h_0 \in \mathbf{H}(x_0) \} \qquad (4)$$

where :

$$x_{t+1} = \gamma(x_t, h_t, \xi_t(x_t)) \qquad (5)$$

$$G_t(x_t) = \text{Max } \{ R_t(x_t, h_t) + e^{-r} E_\xi G_{t+1}(x_{t+1});\ h_t \in \mathbf{H}(x_t) \} \qquad (6)$$

and:

x_t - state of the forest enterprise at the beginning of period t
h_t - management or harvest action in period t
$\xi_t(x_t)$ - stochastic process conditional on x_t
r - discount rate
$R_t(x_t, h_t)$ - return in period t if we begin in state x_t and follow management action h_t
$\mathbf{H}(x_t)$ - the set of feasible management actions given the forest state x_t.
$\gamma(x_t, h_t, \xi_t)$ - a function giving the end of period forest state given the initial state x_t, the management action h_t and the realization ξ_t from the stochastic process

This problem statement is that of taking a decision today that maximizes the expected net present value of all future returns. Note that the possibility of disaster is not excluded in the above model. That is, it is possible, given a sequence of decisions h_0, ... h_{t-1} and outcomes $\xi_0(x_0)$ ... $\xi_{t-1}(x_t -1)$, that we come to a point where the function $R_t(x_t, h_t) = -\infty$ for all $h_t \in \mathbf{H}(x_t)$ or where $\mathbf{H}(x_t)$ is empty. This corresponds to their being no feasible way to supply the industry needs in period t. In that case

[5] R. Marales and A. Weintraub, A model for strategic planing in the management of pine forest industries, Presented at this symposium.

$G_t(x_t) = -\infty$. Note finally that there is no particular requirement that T be finite. However it is well known that, depending on the discount rate r, we can approximate the optimal decision h_o^* by using only a finite number of time periods.

It is important to note the decision and information structure of the problem. First the only decision that one takes with certainty is the current decision h_0. All future decisions h_t depend on the the state variable x_t which in turn depends on the conditional random process ξ. Second, the essential feature of the problem is recourse. One does not take the decision h_t at time 0, but only at time t with full knowledge as to the state x_t and the ability to exploit the action space $\mathbf{H}(x_t)$ to current returns and expected future returns.

If we compare the stochastic programming statement of the problem to the usual harvest scheduling linear programming, using a similar notation, the problem can be written:

$$\text{Maximize } G_0 \quad (7)$$

$$\text{Subject to:} \quad \begin{aligned} G_0 &= R_0(x_0, h_0) + e^{-r} G_1 \ \ldots \\ G_t &= R_t(x_t, h_t) + e^{-r} G_{t+1} \ \ldots \\ G_T &= R_T(x_T, h_T) \end{aligned} \quad (8)$$

$$\begin{aligned} x_1 &= \gamma(x_1, h_1, \bar{\xi}_1) \ldots \\ x_{t+1} &= \gamma(x_t, h_t, \bar{\xi}_t) \ldots \\ x_T &= \gamma(x_{T-1}, h_{T-1}, \bar{\xi}_{T-1}) \end{aligned} \quad (9)$$

$$\begin{aligned} h_0 &\in \mathbf{H}(x_0) \\ h_t &\in \mathbf{H}(x_t) \end{aligned} \quad (10)$$

The notation corresponds to (4-6), with the assumption that $R_t(x_t, h_t)$ and $\gamma(x_t, h_t, \bar{\xi}_t)$ are linear functions and the sets $\mathbf{H}(x_t)$ are described by linear constraints. The $\bar{\xi}_t$ is the "average value" of the process ξ. Note that, in general, it is not possible for this "average" to correspond to the mean of ξ_t since ξ_t is conditional upon x_t.

Note the differences between problem (7)-(10) compared to (4)-(6) First the decision structure is different. The decisions $h_0, \ldots, h_T$ are taken at t=0 once for all time. Furthermore these decisions h_t are taken not with perfect knowledge of a state x_t, but with respect to some "average" state that results from the "averaged process". There is no possibility of recourse if the outcome of the stochastic process is either below or above the "average". Given the enormous number of recourse actions in the forest, we would normally expect to be able to do better than this "average" decision.

If stochastic programming is the correct decision framework, what can we say about exploiting this computationally. In terms of doing this directly, the news is not encouraging. There are two alternatives. One is dynamic programming, the use of which is well known on problems of the form (4-6) (see Lembersky and Johnson, 1975). However the computational requirements of this approach grow dramatically with the dimension of the state vector x_t. The Lembersky and Johnson model has only been applied to single stand situations where it is not possible to capture the recourse possibilities of managing a large number of stands simultaneously. The other approach is stochastic linear programming. Gassman (1989) has illustrated an application of these ideas to examine the effect of fire. The problem with this approach is that its computational requirements grow with the number of possible realizations from the stochastic process. This tends to mean that only highly simplified situations can be modelled.

The encouraging news is that Dempster et. al. report that a hierarchical planning process is actually a good heuristic for solving stochastic programming problems. That is, if we solve the linear programming model (7)-(10) but in a rolling planning horizon framework then this should perform reasonably well. By a rolling horizon, we mean that only the first period solution is implemented and all parameters of the model are updated and the optimal solution re-calculated before proceeding to the next period. By doing this we make possible recourse to unplanned events. There are two questions about this approach that need to be answered. First are there things that we can do to the LP model to make it more suitable for the underlying stochastic programming problem. Second, can we verify that the hierarchical is likely to perform well in this forest management environment.

Making the LP Model More Suitable

We have two suggestions for the question of making the LP model more suitable. First, higher discount rates should be used than might be used in certain environments. If a model has an outcome that the optimal solution obtains much of its economic benefits from periods far in the future, these should be discounted because of uncertainty. A higher discount rate will lower these benefits and lead the model to explore solutions where benefits are obtained earlier when they are less uncertain. The second issue is feasibility. Although, in an uncertain environment, it is desirable to obtain benefits as early as possible, it is not desirable that this be done at the expense of long term feasibility. Thus it is important to focus clearly on how we define feasible harvest strategies. For long term integrated models, the type of constraints illustrated in Appendix 1 appear to be quite desirable since they make it possible to focus on the actual physical capacity of the industry. If these type of constraints are used, then it is possible to use a reserve margin approach. That is we can specify that the minimum supply requirements to the individual sectors (pulpmill, sawmill, etc) be set somewhat higher than would normally be the case. If this is done and a feasible solution obtained to the LP model, then this would increase the probability that actual industry requirements can be met in the uncertain future. This is a quite natural approach to the stochastic program. If we think of (4)-(6) as a two stage problem, the effect of second stage is to induce constraints on the first stage. In other words, there are certain first stage decisions that are feasible if the problem is only solved as a single stage problem but are not feasible when the feasibility requirements of the second stages is considered. If the problem is stochastic, then there is not just one second stage but a number of possible realizations, each of which induces its own constraints on the first stage. The use of reserve margins on the LP model has exactly this effect.

Verifying the Performance of Hierarchical Planning

There are two problems here. The first is that of modelling the process of uncertainty and the second is that of evaluating the hierarchical planning system.

It is probably impossible to accurately model the uncertainties that face foresters. However one useful approach is that of scenario analysis. The problem here is can we generate a relatively small number (10-100) of scenarios that are "typical" of the actual process. If this can be done then the process of "scenario aggregation" can be used either in the formal sense (Rockafellar and Wets) or in a less formal sense. The idea is that we can think of the stochastic problem as being the independent LP problems, one for each scenario, with the additional constraint that all first stage decisions must be the same. More formally, for multi-stage problems, all decisions that have the same information process must be the same. The idea is not new (Wagner, 1975) but can be exploited in a number of ways. First the expected value (probability weighted average) of the independent solutions gives a lower bound on the stochastic problem. Second if we take the first stage solution of the "average" LP problem and use it for each of the independent scenarios, if feasible, this gives an upper bound on the stochastic problem. The difference between these bounds is a measure of the value of information.

The problem of generating appropriate scenarios for forest management problems and then using these to evaluate the hierarchical approach remains open for further research.

CONCLUSION

Hierarchical planning systems have had a strong impact on the planning process of manufacturing and other industries. They offer potential computational advantages but, more importantly, they also offer advantages in implementation in that a well structured hierarchical system reflects the organization and decision processes of the enterprise.

An important issue in hierarchical systems is their ability to deal with the uncertainty that is typical if the real environment. Previous research indicates that hierarchical planning systems are well suited to deal with these issues but research remains to verify these issues and to discover the most effective means of structuring the decision process to cope with this uncertainty.

APPENDIX I - FORMULATION OF AN INTEGRATED MODEL

This model is based on the Model III land management constraints. The wood demand sector is highly simplified with one pulpmill, one sawmill with a chipper, one sawmill with no chipping capability and with one "other demand" sector which we refer to as firewood. These "mills" are best thought of as aggregate representations of the demand in the relevant sectors. This particular aggregation is only one example; others may be appropriate in particular circumstances. This aggregation does however capture the features of substitutability (sawlogs for pulpwood) and of dependent demand (puplwood on chips). For a more detailed discussion see Gunn and Rai (1987).

Variables

- X_{ijt} — hectares of land of harvest zone i in age class j at end of period t.
- C_{ijt} — hectares of land of harvest zone i in age class j regeneration harvested during period t.
- SL_t^k, HL_t^k — volume (m^3) of softwood (SL) and hardwood (HL) sawlogs allocated to use k in period t. Use k=1 corresponds to sawmills with a chipper; use k=2 corresponds to sawmills without a chipper; use k=3 corresponds to pulpmills.
- SP_t, HP_t — volume (m^3) of softwood (SL) and hardwood (HL) pulpwood allocated to pulpmill in period t.
- SP_t, HP_t — volume (m^3) of softwood (SL) and hardwood (HL) pulpwood allocated to firewood (non-pulpmill or sawlog) demand in period t.
- SC_t, HC_t — volume (m^3) of softwood (SL) and hardwood (HL) chips produced at sawmill and allocated to pulpmill in period t.

Constraints

Land Management Constraints for Harvest Zone i

$$X_{ijt}= X_{i(j-1)(t-1)} - C_{ijt} \qquad j=1,J \qquad t=1,T$$

$$X_{iJt} = X_{i(J-1)(t-1)} + X_{iJ(t-1)} - C_{iJt} \qquad t=1,T$$

$$X_{i0t} = \sum_{j=1,J} C_{ijt} \qquad t=1,T$$

Data: J - number of age classes
T - number of Time periods
$X_{i,j,0}$ - hectares in age class j at period 0 (initial)

Mass Balance Constraints for Each Period t

$$\sum_{i=1,I} \sum_{j=1,J} (hsp_{ijt} C_{ijt} + tsp_{ijt} X_{ijt}) = SP_t + SF_t$$

$$\sum_{i=1,I} \sum_{j=1,J} (hsl_{ijt} C_{ijt} + tsl_{ijt} X_{ijt}) = SL^1_t + SL^2_t + SL^3_t$$

$$\sum_{i=1,I} \sum_{j=1,J} (hhp_{ijt} C_{ijt} + thp_{ijt} X_{ijt}) = HP_t + HF_t$$

$$\sum_{i=1,I} \sum_{j=1,J} (hhl_{ijt} C_{ijt} + thl_{ijt} X_{ijt}) = HL^1_t + HL^2_t + HL^3_t$$

Data: i) hsp_{ijt}, hsl_{ijt}, hhp_{ijt}, hhl_{ijt} - volume (m^3) of softwood pulpwood, softwood logs, hardwood pulpwood, hardwood logs, respectively produced by regeneration harvesting one hectare of harvest zone i, age class j in period t.
ii) tsp_{ijt}, tsl_{ijt}, thp_{ijt}, thl_{ijt} - volume (m^3) of softwood pulpwood, softwood logs, hardwood pulpwood, hardwood logs, respectively produced by thinning and other activities on one hectare of harvest zone i, age class j which does not undergo regeneration harvesting in period t.

Allocation Constraints for Consuming Sectors in Period t

i) Sawmill Demand

$$minsl^1_t \le SL^1_t \le maxsl^1_t \qquad minhl^1_t \le HL^1_t \le maxhl^1_t$$

$$minsl^2_t \le SL^2_t \le maxsl^2_t \qquad minhl^2_t \le HL^2_t \le maxhl^2_t$$

ii) Chip Production

$$SC_t = \alpha\, SL^1_t \qquad HC_t = \alpha\, HL^1_t$$

iii) Pulpmill Demand

$$minsp_t \le \beta_1 SP_t + \beta_2 SL^3_t + SC_t \le maxsp_t$$

$$minhp_t \le \beta_3 HP_t + \beta_4 HL^3_t + HC_t \le maxhp_t$$

iv) Firewood Demand

$$minsf_t \le SF_t \le maxsf_t \qquad minhf_t \le HF_t \le maxhf_t$$

Data:

- $minxx_t$, $maxxx_t$ — Minimum and maximum demand for sector *xx* in period t. The sectors *xx* correspond to softwood and hardwood at sawmills 1 and 2 (sl^1, sl^2, hl^1, sl^2), softwood and hardwood at pulpmills (sp, hp) and softwood and hardwood firewood (sf,hf). Note pulpmill demand is in m^3 of chips.
- α — volume of chips per unit volume of sawlogs.
- β_1, β_2, β_3, β_4 — volume of chips produced per unit volume of softwood pulpwood, softwood sawlogs, hardwood pulpwood and hardwood sawlogs respectively.

Objective Function

$$\text{Maximize} \sum_{t=1,T} \phi_t [\, psl'_t (SL^1_t + SL^2_t) + psl''_t SL^3_t + psc_t SC_t + psp_t SP_t + psf_t SF_t + phl'_t (HL^1_t + HL^2_t) + phl''_t HL^3_t + phc_t HC_t + php_t HP_t + phf_t HF_t \,]$$

Data:

ϕ_t	discount factor for period t
psl'_t, phl'_t	price for softwood, hardwood sawlogs ($/m^3) delivered to sawmills in period t.
psl''_t, phl''_t	price for softwood, hardwood sawlogs ($/m^3) delivered to pulpmill in period t.
psc_t, phc_t	price for softwood, hardwood chips ($/m^3) delivered to pulpmill in period t.
psp_t, php_t	price for softwood, hardwood pulpwood ($/m^3) delivered to pulpmill in period t.
psf_t, phf_t	price for softwood, hardwood firewood ($/m^3) in period t.

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ECOSYSTEM CLASSIFICATION AND MAPPING ON NATIONAL FORESTS[1]

Peter E. Avers
Edward F. Schlatterer[2]

Abstract

The Forest Service has issued new national direction to guide the agency toward implementing an ecosystem classification and mapping framework for land and resource management planning. The purpose is to provide an ecologically sound basis for resource management that integrates landscape components of soil, vegetation, landform, geologic material, topographic features, and climate. Ecological types are classified and used to design ecological inventories that stratify land into map units that can be used as capability areas for planning, resource management, and monitoring of resource response. The map units are categories of land that have a unique combination of vegetation, soil, landscape features, etc., and differ from other categories in ability to produce vegetation and respond to management. Interpretations are made for production capability, biological diversity, and to predict ecosystem responses to various management practices. Each Forest Service Region has developed slightly different approaches in the way they classify ecosystems to establish ecological types and ecological map units. These variations are briefly described to show the relationship to the generic national direction.

Keywords: Ecosystem, classification, inventory, mapping, National Forests, ecological site, ecological type, ecological unit, potential national community.

INTRODUCTION

The National Environmental Policy Act of 1969 (NEPA) directed all federal agencies to: "Initiate and utilize ecological information in the planning and development of resource-oriented projects."

Both the Forest and Rangeland Resources Planning Act of 1974 (RPA) and the National Forest Management Act of 1976 (NFMA) require a systematic interdisciplinary approach in planning and management. They also require that comprehensive and appropriately detailed inventories be conducted and used on the National Forest System.

Because forest planning was mandated to be completed for all National Forests within a rather short time frame, it was impossible to conduct ecological inventories for all units for the first round of forest plans. Some ecological inventories were available for some forests, but for the most part, existing functional or component inventories were used as the basis for initial forest planning.

The Forest Service is now nearing the completion of the initial forest planning effort and beginning revision of the first forest plans on a 10-15 year cycle as required by law. It is recognized by many that fully integrated ecological inventories will be needed for this revision process.

The 1990 RPA program recognized the growing environmental concerns of the American public, and emphasizes environmentally sound commodity production. The program also provides a new environmental focus for management of non commodity resources on the National Forests.

The "New Perspectives" initiative provides for a fresh approach to land stewardship and expands the notions of sustained yield and multiple use to include a philosophy of keeping ecosystems intact. New Perspectives stresses the theme of land stewardship, sustainability for all uses and values, the integration of disciplines, and an ecosystem approach.

[1] Presented at the Systems Analysis in Forest Resources Symposium, March 3-7, 1991, Charleston, South Carolina.

[2] Soils Program Manager, Forest Service, U.S. Department of Agriculture, Washington, DC; Ecologist, Forest Service, U.S. Department of Agriculture, Washington, DC.

All of these factors are providing an accelerated stimulus for ecosystem classification and inventory as a basis for sound management, while maintaining healthy, whole sustainable ecosystems.

Background and philosophical basis

There is no theoretically perfect natural system of ecosystem classification and mapping which all users can embrace and use to satisfy their needs. We must be able to classify, map, and interpret ecosystems according to the needs of the user. The needs of the user vary with the issues, management proposed, time, and questions asked. The criteria used for ecological type classification is critical; but even more critical are the design criteria used for ecological unit mapping. The reason map quality is so important is that most Forest Service resource planning and management is centered around geographical information on maps.

The emphasis on vegetation criteria has produced vegetation dominated classifications of ecosystems which can serve only some of the users with the need for management information. The emphasis on soil classification with a heavy emphasis on landform, topography, land systems, and geologic features has resulted in land classifications which only partially serve users needing vegetation management information.

A similar parallel can be made for mapping of ecological units. Vegetation dominated criteria result in ecological units predominately defined by vegetation characteristics, while soils and landform dominated criteria result in map units most useful for defining soil properties and soil characteristics important for management.

Neither system alone provides the needed information for multiple use management for a wide variety of users.

Soil inventory, vegetation inventory, and geologic inventories tend to be single component approaches with some evaluation of other criteria in mapping depending on the needs of the user. All are legitimate ecosystem classifications. They segment the landscape according to some defined criteria based on user need. Virtually all such classifications and maps are trying to define and characterize a response unit for some purpose. The purpose or need and the criteria to meet the purpose or need, defines how the mapped unit is designed. All can argue successfully that they have mapped an "ecosystem" or classified an "ecological type".

This is in fact the way that ecosystem classification and mapping has developed in the Forest Service up until the development of the current framework.

Significant past efforts

For over 75 years the Forest Service has conducted a wide variety of resource inventories that classify land and its resources. These inventories focus on the vegetation and are single purpose in nature. Timber inventories classify sites according to forest type, stand size or condition based on the existing vegetation. Range inventories classify range type, suitability and condition to reflect the kind, amount and quality of forage available for livestock consumption. Soil inventories began in the late 50's and could be considered at least partially integrated. Other single purpose inventories are also conducted for wildlife, water, recreation and cultural resources.

Some of the first efforts to deal seriously with the mapping and classification of land on an integrated basis began with California soil-vegetation surveys in the late 1930's but did not get into full swing until after World War II. The Pacific Northwest and Southern Regions initiated inventories that integrated soils, landform and existing vegetation in the early 1970's. The Intermountain and Northern Regions developed and initiated a Land System Inventory (Wertz and Arnold) in the late 1960's. Soils, landform, geology, and potential natural vegetation were included in these inventories, but the primary focus was landform and soils. Other efforts include Terrestrial Ecosystems developed by the Southwestern Region in the late 1970's. The Alaska Region and the Eastern Region developed modifications of the land systems approach. Bailey published Ecoregions of the United States in 1976, an adaption of the lands systems approach.

In the fifties the Daubenmires developed the habitat type approach. Habitat types are developed on the basis of climax vegetation under the assumption that the vegetation in its climax form, when occupying a site, is the ultimate integrator of that site. Since the 1970's students and disciples of Daubenmire have expanded the coverage of habitat type classification to most of the Western United States and into the Great Lakes Region.

Variations of Daubenmire's method have developed with the realization that, while climax vegetation may be the integrator of a site for some characteristics of the vegetation, many important factors for the management of the land and its vegetation cannot be derived from climax vegetation classification. Variations include the incorporation of soil properties and other significant environmental characteristics as modifiers to the classifications. While these variations are an improvement over habitat types, the resulting classification is still incomplete for providing interpretations for multiple uses.

Since the late 70's, the concept of integrated ecosystem classification and mapping has evolved and was first formulated in 1982 in Forest service Manual and Handbook direction. Since then three revisions have been made to strengthen the policy and direction and achieve a greater coordination of the varying efforts in the Regions, and finally require ecosystem classification and mapping for planning and management.

Current Direction

In an effort to bring divergent systems of ecosystem classification and mapping closer together and unify approaches, new manual and handbook direction has been developed.

In it we have attempted to bring together the diverse approaches used by our Regions and Forests, within a broad framework, with the objective of satisfying as many user needs simultaneously as possible. Basically the current framework provides common definitions, establishes general process, and encourages creative approaches to meet regional needs.

Ecological type classification and ecological unit mapping is an effort to bring soils and vegetation information together to define and describe the most meaningful ecological types and units for a maximum of user needs including definition of capability areas for planning and management.

We believe ecological type and ecological unit descriptions and maps provide significantly better information for multiple use management than can be provided by separate components and/or maps being aggregated for the same purpose. The reason is that in defining and describing integrated ecological types and units, both soils and vegetation experts make simultaneous definition and evaluation of criteria and evaluating them against the needed information in an interdisciplinary way.

With the advent of Geographical Information System (GIS) and greatly improved personal computer capacity and capability, there is a strong tendency in some quarters, to create ecological units from the sum of the parts or some combination thereof. While our current direction allows for such ecological unit identification, we firmly believe that the beneficial effects of the synergism of various disciplines working together to create meaningful ecological units and making interdisciplinary interpretations for them, far outweigh the simplistic quick fix that results from GIS generated units. Boundary problems can be resolved by mutual consent and detailed evaluation of the map unit criteria by the disciplines involved. Interpretations over and above those of the individual component maps are generated through the interaction of the disciplines, resulting in expanded user benefits.

Exceptions are individual component maps which have been defined by an interdisciplinary (ID) team where factors, in addition to the individual component characteristics have been used in design. Ecological units formed from the aggregation of such component maps, approximate the quality of ecological units developed in the aggregate because boundary differences have been resolved and interpretations expanded by the ID team interaction.

Universal System

While the Forest Service has not yet achieved the ideal of a universal ecological type classification system and ecological unit inventory, we are making progress. Our Regional Soil Scientists and Regional Ecologists are working together toward this goal with new direction and quality assurance of National Forest inventories.

In spite of this progress, we do not expect to have a universal system of ecological classification and inventory in place any time in the near or even distant future. The Forest Service is a highly decentralized organization and does does not provide strong central control and direction. We have provided the national framework, but not the detail. In addition we recognize the diversity of land, soils, and vegetation in the United States and the wide variety of our user needs and wants, and allow for considerable variation in design and application of the broad principles we have formulated. We also rely heavily on the quality of our people, their expertise, knowledge and enthusiasm to work out the details as they see fit and as the needs dictate.

Objectives and Policy

There are two primary objectives for ecosystem classification and mapping on National Forests. 1) To provide a uniform ecosystem framework for use in land and resource management planning and; 2) To develop an ecologically based information system to aid in evaluating land capability, interpreting ecological relationships and improving multiple use management.

It is Forest Service policy to use ecological type classification and ecological unit inventories in planning, evaluation, and resource management; and to accomplish these activities with interagency coordination.

Within the national framework, Regional Foresters are responsible for providing specific classification, inventory, and evaluation direction and to ensure that ecological information is used in forest planning and project implementation. Regional Foresters and Station Directors share responsibility for developing standards for ecosystem classification and for the correlation of ecological type descriptions.

Forest Service Framework

Ecosystem Classification and mapping is accomplished by sampling ecological sites, classifying ecological types, and designing ecological units for mapping. Both ecological types and ecological units must be based on and describe vegetation, soils, topographic features, water, climate, geology, and landform.

Ecological sites. A specific location on the land, that is representative of an ecological type.

Ecological type is defined as a category of land having a unique combination of vegetation (potential natural plant community), soil, topographic features (slope gradient, aspect, slope position, and elevation), climate, geology, and landform. Ecological types differ from each other in ability to produce vegetation and respond to management practices.

An Ecological unit is defined as a mapped landscape unit designed to meet management objectives, comprised of one or more ecological types or composed of the set of components listed under ecological type.

The components and general direction for their use in characterizing ecological types and ecological units are described below:

1. Soil -

   Soils are described and classified based on Soil Taxonomy (USDA Agricultural Handbook 436) and correlated as part of the National Cooperative Soil Survey. The range of major characteristics and properties particularly important to management are noted. The spatial distribution and percentage of various taxonomic classes are determined and recorded. The soils are classified to the lowest level needed or practicable to meet management objectives. With soil classification and correlation, ecological unit inventories can serve as soil resource inventories and be published as soil surveys in the National Cooperative Soil Survey.

2. Vegetation -

   Plant communities are described for existing vegetation and for the potential natural community (PNC). Existing vegetation communities are described on the basis of significant differences in species composition, physiognomic or structural features, stand age, or numerical relationships along an ecological gradient. The potential natural community is the plant community that would be established if all successional sequences of its ecosystem were completed without human-caused disturbance under present environmental conditions. PNC differs from climax vegetation in that the influence of the past history of the site and its vegetation is recognized, which may have altered the potential, as well as the existence of naturalized exotic species. If PNC's can not be determined, provisional PNC's can be estimated based on the projection of the existing vegetation into the future and interpretation of abiotic factors.

3. Topographic features -

   This includes slope, elevation, and relief. Slope has gradient, length, and aspect. These features have locally defined classes to categorize and stratify ecological types and units to meet management needs. Often, changes in topographic features signal changes in soil type or plant community, and vice versa.

4. Geology -

   This primarily includes stratigraphy and lithology. Stratigraphy and lithology are characterized for their influence on soil parent material, soil mineralology, land stability, and other factors important to management or land capability. Major classes are defined in the Forest Service Resource Glossary.

5. Climate -

   Local and regional climatic differences important to land management are used to stratify the landscapes for ecological type classification and for map unit design. Broad climatic differences often coincide with physiographic boundries and are helpful when making general (order 4 or 5) inventories. Microclimatic gradients are important to detailed (order 2) map unit design and in classifying ecological types. Regions establish criteria and standards for climatic gradients to meet management needs.

6. Water -

   Areas of the landscape adjacent to streams, lakes, etc., or that have intermittent high water tables have hydrologic characteristics important to management. These areas, often called riparian areas, are classified and mapped using unique water related criteria. Wetlands are transition ecosystems between terrestrial and aquatic and are classified for ecological type and mapped as ecological units. Hydrologic data needed to classify wetlands is collected and correlated with the soils data and used to describe ecological types and design wetland ecological map units. National direction is not yet developed for classifying and inventorying aquatic ecosystems.

7. Landform -

   Any physical feature of the earth's surface having a characteristic, recognizable shape and produced by natural processes. These are defined in the Forest Service Resource Glossary.

Conventions

Except for the requirements to use the above named components in developing ecological type classifications and ecological unit mapping, we have established few hard and fast conventions. The one exception is the convention on naming ecological types. We require the use of a botanical name and a soils/environmental name on all ecological types that are defined. The sequence of which name comes first is optional.

In contrast, the naming convention for ecological units is very flexible. The name will depend on the criteria established for user needs and the local conventions which have been established. The components of vegetation, soil, topographic features, water, climate and geology must be at least described and characterized, but the degree of their use and the sequence and weight given to each component is variable.

Use of potential natural vegetation is encouraged, but our direction allows for use of existing vegetation when potential natural vegetation is not available or not possible to determine. It is preferred that potential natural vegetation be used in all circumstances and uniformly everywhere, but we recognize that, practically, potential natural vegetation cannot be determined in all cases. In the Southeast, for instance, many forested areas were heavily farmed in the early part of this century and many areas suffered very severe soil erosion. Nothing but a short term projection of the potential natural vegetation is possible under such circumstances. We have provided in our direction for provisional potential natural vegetation identification, that is, projections of the existing vegetation into the future, based on existing conditions including vegetation, soils, geology, topographic features and climate.

Ecological Map Unit Design

There are two basic ways of designing ecological units for a mapping program: 1) using ecological type(s) with one or more common landscape components important to management and that, for the purpose of the inventory, override differences in the combined ecological types and 2) stratification of the landscape by climate and physiography and then design of map units using properties of components of soil, geology, vegetation, landform, and topographic features. Interdisciplinary teams often develop variations of these methods based on existing information, management needs, and other factors.

The first way, using ecological types, requires that most ecological types be classified and ecological sites located for reference. The ecological types are the taxonomic units and the ecological units are the map units. The design process for the interdisciplinary mapping team is then centered around determining the ecological types that could best be used to define and characterize ecological map units to meet the objectives of the ecological unit inventory. The classified ecological types in the inventory area either become (1) major components of map units, (2) complexes of two or more or 3) they become inclusions in (1) or (2) above. During the mapping process additional ecological types maybe encountered that require classification, referencing, and inclusion in map unit design.

The second way, using properties of landscape components, requires a good data base for the various components and a systematic process for stratifying the landscape by various component properties. Map units can then be defined primarily by soil, vegetation and landform properties to meet needs. This process also requires an interdisciplinary team. Differentiating components and their properties will change with physiographic area, scale, and management objectives.

Map units are designed in either case by using properties from landscape components, not necessarily taxonomic classes of the various components. For example in wildlands, ranges of soil properties important to management such as soil depth, soil texture and depth to water table may cross soil taxonomic boundaries. It would serve little purpose to separate map units based on taxonomic classes where there are no management implications. Conversely in other instances the range of certain soil properties important to management may be very narrow and would require splitting or phasing soil series or soil families. For example, in recent years intensive work in the Blue Ridge of the Appalachian Mountains has required the establishment of dozens of new soil series. These new soils represent narrow ranges of key soil properties important to ecological relationships and engineering interpretations. In this situation soil taxonomic class can be used to name and define ecological units whereas, prior to that work, taxonomic units were too broadly defined to be of direct use.

Some properties of soils are not used in soil classification, such as phosphorus status or presence of contrasting soil horizons below two (2) meters. These are often important to forest productivity ratings and are properties that need to be considered in ecological map unit design. In these cases soil classes may need to be split or combined for defining ecological units.

Similarly, vegetation taxonomic type, species composition, abundance, dominant species, or vegetation structure are used to map vegetation and can be used in designing ecological map units. The attributes used will depend on the need, scale and purpose of the ecological units. Usually, potential natural vegetation (when known) is incorporated as part of the design because of its usefulness in predicting successional sequences. However, other attributes such as vegetation structure, which is useful in predicting habitat for endangered and other species, may be the dominant vegetation feature used.

The reason for the above discussion is to point out the need for an ecosystem approach to inventory design versus a single component approach. An integrated or coordinated effort designed to stratify the landscape into ecological units is far more likely to produce a map useful for capability area determination for land management planning than a set of single resource inventories to be overlayed in a GIS.

There is one important lesson that needs emphasis, this is: the people who are going to use the inventory must have a say in how the inventory is to be designed. Without this, use and acceptance is an uphill battle, regardless of product quality. This is very important since the use of ecological type information in management planning and environmental analysis is critical to Forest Service programs.

Ecological unit interpretations

Ecological units are interpreted for management by ID team interaction and consensus and represent the collective judgement of the team as to potentials, constraints and opportunities for management. We believe that this approach provides superior interpretations of the traditional factors that are evaluated, as well as additional interpretations of interactions of factors which are important to management which would be normally overlooked in single component approaches. We also believe the interpretations are more precise since the map units being interpreted represent a more ecologically uniform landscape unit and that the interpretations are more spatially accurate.

Research data and treatment response can be related to ecological units and can be extrapolated to like units in other geographical areas. Ecological units will be interpreted for a variety of capability and suitability projections. Interpretations and guidelines are made for map units that will aid managers in making land use decisions. Some of these are:

1. Disturbance responses of plant communities in relation to expected species composition. - This interpretation has application to maintenance of biological diversity.

2. Specific ways to maintain or enhance long-term soil productivity. - These will entail practices affecting physical, chemical, and biological soil properties.

3. Predicting successional pathways to assess the effects of management practices on vegetation.

Correlation

To prevent duplication, ecological types will be correlated across Forest and Region boundries. This kind of work is just beginning. Soils are correlated into the National Cooperative Soil Survey. Continuous correlation of ecological map units takes place within inventory areas by the mapping team and regional quality assurance reviews.

Levels of Ecological Classification and Mapping

Ecological types are described and classified at a specific site and generally represents a small part of the landscape such as a landform or some other ecologically different land segment at the stand or field scale. An ecological site is an ecological type location on the ground with a description of vegetation layers and a soil pit that is described and is representative of a particular ecological type. Ecological types often cannot be shown on maps unless the maps are large scale. An ecological type may include soil classes higher than soil series or include vegetation classes of plant association, series or sub-series. Ecological types are often used to characterize and name ecological map units on order 2 and order 3 inventories. (scales of 1:12,000 or 1:24,000).

Ecological units can be defined and mapped at any scale needed to meet management objectives. Some Forest Service regions have developed a hierarchical system of ecological units from broad (order 5) multi-state units down to detailed (order 2) units as small as 2 to 10 acres that are mapped at scales of 1:12,000 or larger. Higher levels in the hierarchy are defined on broad climatic or physiographic patterns or general soil associations, whereas the large scale units rely on individual landforms, plant communities, and a narrow range of significant soil characteristics. Generally, two basic levels of ecological unit inventories and maps are made. One is a level suitable for forest-wide land management planning, generally order 3 or 4, where map units serve as capability areas. The second level is more detailed, generally order 2, that are used for project planning and implementation of forest plans. The scales are often larger for order 2 mapping. The main difference is detail of mapping, size of map units, intensity of sampling and detail of data collection for descriptions and interpretations.

Coordination with the National Cooperative Soil Survey (NCSS)

Ecological inventories can meet the standards of soil inventory as long as the soil taxonomic units and their spatial distribution are identified for map units. However, problems arise during soil correlation in naming units and in map unit descriptions. We find that, with a little effort, these problems can be resolved. The inventories are similar in that landscapes are mapped and then characterized for soil and other components. For comparison, it could be said that soil is the major component used in designing units in a soil survey, whereas soil is only one of four landscape components evaluated in designing ecological units. In each case soils are classified and their pattern of occurrence is defined. However, descriptions and interpretations are often lacking for the other components in the soil inventory even though they were used in map unit design.

Ecological unit inventories are interchangeably referred to as soil inventories by soil scientists since they meet FS and NCSS soil inventory requirements. In addition, however, they meet requirements for other component inventories and more importantly serve as ecosystem inventories. What the inventory accomplishes depends largely on the objectives established by users and managers at the outset.

Regional Inventory Programs

All regions are either conducting ecological unit inventories or are moving their inventory programs towards that goal. The names for their inventories differ as well as the process they use for classifying ecological types or designing and mapping ecological units. However the results of all efforts have basic similarities in that maps are generated displaying the mosaic of ecosystems on the landscape. In most cases the maps can be displayed at various scales. Interpretations for suitability are provided to land managers involved in planning. The broader scale maps provide interpretations for forest-wide planning and detailed maps for project planning. Regions 1, 3, 4, 5, 9, and 10 have established ecological unit inventory programs in place. Other regions are in various stages of expanding their soil and vegetation inventory programs to be compatible with the current national framework. The process, as well as names, varies by region, but involves close coordination and planning between soil scientists, plant ecologists, and resource managers.

Trends

There will be a continued increase in the use of ecological inventories for modeling responses to vegetation treatment before the treatment is actually made. The models require inventories that provide data or information on vegetation cover, climate, topographic factors, and soils. Soil and vegetation data will emerge as the most critical needs for modeling responses and transferring experiences regarding treat ments and potentials within and among Agencies. Research is needed to quantify soil and vegetation response to management. Ecological type classification coupled with nearly complete coverage of ecological maps will create a universal communication tool about land resources.

New land management planning techniques and new models will require and handle more detailed information for map units than can be derived from current inventories. To provide more complete information, improved map unit design and more intensive sampling will be needed to reduce spatial variability and provide more specific landscape data. There is a need to develop electronic ecological data bases compatible with those used by other FS resource functions and government agencies. The increasing use of high-speed computers and models necessitates that resource data bases are compatible in terms of scale, reliability, and use of terminology. The ecological unit maps will be entered into a GIS. Reliability, quality, and other attributes will be noted to alert users to applications and limitations. As new information and data is gathered in the field, it will be verified and entered into the GIS. Data will be used to drive models and generate alternative management options. There will be less need for published maps and reports. Data information will be obtained through queries of the interactive data base and GIS.

Summary

The Forest Service has established broad national guidance for ecosystem classification and mapping. The national framework includes standard definitions, coordination requirements and a general process to follow. Regional Soil Scientists, Regional Ecologists and others are jointly developing and implementing regionally tailored programs for National Forest implementation. The goal is to allow maximum regional flexibility within the national framework. Flexibility is needed to meet the variety of physiographic conditions, knowledge, current data bases, and management objectives in the regions.

THE ROLE OF AN ECOLOGICAL CLASSIFICATION SYSTEM IN FOREST PLAN DEVELOPMENT AND IMPLEMENTATION[1/]

Robert N. Brenner and James K. Jordan[2/]

Abstract.--An ecological classification system was tied to decision levels in the development of a national forest management plan. The role of the system as an information source and spatial tie to the ground for the design of prescriptions, estimation of yields and treatment costs, and development of management standards and guidelines presented. Use of the system in forest plan implementation is followed with suggestions for improvements.

Keywords: Decision levels, prescriptions, yields, costs, standards and guidelines, ecological unit.

ECOLOGICAL CLASSIFICATION SYSTEM

Classification and inventory of ecological units began in the Eastern Region, R-9, on a limited basis during the early 1970's (Russell and Jordan 1991). The R-9 Ecological Classification System (ECS) was institutionalized in 1979 when the ECS Handbook chapter was issued (Forest Service Handbook 1909.21, Chapter 30).

The R-9 ECS is structured as a hierarchial framework similar to that of the Lands Systems Inventory (Wertz & Arnold 1971) concept that was developed earlier in the western United States. This nested hierarchy facilitates development of ecological units (FSM 2060) at different levels of resolution based on management needs (Nelson, Russell, and Stuart 1984)

Table 1.--Hierarchial Levels of R-9 ECS (Forest Service Handbook 1909.21 - Eastern Region Land and Resource Management Planning Handbook, Chapter 30, 1979, working draft revision)

Level	Primary Differentiating Criteria	Typical Size
Province	Geomorphology, Climate	Multi-state
Section	Geomorphology, Climate, Vegetation	Thousands of square miles
Subsection	Climate, Geomorphology Vegetation	Tens to hundreds of square miles
Landtype Association (LTA)	Landforms, Natural Overstory Communities, Soil Associations	Tens to thousands of acres
Ecological Landtype (ELT)	Landforms, Natural Vegetative Communities, Soils	Tens to hundreds of acres
Ecological Landtype Phase (ELTP)	Soils, Landscape Position, Natural Vegetative Communities	Ones to tens of acres
Site	Soils, Landscape Position, Natural Vegetative Community	Less than one acre

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1/ Presented at the Symposium on Systems Analysis in Forest Resources, Charleston, SC, March 3-7, 1991.

2/ Operations Research Analyst and Soil Scientist, respectively. U.S. Department of Agriculture, Forest Service, Ottawa National Forest, Ironwood, MI 49938.

Provinces and Sections were derived from Frennaman's Physiography of the Eastern United States. These broad, natural physiographic divisions help explain and organize information about natural environmental differences and similarities among the national forests in the region.

Subsections in the Lake States area are being developed in a cooperative partnership project with the Upper Great Lakes Biodiversity Committee; The Nature Conservancy; Michigan, Minnesota, and Wisconsin State Heritage Programs; and others. Criteria for delineating subsections include macroclimatic zones and major glacial physiographic landforms (Russell and Jordan 1991).

Immediate and future applications include regional biodiversity; landscape ecology, correlation of ecological units among Lake States National Forests; the initial stratification of an ecological classification of state, county, and privately-owned lands; future forest planning; and others.

The Landtype Association (LTA), Ecological Landtype (ELT), and Ecological Landtype Phase (ELTP) levels are sometimes referred to as the "working levels" of the ECS because to date they have received by far the most use. These are most useful at the Forest level for land and resource management planning and in the implementation of Forest Plans.

The LTA level: Landtype associations generally number between about 10 and 20 per National Forest. This level was used extensively in the forest planning process in the Eastern Region. The primary use was to aid in allocating land to "management areas" and developing desired future conditions.

The ELT level: A few National Forests used ecological landtypes for Forest level planning. More commonly, however, the ELT level is used for more detailed planning on subdivisions of National Forests, management areas or opportunity areas. ELT's commonly repeat across the landscape in a predictable pattern within an LTA.

The ELTP level is the most detailed, site-specific level that is normally mapped on an operational basis. It usually provides the level of detail of land capability-suitability information that is needed for project level applications. ELTP's commonly repeat across the landscape in a predictable pattern within a given ELT. ELTP's can be thought of as mapped representations of sites.

The above levels are all ecological units, mapped segments of the landscape designed to meet management needs. Ecological units are used to determine land capability for a wide range of resource management prescriptions, evaluate costs and benefits, and predict ecological response of actions and/or non-action applied to any given piece of land.

The "site" level: The site is the classification unit, the ecological type (FSM 2060), the primary data collection unit. Sites by themselves are not usually delineated on maps except for special purposes where there is need for extremely site-specific information.

BACKGROUND TO OTTAWA NATIONAL FOREST ECOLOGICAL CLASSIFICATION SYSTEM

The Ottawa National Forest is located in the western part of the Upper Peninsula of Michigan, in the southern Superior Section of the Superior Uplands Province. Ecological classification began on the Ottawa during the early 1970's in response to a need for land capability information for Forest planning. Very little information about basic resources (soils, natural vegetation, glacial geology) was available at that time (Russell and Jordan 1991).

The Forest was first divided into 20 LTA's based on major glacial landforms, areas of bedrock control and outcrop, and major post-glacial erosional landforms (Jordan 1982). The Forest was also divided into three distinct macroclimatic zones based on climatic differences caused by proximity to Lake Superior. LTA's and climatic zones provided the basic land capability-suitability information used in the Forest planning process.

The Ottawa National Forest Leadership Team recognized the need for more detailed levels of ecological classification in 1977. Subsequently the Forest entered into a cooperative agreement with Michigan Technological University to fully characterize and analyze stratified, randomly selected sample areas representative of all LTA's, a 2 percent sample of the ecosystems of the Forest. Within each sample area, systematic sampling was completed for soils, landforms, and total vegetation. Through the use of computer ordination models, vegetation relationships were established. Site concepts (ecological types) were developed and mapping unit (ecological units) concepts were developed based on the observed recorded and analyzed soil, landform, and vegetation relationships (Jordan 1982).

From the detailed analysis of soils, vegetation, and landforms, the Ottawa developed ecological types, and from the ecological types, ecological landtype phases (ELTP's) for mapping were built. Each ELTP is composed of a major site unit (ecological types) and usually one or more minor site units (mapping inclusions).

The process of developing, classifying, and mapping ELTP's continues today and presently covers approximately 75 percent of National Forest System lands in the Ottawa National Forest. However, not all of the Forest will be mapped to the ELTP level; areas where management information needs do not require that level of detail have been identified and are or will be mapped to the ELT level (Russell and Jordan 1991).

Concepts, mapping, verification, and development of interpretations continue with involvement of many scientists from the North Central Forest Experiment Station, and universities in Michigan, Minnesota, and Wisconsin. Correlation with adjoining National Forests has begun and will strengthen the use of the ECS.

OTTAWA PLANNING ENVIRONMENT

The purpose of forest planning is to ensure that goods and services are provided in an environmentally sound manner and that the public receives the maximum net benefit.

The Forest Plan for the Ottawa National Forest was designed to guide all natural resource activities through multiple use goals, objectives specifying outputs, and activity levels per time period, management prescription, and management standards and guidelines (Forest Plan 1986).

The National Forest Management Act (NFMA) of 1976 defines forest planning as an issue-driven process designed to assess the need for change in management of the Ottawa National Forest. Intensive public involvement ensured that the issues were those actually perceived by the public as well as those identified by the Forest Service. These issues, concerns, and opportunities were then developed into management problem statements.

Management problem statements guided the planning process. Understanding the Forest's resource condition, relationships, and potential was essential to building realistic alternative Forest plans which addressed the problems.

Summary of Management Problems

Five major management problems were identified which dealt with the Forest transportation system, wildlife habitat, vegetative composition and management, landownership, and wilderness (USDA Forest Service 1986c). Basically each dealt with how much should be produced or maintained, where on the Forest this production should occur, and what standard of management was appropriate.

To illustrate, the wildlife habitat problem required the Forest planning team to identify the composition, arrangement, and age-class structure of vegetation which would, given other resource objectives, provide the best habitat conditions for a wide variety of wildlife species. Habitat needs for threatened and endangered species, including gray wolf and bald eagle had to be considered as well as habitat for game species including white-tailed deer and ruffed grouse which are of particular public interest.

Responses to these problems were ultimately spelled out in the Forest Plan. The Forest Plan designated management areas within the Forest and assigned both long and short term goals and objectives to each. The Forest Plan is primarily a strategically focused document. Site-level decisions on site-specific projects were not set in the plan. Decisions on site specific projects designed to implement elements of the plan are made after more detailed levels of analysis the site scale.

The identification of decision levels helped shape the analysis performed on the Ottawa and the information and data sources used to construct the tools and models used in the analyses. The ECS provided information of appropriate scale to these decision levels.

ROLE OF THE ECOLOGICAL CLASSIFICATION SYSTEM IN FOREST PLANNING

A Forest planning model was developed on the Ottawa to encompass several levels of analysis and decison-making (Brenner, et al 1985). These decision levels were used to define the scope, detail, and precision of information appropriate to address resource management problems on the Forest. The three levels were forest-level, management area-level, and project-level.

Forest-level analysis focused on the amounts of resource goods and service to be produced over time, the allocation of Forest lands to large management areas, each area focused on a desired future condition; and finally, the schedule of management treatments and activities which might occur in each management area over 10 years (Appendix Volume 1986). The linear programming model, FORPLAN, was incorporated at this level to help analyze the efficiency and effectiveness of various management strategies.

Analysis of choice within management areas, often termed "area analysis" or "area based forest planning" (Connelly 1988) focused on spatially arranging the set of activities and treatments in the area to best move the area from its existing condition toward its desired future one. Management areas occur in 5,000 to 100,000 units which are frequently broken into sub-units called opportunity areas.

Project-level analysis and decision-making is the third leg of the Ottawa model and deals with project layout and design. Choices on specific practices, vegetation regeneration options and methods, harvest methods, road standards and the like are made. Sufficiently detailed and thoughtful analysis must be made here to ensure compliance with National Environmental Policy Act of 1969 (NEPA).

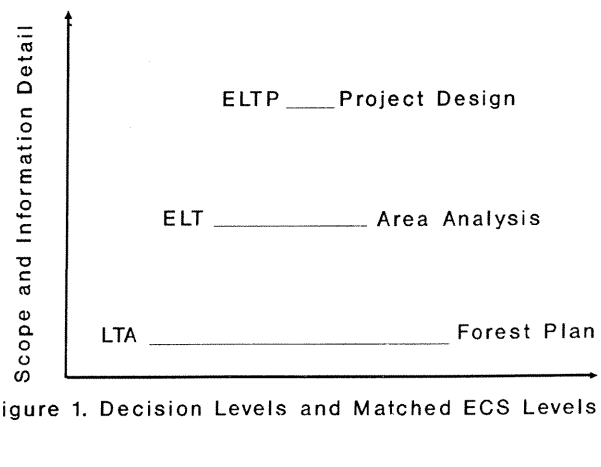

Figure 1. Decision Levels and Matched ECS Levels

ECS provided information of detail, scope and precision appropriate to each of these three decision levels. Further, because the classification system is corporate and interlinked between levels we were assured that decision choices made at each level were guided by a common set of assumptions and relationships represented in the system.

Table 2.--Factors of the Wildlife Problem Influenced by ECS

Management Problems	Key Problem Elements	Factors Influenced by ECS
Wildlife	- Deer and grouse popl - Aspen acreage - Thermal cover - Coordination between timber and wildlife - Habitat for TE&S species	.Veg. composition .Habitat for T&E species .Potent. veg. comp. .Temp. openings .Road density as relates to semi-primitive areas

Analysis Areas

The Forest land area was stratified into units of similar attributes called analysis areas (USDA Forest Service 1986c). Initially a long list of possible delineators was identified which would allow for differentiation of costs, output levels, and analysis of Forest planning problems.

Broad spatial arrangement was provided by ECS in Forest analysis through LTA's or combinations of LTA's (Level 1 in our FORPLAN model). These ecological units provided information on suitability for vegetation composition, wildlife habitat potential, economic considerations, potential productivity, inherent vegetation variability, physical and biological limitations and other biophysical spatial and temporal information.

The Ottawa National Forest contains 20 landtype association (LTA) units. Criteria for delineating the LTA's included major glacial landform, areas of bedrock control and outcrop, and major post-glacial erosional landforms.

Three additional delineators completed the identification of analysis areas.

Vegetative Types - Vegetative types were grouped primarily to relate to the wildlife and vegetation management Forest management problems. Specifically, these vegetative types were grouped because they produced a similar species product mix, provided similar wildlife habitat conditions, required similar management practices, had a similar schedule of management practices, and had similar timber product and other benefit values.

The use of vegetative type as an identifier allowed the Forest to track the changes in vegetative composition over time. This also provided a mechanism to more accurately predict future species/product mixes. The stratification of vegetative type allowed the Forest to more accurately represent schedules of management practices and the most variation associated with different vegetative types.

The six vegetation types are aspen and paper birch; northern and lowland hardwoods; white spruce, red and white pine; balsam fir and jack pine; mixed swamp conifers and lowland black spruce; and hemlock.

Age Classes - Age classes used varied according to type and the existing age class distribution on the Forest. It was an important identifier because it controlled scheduling and was the link to yield tables from which harvest and inventory volumes were calculated.

Age classes were structured based on existing acreage distribution within the type, length of rotation, differences in yield, and intensity of management. Age class was critical since yield tables must represent standing inventory volume and harvest volumes. Broad age classes require more averaging and represent a greater range of yields.

Stocking Classes - "Low" and "high" stocking classes were used in the hardwood vegetation type. This delineation provided more accurate yield data from partial cuts in the first two decades.

Prescriptions

A management prescription is a set of treatments or practices needed to create a desired Forest condition in a management area and to produce specified outputs while protecting all resource values to established standards.

Prescriptions were developed at two distinctly different levels of detail which can be differentiated as management area prescriptions and per-acre FORPLAN prescriptions.

Management area prescriptions describe the long-term desired conditions for management areas. Management areas are defined on the Ottawa as large (5,000 to over 100,000 acres) heterogeneous, contiguous units of land that are managed under a single management area prescription.

Management prescriptions are stated in two parts. The first part is a narrative that describes the purpose and desired future condition of the land. This includes vegetative type composition objectives for the management area, planned recreation opportunity spectrum (ROS) class the area will be managed for, desired road density, and what silvicultural systems are emphasized.

The second part contains the standards and guidelines describing how management activities will be carried out to achieve the desired forest condition.

The following is an example management prescription narrative (USDA Forest Service 1986c).

> Prescription 2.1 - Provides a condition that emphasizes late succession community types within a motorized recreation environment. Maintains potential conditions for low to moderate populations of game species such as deer and ruffed grouse. Maintains moderate to high amounts hardwood type along with associated timber products and habitat conditions.
>
> Emphasizes uneven-aged management of the hardwood type to provide for high visual quality, production of high quality hardwood sawtimber and veneer, and habitat conditions for wildlife species such as the red-eyed vireo which are representative of this community type. Provides an appearance that is predominantly forested with occasional openings.

All management prescriptions followed the framework of themes stated in the Regional Guide - Direction for Land and Resource Management Planning in the Eastern Region (1983).

Per-acre FORPLAN prescriptions, on the other hand, are focused on individual analysis areas and represent allocation and scheduling strategies for that area as a potential piece of a large management area-management prescription.

Key variations within management area prescriptions were represented in FORPLAN prescriptions and vary by management intensity (USDA Forest Service 1986c). These include, on an analysis basis, such items as:

- Silvicultural regime. Practice and timing of those practices, range of rotations, thinning options (thin cycle or thin), and maintenance or conversion of type.

- Planning, design, layout, and control. Degree of timber/wildlife coordination, degree of emphasis on market and market/non-market benefits, amount of time/concern given to spatially arranging the vegetative composition to address specific concerns, primarily wildlife habitat, and amount of site-specific information/analysis needed at project level.

- Road standard mix. What mix of road standard is to be constructed and cost of local road construction (cost varies by road standard mix, LTA, and amount of additional road needed to meet desired road density).

This range of choice allowed the Forest to conduct an analysis of the problem and consider a broad range of alternatives to resolve these problems in an efficient manner.

Management area prescriptions were not originally written specific to any location(s) on the Forest. LTA's could be suitable for one or more of these management area prescriptions. The suitability of each management area prescription to LTA's needed to be determined.

The criteria used to determine suitability included:

- Existing vegetative composition.
- Tree species potential - percentage of area.
- Potential productivity by working group.
- Percentage composition by site unit (ELTs).
- Existing ROS class.
- Existing road density.
- Unique wildlife habitat potential.
- Landownership pattern.
- Road construction cost.
- Existing and potential wildlife habitat.
- Specific public issues.
- Existing sensitivity levels.
- Existing visual quality objectives.

The following table indicates some of the management area prescriptions which were suitable on each LTA.

Table 3.--Examples of Suitable Management Area Prescriptions by LTA

		Prescription					
LTA	Acres	1.1	2.1	3.1	3.2	4.1	6.1
1	28,788	X		X	X	X	
2	178,478	X	X	X	X	X	X
3,4,7	134,910		X	X	X	X	X
5	50,691		X				X
6	56,705	X	X	X			X
9,10	79,420		X	X	X		X
11	47,016		X	X	X		X
12,13	66,012	X	X	X	X		X
14,17	92,243	X		X		X	
14A	11,100					X	X
16,19	70,567	X		X			X
18	12,156	X		X		X	X

Standards and Guidelines

Standards and guidelines were developed to guide the implementation of management practices to meet the multiple use objectives for each of the management areas as required in the National Forest System Land and Resource Management Planning Rules and Regulations (NFMA regs.) of 1982 (36 CFR 219.27).

The desired condition described in each management area prescription directly influenced the development of the Forest Plan standards and guidelines. All management practices implemented on-the-ground within a management area will follow the management direction provided by these standards and guidelines.

The costs of management practices within the prescriptions reflect the support costs of resource staff specialists needed to ensure that standards and guidelines are met. The cost of achieving given standards and guidelines do vary by analysis area, based on site conditions such as ecological landtype, vegetative type, and management prescription to be achieved.

Resource yields estimated for use with FORPLAN prescriptions also reflect the standards and guidelines as they will be implemented on different analysis areas within a management area.

Examples of standards and guidelines based on information drawn from ECS are presented below (USDA Forest Service 1986a).

Give particular attention to landtype association (LTA's) 1, 5, 6, 13, 16, 18, and 20 using an erosion prevention practice preferably within the growing season in which the disturbance occurs. Follow techniques presented in Watershed Improvement Handbook (FSH 2509.15) and Soil and Water Conservation Handbook (R-9 FSH 2509.22).

> Utilize broadcast burns on upland sites in LTA's 1, 14, 14a, 15, 17, 18, and 19 only when available soil moisture is present in the upper portion of the mineral soil. Make determination of sufficient soil moisture on a case-by-case basis as part of the burn plan and implementation.
>
> Give priority to the use of mechanical site preparation equipment that tends to mix soils (e.g., discing) as opposed to massive scarification (e.g., root raking), in seedbed preparation and plan competition removal in LTA 1, 5, 6, 12, 13, 14, 14a, 15, 16, 17, 18, 19, and 20.

Match regenerated timber stand boundaries to natural soil-site boundaries to the extent practicable.

<u>Resource Yields</u>

Resource yields were developed to represent the expected levels of outputs or effects of the prescriptions in the Forest analysis.

Timber yield estimates for existing and regenerated stands were influenced by ECS. Timber productivity classes for existing stands by LTA were based on mean existing site index. Vegetative age classes were stratified into several productivity classes. Productivity class yields were weighted by the proportion per LTA to build FORPLAN yield tables. Six multi-species, multi-product yields could be tracked in each table.

Timber productivity for regenerated stands was based on potential productivity estimates from the Forest's ECS data. These estimates were expressed in terms of a mean site index, by LTA, and by vegetative group.

The FREP-STEMS model was the primary tool used to simulate timber yields for stands on the Ottawa.

<u>Cost and Additional Analyses</u>

Wildlife yield estimates were developed around groups of LTA's with similar characteristics in current wildlife-user history, habitat potential, ease of habitat maintenance or expansion and climatic conditions. ECS data was not a factor in defining yield classes or estimating yields.

ECS was a key determinate for reliable activity cost estimates which formed a key element of our Forest analysis. A wide set of cost variations were developed for vegetative treatments and road management activities.

Road construction costs ranged from $8500 to $25,000 per mile on different LTA's for timber management options of the same intensity. This proved very important to our modeling exercise and had a strong impact on solutions.

A comparison of contributions to present net value from a set of identical FORPLAN timber management prescriptions ranged by nearly 600 percent from one LTA to another with road construction costs accounting for most of the variation.

Costs on the Ottawa were found to vary from Forestwide averages due to several basic factors including physical or biological site factors, vegetative-type management, management intensity, and harvest method. Cost variations due to physical or biological factors were represented by LTA's. An example is artificial reforestation which was found to vary in cost by soil type, terrain, and plant competition all of which were drawn from ECS (USDA Forest Service 1986c).

Sale harvest administration is another management activity in which data from ECS had a significant effect on cost estimates to be used in our Forest Plan analysis. We found that the intensity of on-site administration will vary based on characteristics of the LTA which create increased risk of watershed problems or have more soil related limitations. Steep slopes, watershed problems, soil limitations restricted operating periods are more likely on some BLU's and result in higher sale administration costs.

Table 4.--Sale Harvest Administration Cost by LTA Group. (Change from Forestwide average cost of $3.04/MBF)

Working Group	Treatment Type	LTA Cost Groups High	Med.	Low
Hardwoods	Selection	+$1.50	+0.75	-1.00
	Shelterwood	+ 3.50	+2.75	+1.00
	Thins	6.50/ MBF	5.00/ MBF	4.00/ MBF

(Cost estimates are in 1982 dollar terms)

An analysis was completed to determine existing road densities by arterial, collector, and local standards. Estimates of desired road densities to support management prescription objectives was performed for each LTA. ECS data representing landform, surface to bedrock, and road construction cost was used along with timber stand and other resource data to develop local road construction estimates for each management prescription for each LTA.

An analysis of timber harvest feasibility was completed. Conversions between hardwood and softwood species are subject to bio-physical limitations imposed by environmental conditions at the site. ECS data was used to identify these limitations so they could be represented in our Forest analysis.

Conversion potentials by ELT for species groups were studied and then combined into LTA totals. FORPLAN constraints were built from this information limiting the vegetative type-to-type conversion for each BLU in the model. This had a dramatic effect on the ability of our model to accurately portray vegetative composition change over the planning/analysis time horizon.

ECS provided a valuable source of data and information which was used in the development of many components of our Forest planning model. As discussed in the following section, ECS also played a role in the conduct of the analysis itself.

THE ECOLOGICAL CLASSIFICATION SYSTEM IN FOREST PLAN ANALYSIS

The National Forest Management Act (NFMA) regulations (36 CFR 219) requires that a broad range of reasonable alternatives be developed during Forest level analysis. Our Forest analysis was structured to determine the range of resource products, services, and conditions possible within the limits allowed by acreage and resource potentials. As the preceding section established, ECS played a significant role in mapping out Ottawa production frontiers.

Constraint sets were built for use in the FORPLAN model to represent many of these production or activity limits. Species/type conversion feasibility constraints were added to the FORPLAN model after it became evident that conversions were exceeding the realistic physical and biological limits identified through ECS data. The following table shows forestwide limits, LTA limits were imposed as well (USDA Forest Service 1986c).

Table 5.--Type Conversion Constraints

Type Conversion	Constraint
Hardwood to aspen	23,000 acres*
Hardwood to balsam fir-jack pine	14,000 acres**
Aspen to balsam fir-jack pine	30,000 acres**
Aspen to hardwood	30,000 acres***

* Based on the Forest's ability to regenerate naturally from root suckers over the first three decades.
** Advanced regeneration or inadequate seed source is present.
*** Present aspen occurring on strong sites.

During the analysis a decision was made to coordinate LTA and management area boundaries in the final spatial layout of Forest alternatives. Different transportation road densities limits for each possible combination of LTA and management prescriptions were developed. These relatively simple constraints considered existing road density within each LTA, road density limits for the recreation opportunity class of the prescription and economically efficient system density for each vegetative type.

Work previously had been done to identify LTA groups with similar characteristics of hunter use, wildlife habitat potential, ease of habitat control, and climatic conditions. This information was used when pertinent to a planning alternative to constrain solutions favorable to certain species habitat conditions

Many constraints were linked into the model through the spatial ties LTA's provided. Among these were even-aged, selection and thinning, harvest acreage constraints, and long-term vegetative composition constraints.

The final spatial layout of alternatives was done by the Forest planning team after an interpretation of FORPLAN model results. Of particular importance was the designation of a management prescription. Our FORPLAN model had limited ability to allocate large areas to long-term coordinated conditions specified in management prescriptions without heavy constraining.

While crucial elements were often constrained, other modeled elements were not. A comparison of existing vegetation with FORPLAN model composition results and with management prescription components including vegetative composition, silvicultural emphases, and road system characteristics was made for each LTA. This helped the team to make assignments to LTA's which best represented FORPLAN solutions. In some cases, an LTA might be split between management prescriptions based upon FORPLAN results and/or due to variations across the LTA in biological, physical, visual, or social factors which were not modeled. Indeed some management prescriptions were never given the option of allocation to some LTA's. For example, several management prescriptions contained a key element of producing high quality hardwoods. ECS data showed this to be not possible on some LTA's although low quality hardwood species and products might be produced. As a result, per-acre FORPLAN prescriptions for high quality hardwoods in these LTA's were not built into the model.

ECOLOGICAL CLASSIFICATION SYSTEM USE IN IMPLEMENTATION

<u>Integrated Resource Management</u>

National forest management plans rely heavily on two keystones. One is defining broad, long-term goals for units of the Forest. These goals encompass an entire spectrum of forest resource goods, services, and conditions. Different areas have different mixes of resource goals. The second keystone is to understand that jointly foresters, biologists, engineers, and others may achieve their goals more efficiently and with better results if they work together.

A series of steps were developed which help mesh the principles of integrated resource management (IRM) with forest plan implementation (USDA Forest Service 1985). Principles underlying IRM which are important to forest plan implementation include the following four.

1. Learn to work with the common, broad, and long-term interrelated resource objectives for an area.

2. Foster a situation where individuals of different backgrounds, interests, and values can come together.

3. Promote opportunities for public participation at meaningful points in the process.

4. Finally, produce a forest richer and more responsive to our needs across the entire range of resource issues and concerns.

The Forest Service publication, "Working Together for Multiple Use" (USDA Forest Service 1985), defines six general steps for implementing a forest plan. The steps are as follows:

1. Opportunities. Identify areas of land which offer the best opportunities to implement the forest plan.

2. Analysis. Spatially arrange the desired future condition and identify projects to ensure an integrated approach to forest management.

3. Schedule. Schedule and budget projects that best meet forest plan management direction.

4. Design. Design projects to include integration needs for all resources and values.

5. Execute. Complete projects as designed.

6. Protect and Manage. Be a Good Host and provide for public health and safety. Protect and manage resources and property values.

The benefits of IRM are many. Frequently jointly produced goods and services, such as timber production and habitat enhancement, can be had more efficiently. Participation or the opportunity to be a member of a team developing and considering choices can help build ownership and our understanding of resource potentials by improved sharing of values, inventories, and information. An interdisciplinary team who really shares can come up with many "best" management options.

Opportunity Area Analysis/Ecological Land Type

For each management area, the Forest Plan established a desired future condition which includes vegetation composition, spatial requirements, key wildlife habitat emphasis (game and non-game), timber product emphasis, road densities, recreation opportunity spectrum (ROS) classification, and more. The ranger district ID team supplemented with other resource specialists, analyze and prioritize potential projects which begin to move the area toward the desired future condition. Local issues, concerns, opportunities, and demand are now considered along with the forestwide situation.

The ELT maps (7.5 min. quad base) and information help to identify, display, and describe what alternative arrangements within the context of the desired future condition are possible and not limited in scope by what currently exists.

Along with potential projects, long-term road corridors, areas of even-aged hardwoods, uneven-aged hardwoods, balsam fir/jack pine, spruce/red and white pine, hemlock, lowland conifer, minimum level management areas, deferred areas, special wildlife habitat (old growth), wild and scenic river study corridors, and more are mapped.

The ELT provides capability information for:

1. Determining location of long-term local road corridors. Local roads have been determined by standard of road for each ELT. Operating periods by ELT help determine the standard of local road possible for opportunity areas (OA).

2. Determining the best areas for hardwood sawtimber, softwood sawtimber, aspen, softwood pulpwood, hardwood pulp, and hemlock.

3. Areas of even-aged and uneven-aged management of northern hardwoods relative to vegetation management objectives for the OA.
-Even-aged sugar maple reproduction when aspen is not a feasible alternative over the long term for adjacent thermal cover browse.
-On certain ELT's, opportunities are better for emphasizing mid-tolerant northern hardwood species.

4. Comparing possible wildlife habitat component opportunities and their spatial arrangement for most efficient and effective options for all resources considered.
-ELT helps identify where thermal cover, summer range, permanent openings, mast (overstory, shrub, and ground layer), and old-growth areas.
-spatial arrangement considerations may be more important than simple vegetation composition. For example, it is important to have areas where summer range is directly adjacent to winter thermal cover.

5. Successional trends, soil conditions relative to natural regeneration, and others identify opportunities for restoration of old-growth ecosystems.

Along with ECS information, the vegetation management information system (VMIS) of 1987, aerial photographs, topographic maps, compartment maps, wildlife surveys, botanical surveys, and others, are the major tools for determining spatial and temporal arrangements.

Project Design/Ecological Landtype Phase

The allocation of scheduled activities and outputs are for management areas through forest level planning. Specific projects are identified through opportunity area (OA) analysis. Projects are designed through a continuation of the integrated resource management process. More site-specific alternative practices are considered using the ecological landtype phase (ELTP) units and existing information to design projects in the short term. ELTP's provide capability information on specific species productivity, road and landing location, equipment operating periods, plant competition, site preparation alternatives, specific wildlife habitats and species relations, and more.

The ELTP maps (4"-1 compartment map base) and information helps to provide the site-specific detail necessary to design and implement projects. Relative to biodiversity, ELTP information includes specific wildlife habitat opportunities, thermal cover by species, wetland components, horizontal and vertical diversity opportunities, ground cover habitat, shrub habitat, successional patterns, berry and mast production opportunities, and others.

Specific potential wildlife habitat information includes wildlife species specific habitat opportunities, identified opportunities to improve wildlife habitat for berry and mast production, thermal cover component by species, aspen component, specific wetland components, diversity (both horizontal and vertical) opportunities, ground cover habitat, shrub habitat, opening habitat, and others.

These are described for major site units and minor site units so we are getting very site-specific here.

Timber product management information includes potential productivity by species, roads and landing location, operating periods, windthrow hazard, plant competition, site preparation, and others.

Additional information is provided for engineering, recreation, watershed management, and others. ELTP mapping is done on the same compartment map base (4" - 1 mi.) as our timber typing.

FUTURE/CONCLUSION

The American people, through their elected representatives, have directed that National Forests are to be managed as ecosystems to provide a sustained yield of a wide array of values, uses, goods, and services. National Forest policy directs that ecological classification and inventory shall be used to help accomplish this (Russell and Jordan 1991).

The Eastern Region (R-9) of the National Forest System uses a multi-level, hierarchical ecological classification system (ECS). The hierarchical framework facilitates mapping of ecological units at different levels of site specificity in order to satisfy different management needs. Activities in ecological classification are on the increase on National Forests all across the Eastern Region.

The focus of this paper has dealt with what ECS is, how it was incorporated into the Ottawa National Forest planning process, and how it is used in implementation of the Forest Plan.

The following discussion presents several illustrations and recommendations for improvements in the role of ECS in forest planning and implementation in the future.

Better Land Capability Information

At the time of developing the first Forest Plan, the source of ECS data and information was a stratified random sample, about 2 percent (20,000 acres) representation of the Forest ecosystems. Before the Forest Plan revision, all three operational levels of ECS (LTA, ElT, ELTP) will be completed for the entire Forest.

Ecosystem Basis for Management

Forthcoming is an "Eastern Region: Positioning for the Future" statement which directs the National Forest to manage ecosystems rather than individual resources.

Future Forest planning efforts will use ecosystem units as the basis for spatial analysis, landscape design, land capability information, and land management decisions.

The Ottawa National Forest is working in partnership with Michigan's Natural Features Inventory group to develop and implement a systematic sampling procedure of our ecological units to determine the probability of occurrence of threatened and endangered plan species and, when found, their site requirements and management needs.

Many Forest Plan standards and guidelines directly address the issue of biological diversity. Direction to emphasize natural regeneration on the Forest will improve intra and inter stand diversity both horizontally and vertically. The ECS is required to identify land capability, mitigating requirements, and specific management situations for all management prescriptions and practices. Stand boundaries are being aligned with ECS mapping unit boundaries. ECS provides site-specific information on succession of the various habitat types found throughout the Forest.

Regional Correlation of the Ecological Classification System

Future Forest planning efforts must address regional and some global issues, concerns, and opportunities. This will require more coordination between National Forests in their Forest planning. Recently the Ottawa National Forest initiated the correlation and development of ECS with our adjoining sister forest, the Nicolet National Forest. These Forests share the same ecological units over an extensive portion of both Forests. Land capability response will be the same.

The Ottawa National Forest is one of the champions for a regional ECS classification; i.e., Minnesota, Wisconsin, Michigan. In partnership with the Nature Conservancy, the Upper Great Lakes Biological Diversity Committee, universities, the North Central Forest Experiment Station, and others, we are developing a regional map of ecosystems. One application already agreed to by the Lake States National Forests is the use of this regional ECS to identify, allocate, and establish representative and distinct Research Natural Areas.

Geographic Information System

Geographic information systems (GIS) will play a major role in spatial analysis, landscape design, and other applications of ECS in future Forest planning.

The Ottawa has a portion of operational level (LTA, ELT, ELTP) ecological units entered into a geographic information system and is applying landscape ecology principles in learning some spatial analysis and landscape design techniques.

Two such research projects underway in partnership with the University of Minnesota (Duluth) and North Central Forest Experiment Station involve: (1) using GIS/ECS and current research on black bear to identify seasonal habitat needs through refinement of the black bear habitat suitability index and their relationship to ecological units on a computer model; and (2) quantifying patterns of floristic diversity and spatial complexity in context of the operational levels (LTA, ELT, ELTP) ecological units on two Michigan National Forests. Spatial complexity differs among these ecological units.

Cumulative Effects

Our ability to measure resource output under differing circumstances is good in most cases. Indeed, most of our attention in the plan analysis was focused there. Our ability to measure environmental, social, and economic pacts of those outputs and conditions could be improved to be more meaningful to the decisionmakers. A portion of this concern would be addressed by most closely linking issues with impact analysis and with improved verbal and writing skills to express it.

ECS will help us do a better job of assessing cumulative effects on an ecosystem basis.

Conclusions

The National Forest Management Act and its implementing regulations specify that an interdisciplinary approach be used in forest planning. For the Ottawa National Forest planning exercise, ECS was key to ensuring the many resource experts involved had a common basis for interdisciplinary communication and understanding.

The ECS on the Ottawa proved to be a vital tool and information source. ECS helped us to develop a better understanding of the ecological relationships at work within our Forest. This understanding gave rise to a greater range of ideas, options, and analyses which proved themselves in better decisions.

The Ottawa continues to use ECS on a daily basis in Forest Plan implementation, the design of resource projects, and in the preparation of National Environmental Policy Act (1969) analyses. We continue to work toward the completion of ECS surveys and maps as well as management interpretations.

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DIMENSIONS OF SCALE IN LANDSCAPE ANALYSIS

Fran Evanisko[2]

Abstract. -- Scale is a key concept in geographic analysis. However, analysts often fail to adequately consider the impact of scale when analyzing geographic distributions and interactions. Recently, geographic information systems (GIS) have made complex geographic analysis over broad areas feasible. Digital processing of spatial data has made scale and resolution more important and difficult to deal with. This paper discusses the dimensions of both scale and resolution as they apply to landscape analysis and attempts to show how they are related.

INTRODUCTION

It is a fact that geographic investigations can give significantly different representations of spatial patterns depending on the scale of analysis. Increasingly, forest managers are expected to assess the implications of management alternatives and activities beyond the site, to consider broader landscape impacts. This necessitates sampling and using remote means of gathering information that result in maps. This is problematic, particularly when variables such as the sizes, shapes, and spatial arrangement of natural land units are important to consider.

Maps can be valuable tools for helping to understand the world, but maps are also notorious for their propensity to mislead. Maps are models, and as such, they are simplified abstractions of the reality. Analysts share the responsibility to ensure that geographic information used in decision making are instructive generalizations rather than misrepresentations.

The thesis behind this discussion is that many of the difficulties encountered in geographic analysis are, in some way, related to scale. Thus a proper consideration of scale may lead to more useful databases, more efficient analyses, and may provide a more credible basis for decision making. My purpose here is to discuss the various meanings of scale, illustrate some examples of scale problems in databases, briefly review some current literature that discusses the importance scale in landscape analysis, and make some recommendations.

Scale is a familiar and apparently simple concept, however, that it is often misunderstood, or only partly understood. It is surprising how often people confuse the terms large-scale-map and small-scale-map. Other indications that scale is not properly understood include: investments in costly large scale aerial photography projects when much less costly, high altitude photos provide the same information value, combining data of varying or unknown resolution without considering the consequences, justifying the use if of photographically enlarged maps by need of greater accuracy (I have seen 1:62500 maps blown up to 1:8000), the idea that for general planning, accuracy is not as important (confusing accuracy and precision), and failure to distinguish between spatial scale and categorical scale.

A dangerous misconception in the digital era is the idea that scale is now of lesser importance than it used to be since data can be easily rescaled. However, just the opposite is true, because it is now easy to integrate data that should not be integrated, and it is more difficult to tell by visual inspection when maps have been rescaled.

Scale is important because it has implications for cost, the kinds of analysis that are appropriate, and the reliability of estimates.

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[2]Geographer
Klamath National Forest
USDA-Forest Service
1312 Fairlane Rd
Yreka, CA 96097

SCALE AND RESOLUTION

Etymology

Scale is a complex concept having many meanings. The Oxford English Dictionary includes ten separate entries for scale, with no less than 50 variations, most having nothing to do with mapping or analysis. However all of these various meanings derive from two apparently disparate sources. One, from Old Norse "Scâl", refers to a shell, husk, or drinking cup, and hence the notion of weighing scales. The second, from Latin, "scāla", means to climb and thus the notion of a graduated succession or progression. In the realm of geographic analysis both of these apply.

Resolution is also a complex concept. It comes from Latin "resolvo", meaning to loosen or dissolve. It is interesting that "resolvo" is synonymous to the German "analyse" which also means to loosen or dissolve.

How is it that the ideas of scale and resolution are so intimately related? I think it's because resolving patterns so often involves manipulating scale. What differentiates concrete reality form abstract representations or images is, that, as one moves closer to real objects, increasing levels of detail are revealed, limited only by the acuity of senses or the precision of instruments. On the other hand, in viewing a human representation of objects, realness quickly vanishes as soon as one exceeds the limits of scale, and no more detail is revealed. Consider, for example an ultra-realistic painting. We may be astonished by its realness from a certain distance but, as we move closer, we may also be surprised at how little the faces looks like a real faces or at how little the grass looks like real grass. We have moved too close to the painting, and have exceeded the limits of its scale. In geographic analysis, it is vital not to confuse concrete reality with abstract representations of it, and not to exceed the limits of scale.

Meanings of Scale

In the context of geographic information, scale has six meanings.

1. map scale
2. positional accuracy
3. level in a categorical hierarchy (specific --> general)
4. position along a systematic spectrum (simple --> complex)
5. measurement scale (computationally impotent --> computationally potent)
6. level in a spatial hierarchy (small area --> large area)

Map Scale

The representative fraction is a commonly used expression of map scale. It can be stated as a fraction (1/24,000), as a ratio (1:24,000), or it is may be converted to an equivalence (1 inch to 2000 feet). Map scale has come to imply a positional accuracy. For example, National Map Accuracy Standards require 90% of well defined points to be located within 0.02 inches of their true location at 1:24,000 scale.

However, map scale alone is not a reliable indicator of positional accuracy or of map resolution. Natural resource data are often transferred from source materials to base maps using questionable transfer techniques, such as ocular transfer (eyeball mapping) or monoscopic or stereoscopic transfer scopes which are known to be unreliable and provide no information regarding positional accuracy.

Furthermore, the scale of a base map may be less important to map resolution than other factors such as interpreter bias or mapping methods. For example, maps of geologic regimes or vegetation types often show considerable variation in map unit size even though they are depicted at the same scale and use the same classification system. Positional accuracy and map resolution cannot be inferred from the scale of the base map on which they are depicted.

Positional Accuracy

The scale at which cartographic products meet accuracy standards is often taken as a representation of scale. There is no generally accepted positional accuracy standard for natural resource mapping, and acceptable levels of error may vary by application. Recognizing that positional accuracy requirements vary according to application, the American Society of Civil Engineers and the American Society of Photogrammetry are recommending the use of statistical expressions of positional accuracy (Veregin, 1989). Since most broad based resource inventories and analyses are based on 1:24,000 mapping, positional accuracy for planning and analysis is often limited by standards for 1:24,000 maps. However, direct entry of spatial data, allows data to be stored as precisely as they are measured, eliminating the need to degrade them to the level of a less precise base map. For display purposes, data may be later manipulated to conform to a base map.

Level in a Categorical Hierarchy

Scale is often used in reference to a level in a categorical hierarchy. For instance biologists may study organisms at the species level or at more general levels of genus, or family. Similarly soils may be mapped at the scale of the soils series or at the scale of soil order. In this case, scale refers to a position along a continuum between specific and general.

Position Along a Systematic Spectrum

Scale is also used in reference to position along a systematic spectrum. In ecology, for example, studies may relate to individuals, populations, communities, or ecosystems (Odum, 1971). Generally this spectrum represents a progression from lesser to greater complexity.

Measurement Scale

There is a hierarchy of measurement scales based on their power in quantitative analysis:

1. nominal
2. ordinal
3. interval
4. ratio

Measurement scale is a limiting factor in determining the kinds of analysis methods and models that may be legitimately applied to data sets. There are well defined rules dictating what kinds of operations are allowable for nominal, ordinal, interval, and ratio data. It is always possible to move backwards along this scale (e.g. one can derive ordinal groupings from interval or ratio data, but it is not possible to derive interval data from ordinal groupings). Use errors often arise from using operations on data types which do not support them.

Level in a Spatial Hierarchy

Finally, the word scale is often used in reference to the spatial extent of a study. Generally a small scale study is one confined to a small area (site specific) while large scale studies are extensive (covering broad geographic areas). Usually, as the spatial scale of a study increases, map scale (for practical reasons) decreases, and so does categorical scale.

There is often an implicit assumption that these various dimensions of scale (particularly categorical, systematic, and spatial) vary together in well ordered ways. However, this is not generally the case, and it is important to keep these ideas distinct. It is also important to keep clear the distinction between the scale of concrete natural variation, the scale of conceptual models, and the scale of data.

Meanings of Resolution

Resolution refers, in some way, to the level of detail inherent in a data set. Resolution has four meaning relevant to geographic information:

1. categorical resolution (number of classes)
2. sensitivity (minimum discernible difference)
3. temporal resolution
4. spatial resolution

Categorical Resolution

Categorical resolution simply refers to the number of categories in a classification system.

Sensitivity

Sensitivity refers to the minimum discernible difference. For example, it may be the minimum increment of measure of a vernier, or in the case of digital scanner systems, the number of discrete grey levels for a data channel. It also may refer to how fine measurements or interpretations need do be to distinguish between classes. Usually, some categories in a classification system are easy to distinguish between and others difficult. For example, it may be easy to distinguish between classes which have drastic differences in vegetation amount while it is more difficult to distinguish between categories with similar vegetation amount but different structural characteristics. The sensitivity required to distinguish between classes is also effected by contextual considerations, for example the degree of contrast between an object and the objects or background that surround it.

Temporal Resolution

Temporal resolution refers to the time frame over which successive measurements are taken. Temporal resolution is important to consider when inventorying and monitoring dynamic systems, particularly when it is necessary to integrate data collected over long time periods.

Spatial Resolution

Spatial resolution refers to the smallest discernible spatial unit. For photographic systems (film/camera combinations) , the spatial resolution is usually expressed as the maximum number of line pairs per unit of distance that can be clearly detected on a photographic product. For digital imagery, spatial resolution is usually expressed as pixel size. For field surveys the spatial resolution may be expressed as the typical intersite distance or sample density.

It is important not to confuse the spatial resolution of source imagery with the spatial resolution of a map. Human interpreters, for instance, integrate and generalize information from aerial photographs in complex and unpredictable ways, and map resolution, where human interpretation is involved, is more a function of subjective factors than it is a function of image resolution. When objective methods are used for mapping (e.g. digital image processing), map resolution can vary greatly depending on the algorithms used.

It is also important not to confuse the spatial resolution of a map with the minimum mapping unit. Often, in land inventories, land units below a certain size are not recorded or are summarily deleted from the database because they are considered inconsequential to the purpose of the survey, this limit is the minimum mapping unit. To say that the minimum mapping unit is five acres means that land units less than five acres are not recorded and does not imply that the map has a spatial resolution of five acres. In fact, when mapping is accomplished by aerial photo interpretation map resolution is difficult to determine, and resolution is likely to vary considerably between different categories on the map and between different interpreters.

These many aspects of scale and resolution are related in complex ways. As digital processing of geographic data becomes more prevalent, these relationships are becoming weaker. In analog photogrammetry, there are fairly standard relationships between image scale, mapping scale, and positional accuracy. In digital photogrammetry and remote sensing, these fixed relationships no longer apply.

Usually there are trade-offs between different kinds of resolution. For example in order to increase temporal resolution (acquire imagery more often) it is usually necessary, for economic reasons, to accept lower spatial resolution (fly at a higher elevation), or superior spatial resolution of panchromatic film may be sacrifices to gain spectral sensitivity in the infrared range for certain kinds of vegetation analysis.

SOME EXAMPLES OF SCALE AND RESOLUTION PROBLEMS

Distributions based on samples are always suspect, since patterns are often artifacts of the density and spatial distribution of the samples, spatially correlated errors, or analytic techniques grounded in assumptions that don't apply. When analyzing spatial distributions on maps, the sampled nature of the data is often ignored, not well understood, or goes entirely unacknowledged. Geographers often differentiate between three kinds of distributions: random, clustered and dispersed. Spatial distributions are assumed to result from spatial processes.

Figure 1a illustrates a random point pattern, while Figure 1b illustrates a clustered pattern. The clusters however, are dispersed and the points within the clusters are also dispersed. It would be dangerous to consider these patterns as resulting from a natural spatial process without knowing the characteristics of the data source. As it turns out these patterns are the result of a sample. Figures 2a and 2b illustrate the sampling designs for Figures 1a and 1b respectively, and Figure 3 illustrates the population from which both samples were drawn. The patterns on Figures 1a and 1b reslult from the relationship between the density and distrubution of the point samples and the points in the population. This of course is a contrived situation intended only to illustrate that one cannot assume that patterns on maps are reflective of underlying spatial processes without knowing a lot about the characteristics of the data sources and the mapping methods.

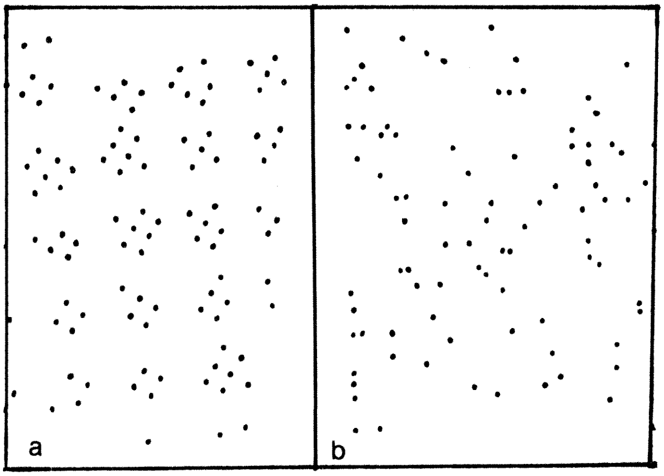

Figure 1: Point Patterns

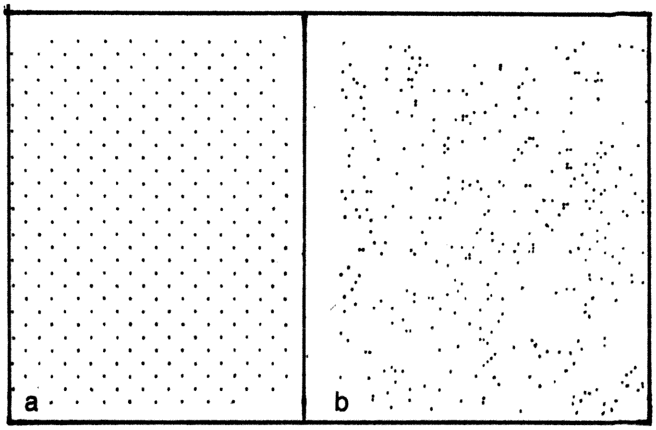

Figure 2: Sample Design for Point Patterns

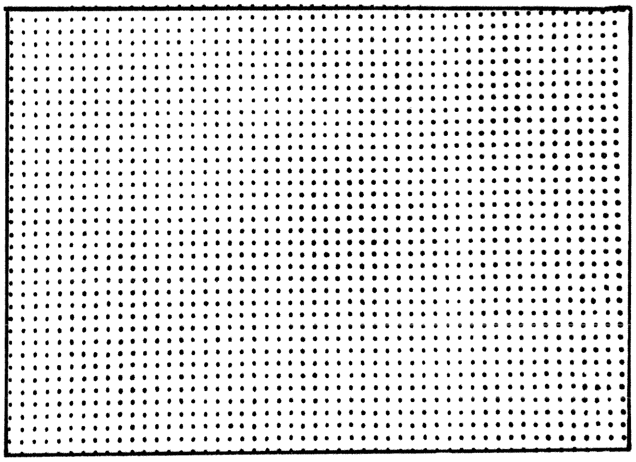

Figure 3: Population for Point Patterns

Figures 4 - 7 show similarly deceptive examples of spatial patterns from real spatial databases. Figure 4 is a portion of a vegetation stand map. There is no reason to believe that the noticably larger map units on the northern third of the map are reflective of different ecological conditions from the southern portion. The difference in the map unit sizes are likely the result of different interpreters. Figure 5 illustrates the common problem of striping found in digital elevation models (See Veregin, 1989 for an explanation). Figure 6 and 7 show slope maps for a 7.5 minute quadrangle in northern California. Figure 6 results from manual interpretation of a 40 ft. contour interval map while Figure 7 was computed from a 30 meter digital elevation model. The slope classes on both maps are the same but the spatial resolution is considerable different.

These figures illustrate that factors having nothing to do with ecology can have a substantial impact on map patterns. The problem is compounded when several layers of data are integrated to produce a composite.

Figure 4: Vegetation Stands

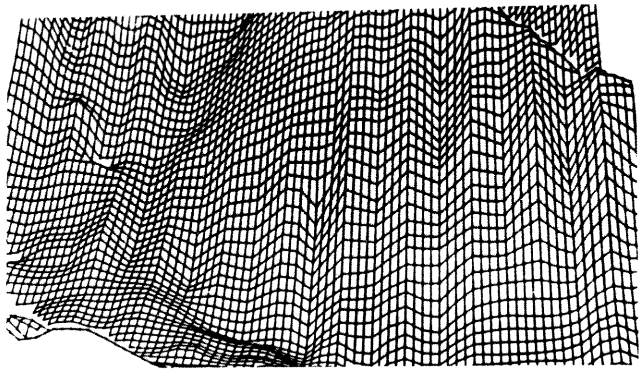

Figure 5: Elevation Model Striping

Figure 6: Slopes Interpreted From a Map

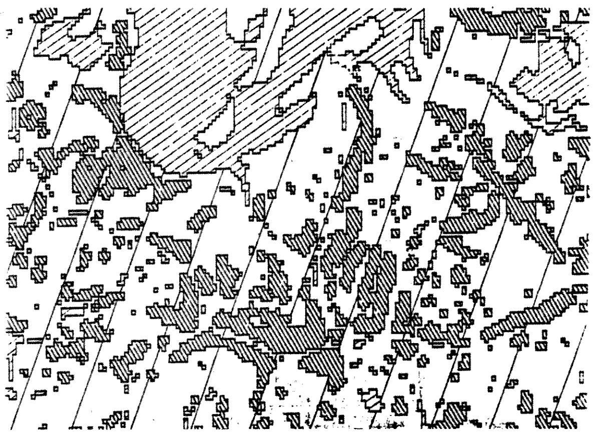

Figure 7: Slopes Computed From DEM

LITERATURE DISCUSSION

There is a large amount of literature relevant to issues of scale in landscape analysis. I would like to briefly discuss several works that represent the gamut of discussion of scale and resolution in the literature I am familiar with.

The Geometry of Nature

Mandelbrot's exposition of fractal geometry, if it does not provide ultimate solutions, sets the tone for future analysis of natural systems. Mandelbrot (1982) claims that compared with standard geometry, nature exhibits not simply a higher degree but an altogether different level of complexity. Measures such as as length and area of natural patterns often vary drastically with scale. But there is often a range of scales over which a natural pattern will exhibit a constant degree of irregularity or roughness, the measure of

Mandelbrot reminds us that nature does exist apart from Man, and anyone who gives too much weight to any particular scale of measurement, lets the study of nature be dominated by man, either through his typical yardstick size or his highly variable technical reach (Mandlebrot, 1982). For some elements of geometry, looking for a characteristic scale becomes a distraction (Gleick, 1987).

Fractal theory emphasizes the fact that the scales at which natural entities exist and processes operate is for practical purposes infinite. Certain geometric measurements such as boundary length, patch size, and perimeter to area ratios are highly variable across scales and are thus suspect as indicators of complexity or fragmentation. Uncertainty regarding such measures cannot be legislated away (Mandelbrot, 1982). Therefore, it is best, when possible, to use variables and analysis methods that are invariant within a relevant range of scales, or, when scale dependent measures are used, to seek relationships between the complexity of patterns at relevant scales.

The degree to which fractal geometry can be incorporated into predictive models of natural processes is not yet known. However, it is evident that the concerns regarding the stability and meaningfulness of certain elements of geometry to natural distributions are valid and cannot be ignored.

Scale Dependence of Vegetation Assemblages

John Matthews (1979), illustrates the effects of categorical resolution, spatial resolution, and analytic methods on the characterization of vegetation assemblages. The purpose of his study was to examine spatial relationships of assemblage types at four levels of resolution [categorical resolution] at four quadrant sizes [spatial resolution]. His intent was to describe the spatial patterns of vegetation assemblages and to explain the patterns in terms of time and environment.

Since his method is important to the point of this discussion, I will describe it briefly. The size of the study area was about .6 sq. miles (1.5 sq. km). The sample was spatially stratified by imposing a 7 x 13 grid over an aerial photo of the study area and selecting eight points randomly within each grid cell. At each of the sample site a 16 square meter quadrant was subdivided into 1 meter quadrants. This allowed analysis to be accomplished at 1, 4, 9, and 16 meter spatial resolution. The field inventory noted the presence or absence of some 45 plant species within each 20 x 20 centimeter subdivision of each 1 meter grid cell. This design results in a sample size of 291,200, 20-centimeter inventory cells (Matthews, 1979a).

The analytical strategy was to simplify the structure by employing several different classification techniques. The analysis tested the sensitivity of resulting vegetation assemblages to three classification techniques, four spatial resolutions and four assemblage resolutions. Matthews analyzed all permutations of the four spatial resolutions, four assemblage resolutions and three classification techniques.

Matthews concluded that contiguity of spatial patterns is a function of spatial and categorical resolution and procedures used. In more complex vegetation the problem can only be multiplied. He raises the question as to whether discrete types exist as natural groupings. He points out that sampling design may not catch certain patterns due to spatial autocorrelation in the distribution, i.e. riparian zones. Matthews suggests that substantial insights about the relative importance of ecological variables in defining vegetation patterns have been obtained by carrying out analysis at different levels of resolution and comparing results. He cautions that there is nothing to prevent classification in a continuum, but if the types produced by classification are no more than an arbitrary dissection of the data, then the data have been forced into a straight jacket which may distort reality and restrict hypothesis.

Matthews feels that ecological system methodology is one step closer to the recognition of the complexity of relationships in the real-world vegetation landscape. However this methodology, by emphasizing environmental relationships, generally neglects spatial and temporal relationships.

With respect to this discussion Matthews' work is important because it makes clear the distinction between the effects of categorical aggregation and spatial aggregation. They are different processes. This analysis is bases solely on field sampling and does not rely on remote sensing data, illustrating that the problems associated with mapping and analyzing community patterns are not necessarily alleviated by field mapping. When remote sensing is used, the problems are compounded since we then need worry not only about the scale of natural patterns but also about the resolution of the remote sensing data and how the two relate.

The Problem for Remote Sensing

Since 1986, Alan Strahler, Curtis Woodcock, David Jupp, and James Smith have collaborated on a series of papers which consider the relationship between landscape complexity, resolution of remote sensing data, and image analysis. Some of the papers in this series include **On the nature of models in remote sensing** (Strahler, Woodcock, Smith, 1986), **The factor of scale in remote sensing** (Wookcock, 1987), and several papers discussing regionalized variables, regularization and the use of variograms in remote sensing (Jupp and Strahler, 1988, Woodcock, Strahler and Jupp, 1988a-b). In these papers, concerns similar to Matthews' are extended to the remote sensing problem. The remote sensing problem is to infer order in the properties and distribution of matter and energy in a scene by analyzing an image. A scene, is the spatial and temporal distribution of matter and energy fluxes in the environment, and an image is a set of sensor measurements (Strahler, Woodcock, Smith, 1986).

On the nature of models in remote sensing provides a taxonomy of models used in remote sensing. The authors distinguish two types of scene models: discrete and continuous. Discrete scene models assume that there are discontinuities where properties change abruptly. The scene is composed of distinct elements. With continuous models, changes in matter are taken to be everywhere continuous. The scene is taken to be a differentiable curved surface.

This dichotomy is reminiscent of the dichotomy between the wave and particle theories of light. The question as to which one is true is answered relative to practical considerations. In forestry discrete scene models predominate, for example the landscape mosaic.

The authors suggest a further dichotomy of scene based on the size of the scene elements and the resolution cell of the sensor: H-resolution models where scene elements are several times larger than image resolution cells and L-resolution models where scene elements are several times smaller than image resolution cells. It is difficult to characterize models when element size and cell size are similar. This paper suggests that we need to pay closer attention to the relationship between the size of scene elements and the spatial resolution of the sensor. Effective ecological modeling may require formulation of models specific to the size of elements and resolution cells.

In **the factor of scale in Remote Sensing**, Woodcock and Strahler suggest that selection of appropriate resolution is a complex problem, since it is dependent on the type of environment, the kinds of information required, and the analytic methods employed. They propose that graphs of local variance as a function of their spatial resolution are helpful in determining appropriate analytic methods for available sensor data in various environmental settings. Some authors have demonstrated that classification accuracy often decreases as spatial resolution increases, attributing the loss of accuracy to increased local variability which they call "noise" (Toll, 1985). Woodcock and Strahler point out that this variability is not "noise" but is rather information about the scene structure. They attribute the loss f accuracy to inappropriate methods rather than to ncreased resolution.

For example, in agricultural settings, local ariance at 30 meters is low, indicating that spec- ral classifiers which assume a high degree of spa- ial autocorrelation may be appropriate. Whereas n forested settings, local variance is high at 30 eters, suggesting that spectral classifiers may ot be appropriate.

Woodcock and Strahler recommend that texture easures be used in conjunction with spectra data here local variance is high. Use of texture im- lies that scene elements are not spatially homo- eneous at the resolution of the image cells.

In several papers, Strahler, Wookcock and Jupp iscuss regionalized variables, regularization (the ffects of generalization) and the use of vario- rams as a means of inferring the size and distri- ution of scene elements from images. They point ut that while use of digital remote sensing tech- iques has increased the use of information from he spectral domain, there has been a reduction in he use of information from the spatial domain. hese investigators are attempting to develop meth- ds for making better use of texture and context in mage analysis. Strahler and Woodcock have been eveloping invertable canopy models which employ egionalization procedures as opposed to conven- ional supervised and unsupervised classification rocedures.

In the context of this discussion, the important oints of these papers are that remote sensing mod- ls should consider the relationship between the ize of scene elements of interest and the reso- ution of the image, and in areas where local ariability is height at the image resolution, ana- yses which incorporate textural information may be ore appropriate than purely spectral classifiers.

cological Subdivision of Land

Bailey (1988) states that we are motivated to ivide the landscape into component ecosystems by fforts to model the behavior of ecosystems under ifferent management scenerios. This point of view ssumes that there are ecosystem types that will espond similarly to similar management activities, hat ecosystems are nested spatially, and that eco- ogical types can be reliably mapped.

Bailey suggests that in nature, there are vari- us spatial scales at which ecological process perate. At any spatial scale, factors that con- rol climate (i.e. energy and moisture distribu- ions), are most important in controlling cosystems, i.e the volume, diversity, and struc- ure of life forms. This contention seems to be orn out in the ecology and biogeography litera- ure. (Odum, 1971, Brown and Gibson, 1983). The mplication for landscape stratification is that tratifications should be based on the factors that re the most important climatic controllers at the cale of the analysis.

Bailey identifies three scales at which envi- onmental processes operate: the macroscale, the mesoscale and the microscale. The macroscale re- fers to the global level. At this level the dominant controlling factors are latitude and con- tinental position. The mesoscale refers to the physiographic regional level at this scale major landforms and elevational differences are dominant factors. At the microscale, the local level, fac- tors controlling moisture availabilty, e.g. edaphic factors and local topography, become increasingly important. It is important to note, however, that even in his small study area, Matthews found that the importance of ecological factors varied depend- ing on the scale at which he analyzed his data.

These works are important in that they point out that different variables are important at different scales of analysis. Bailey, however, does not dis- cuss in detail how to determine the sampling reso- lution required to adequately delineate ecological type boundaries at these ecological scales.

Frank Davis and Jeff Dozier used a mutual in- formation analysis technique to develop an eco- logical land stratification for an area near Santa Barbara California. The method was first described by Phipps (1981) in a paper titled Entropy and Com- munity Pattern analysis. The procedure is well suited to the kind of landscape stratification recommended by Bailey. The model is appropriate for use with nominal data (which we are often obliged to rely on) and provides a systematic method for determining which maps of ecological factors provide the best predictive value in re- lation to a variable of interest, in this case community types.

The method analyzes the interaction between a dependent variable and ecological factors by way of contingency tables. The model sees a pattern as a system whose freedom to take any particular state from among a possible set of states is constrained by ecological factors. The procedure seeks to re- duce the entropy in the community pattern by a neg- entropy provided by the maps. Since all variables are treated as nominal variables, quantitative variables must be converted to binary maps thus giving up some information. But this seems better than creating artifacts by treating nominal vari- ables as quantitative variables. The procedure has an advantage over multiple regression models in that it operates without any restrictions on data structure and distributions and is consequently well suited to spatial modeling (Phipps, 1981).

Mutual information analysis is a means of ex- trapolating from areas where intensive ecological inventories to areas where only extensive data area available. It may provide a way to construct bet- ter ecological models for forest analysis relying on digital remote sensing, and may provide a needed link between broad area inventories and detailed ecological surveys.

RECOMMENDATIONS

Landscape analysis requires a multi-stage ap- proach. Proposed strategies suggest stratifying the landscape at several categorical and spatial scales. Since it will not likely be possible to accomplish and maintain intensive ecological field surveys everywhere. Landscape analysis will require effective methods for extrapolating from areas where there are intensive surveys to broader regions. This will require coordinating multistage surveys.

When constructing spatial databases, be aware of the typical sizes of objects that need to be coregistered and use transfer methods that can produce the required accuracy and report on the magnitude and distribution of positional errors. Pay more attention to variability introduced by subjective factors and ensure that interpretations are sufficiently repeatable. If they are not, find out why.

Use analysis methods that incorporate information about uncertainty. For example, in the case of classification error, a vector for a map class from a confusion matrix can be used as a probability vector for the map class in a stochastic model. Map residuals from all analyses and attempt to explain spatial dependence in error distributions. Keep clear the distinction between statistical significance and operational significance. Confidence intervals have no meaning in the absence of knowledge regarding tolerances.

Know the underlying assumptions of the models being used. In geographic analysis, be wary of assumptions of: normality, independence between variables, homogeneity and random spatial distributions. Use models that are logically consistent with the most limiting measurement scale of the data, and convert all variables to the most limiting measurement scale.

Recognize that different variables are important at different scales and at different places. Specific models should be used only at the scales and at the places for which they were developed and tested. Don't include variables unless it can be demonstrated that they make a significant contribution to the analysis.

Move away from attempting to characterize classes toward characterizing places. Predictive models require location specific values. When feasible, replace procedures that lump with procedures that interpolate (Burrough, 1989).

Most importantly, keep clear the distinction between objective reality and abstract representations. Are ecosystems natural beings or human constructs? On one hand we speak of them as living beings and on the otherhand we talk about defining them in terms of management objectives. Since the amount of sampling, and the nature of analyses are limited by economic constraints, often landscape patterns, as depicted on maps, may more a be a reflection of economics than of ecology.

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TI ANALYZER: A PROCEDURE FOR MANAGING AND PROCESSING TREE IMPROVEMENT DATA[1]

John W. Armstrong[2] and Gerald C. Franc[3]

Data management and analysis for the Northern Region's tree improvement program is provided by a comprehensive, user-friendly software program called TI Analyzer. TI Analyzer provides a variety of services and outputs including data transfer, error checking, merging and appending, reformating, statistical analyses, estimates of heritability and gain, and computer-generated field maps.

The Northern Region of the U.S. Forest Service includes the National Forests and Grasslands of northern Idaho, Montana and western North and South Dakota. The commercial harvest of timber within the region is of relatively high importance especially on the more productive Forests in Idaho and Montana west of the Continental Divide. The National Forest Management Act requires that harvested stands be regenerated within a period of 5 years. Good silviculture and economics further dictate that, when non-stocked stands are to be planted, whether they were created by timber sales or by fire or some other natural catastrophy, they be considered for planting with material of known genetic worth, selectively bred for good growth and adaptation to the site.

Selective breeding programs are currently under way for six conifer tree species in the Northern Region. The species are western white pine, ponderosa pine, Douglas-fir, western larch, lodgepole pine and grand fir. Three more species, Engelmann spruce, whitebark pine and Pacific yew may be added to the program in the near future.

Overall direction, planning and data analysis for the Northern Region's tree breeding program is provided by a small staff of professional and technical specialists with technical guidance and basic genecology data provided by the Silviculture and Genetics Project of the Intermountain Experiment Station. The selection and collection of wild-parent plus trees and the establishment, maintenance and measurement of genetics tests are done by the appropriate National Forest units. All tree breeding activities are coordinated with the Inland Empire Tree Improvement Cooperative.

Data from the genetics tests are collected on a, more or less, regular schedule with some variation between species programs. Measurements are taken using electronic field recorders, eliminating the need for subsequent keypunching and minimizing costs and the added potential for keypunching errors. National Forest units are interconneted by an electronic mail system and data are transfered to and from units electronically.

Some of the features of the Northern Region's tree improvement program are:

1. In each species program, breeding is carried out within biologically defined breeding units. The breeding unit boundaries represent the maximum distance that local sources can be moved without experiencing maladaption. Geographic location and elevation account for a great majority of the variation within a species and this is reflected in the breeding unit maps.

2. Progeny from wild-parent plus trees in each individual breeding unit for each species program are tested in short-term, farm field type tests called "early selection trials". These tests are planted at close spacing on low elevation, mild sites. They are intensively managed to minimize environmental stress and to maximize the expression of growth. The final measurements are usually taken at the end of the fifth growing season.

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2/ John W. Armstrong, Computer Programmer Analyst, USDA-Forest Service, 1221 South Main St. Moscow, ID 83843

3/ Gerald C. Franc, Selective Breeding Specialist, USDA-Forest Service, 1221 South Main St., Moscow, ID 83843

3. While growth is the trait of interest in early selection tests for all species, white pine is also screened for resistance to the fungus disease, white pine blister rust, and Douglas-fir and western larch are scored for cold hardiness.

4. Data from the early selection trials are used to identify superior genotypes for both seed orchards and breeding orchards. The Northern Region's breeding programs call for "forward" selection in which additional gain is achievied by selecting best individuals in best families and then using these individuals or clones of these individuals in the seed orchards and breeding orchards rather than cloning material from the wild parent tree.

5. Select materials from the early selection trials are outplanted in long term performance tests within the breeding unit to evaluate fitness on natural sites. These tests may be established with half-sib seedlings from the same family or with rooted cuttings from the select trees themselves if an operational rooting procedure is available. Measurements from the long term performance tests are used to "fine tune" the seed orchards. The tests also serve as a source of material for advanced generation breeding.

The size of the Northern Region's program has made it desirable to have a rather comprehensive software program to manage the collection, maintenance and analysis of the data generated. Since such a software program is not available on the open market, it has been necessary to develop this program "in house". The program that eventually evolved and is described in this paper is called "TI Analyzer"

To meet the changing needs of the Northern Region's breeding programs, TI Analyzer has been modified and updated several times. In its present form, TI Analyzer provides the following:

1. A means for downloading and uploading datafiles to and from hand-held field recorders and the mini-computer system in use in the Region.

2. A means for using the mini-computer system for electronically transfering datafiles to and from the National Forest units in the Region, and the Data Manager.

3. A method of error checking datafiles after they have been transfered.

4. A means for viewing and editing datafiles by the data manager and by the National Forest units under the guidance and control of the Data Manager.

5. A means for merging or appending datafiles when the data to be analyzed is coming from more than one test site, when subsequent measurements are to be added to existing data sets, or when situations arise at the test sites that dictate the need for opportunistic, non-scheduled measurements.

6. A method for re-writing datafiles and getting them into the proper format for analysis.

7. A summary of each test, by replication, in silvicultural terms, ie, survival, damage, average height, etc.

8. A statistical analysis of the datafiles that takes into consideration homogeneity of the data, family imbalance, differences in site, genetic variation, least significant differences, etc.

9. A provision for the creation of "temporary" data sets from the original datafile that can be manipulated to answer "what if" questions.

10. A series of reports that identify best individuals in best families, using conventional ANOVA procedures for balanced data or Best Linear Prediction for data with a significant amount of imbalance, ranked from best to worst, sorted by row and column and with "wildcard" trees (outstanding individuals in low ranking families) identified.

11. An estimate of heritability and gain for the material in the program.

12. Computer generated plantation maps by family, trait, or damage, with or without elite trees highlighted, and with any other enhancements needed by the plantation managers.

Following is a detailing of most of the reports generated:

ANAHOMOGEN - A homogeneity of variance table which, along with the deviation tolerance (in ANAPROF), is used as a basis to determine how to adjust traits (usually heights): by regression or by standard deviates.

ANAPROF - Family Profile Report, showing mean family adjusted trait, overall and by rep, one family per report line. At report end it shows various totals: family count, number of unbalanced families (any zero tree count in reps), under-represented families (family tree count less than 5). Flags show where the maximum tree count per rep is exceeded. Deviation tolerance is an indicator of how close tree counts per family, per rep have managed to stay to the original experimental design intentions. It is the tree count deviation from the largest tree count per family, across the reps at a given site, and gives an idea of family balance.

ANABESTN - Best n trees of top n% families. Report headers are as follows: Family number, family tree count, mean family trait (usually height), percentile rank of the mean family trait, and family percent damaged (disease or structural). The remaining headers across the page top refer to the top ranking individual trees within that family: Adjusted height, individual rank (1..5), acutal height, previous height, rep, row, column, tag status, and damage code or site name.

ANASKIPPED - A list of families skipped in processing due to an insufficient total tree count in the reps. Usually 4 or 5 is an acceptable minimum (prompted for).

ANA_MR_OUT - Family Mean Ranking Report, showing all families ranked on their mean trait.

ANAELITELIST - A list of elite trees for field use in that they are sorted by rep, row and column, or rep column and row - prompted for.

ANAWILDCD - Wildcard Trees Report, showing trees from the original base dataset that are higher (rating) than the average actual trait value of trees in the Best n report, not in the Best n report.

TI Analyzer is truly user-friendly and runnable by the programmer and non-programmer alike. Data managers, geneticists, foresters, statisticians, or just about anyone associated with the tree improvement program could use it. Getting the data correctly put together for TI Analyzer requires some basic computer skills; however, there is a main menu option allowing a simplified, automatic way to get data into "Analyzer" format.

As a package, in terms of commercial programs on the open market, it's features include:

1. Menu driven screens.
2. Error trapping for:
    - user responses.
    - data content.
3. Independence from any other utility or package (it is written in Fortran 77 and operating system macros).
4. High speed data access via binary searches on lists sorted by quicksort.
5. Maintainable and readable source code via:
    - Program prologues and line-by-line comments.
    - Self-definitive datanames, using the 32 character maximum length allowable, when advantageous to do so.
    - Program variables, datanames and language commands differentiated via upper and lower case, underscores, etc.
    - Usage document, "analyzer.doc".

Currently, TI Analyzer runs only on Data General equipment, but it is written in such a way that it could be ported to DOS or Unix in a relatively short period of time. It comprises 13 separate source code files and 9 CLI Sort-Merge macros.

STOCHASTIC PRICE MODELS AND OPTIMAL HARVEST STRATEGIES FOR LOBLOLLY PINE DEPEND ON MARKET EFFICIENCY [1]

Robert G. Haight and Thomas P. Holmes [2]

Abstract.— The efficiency of southern pine stumpage markets depends on the interval of price observation. Therefore, these markets provide an opportunity to study the effects of market efficiency on stochastic price models and optimal harvest strategies. This paper constructs time-series models for loblolly pine sawtimber prices in the Piedmont region of North Carolina using quarterly and monthly observations between 1977 and 1988. Optimal harvest strategies for a single-rotation model are numerically estimated using dynamic programming. For the quarterly interval (the efficient market), the price model is a random walk. The optimal strategy is the same as that obtained with a deterministic price: harvest when stumpage price is less than an age-dependent reservation price. Significant losses may be incurred with a reservation price policy that times harvests to periods when prices are high. The price model for the monthly interval (the inefficient market) is a first-order, autoregressive process for price changes: the predicted price change is inversely related to the past price change. The optimal strategy is to harvest when stumpage price is greater than a reservation price that depends on age and last month's price. Gains in present value are made by timing harvests to periods when prices are high. These results emphasize the importance of the decision cycle and market efficiency when estimating price models and optimal harvest strategies.

INTRODUCTION

Recognizing that stumpage prices fluctuate considerably over time, several authors have formulated timber harvesting problems that incorporate stationary stochastic models of stumpage prices. An implicit assumption with stationary price models is that current and past stumpage prices may be used to predict next period's price change. This information is exploited by determining adaptive harvest strategies: timber harvests are timed using the simple rule of "cut only when prices are high." For even-age management, the stand is clearcut whenever the observed stumpage price is greater than an age-dependent reservation price (Norstrøm 1975, Lohmander 1987, Brazee and Mendelsohn 1988). For uneven-age management, harvesting takes place when aggregate stand value is greater than a stand reservation value, and harvest intensity increases with increasing stand value (Kaya and Buongiorno 1987, 1989, Haight 1990). Such strategies provide significantly higher returns than do cutting practices that are not price-responsive and are based on average prices alone.

The assumption that current and past prices may be used to predict future price changes is not consistent with the so-called efficient market hypothesis. A necessary condition for an efficient market is that all past information about asset price cannot be used to produce a better estimate of the future price than the capitalized current price (Washburn and Binkley 1990, p. 403). While much

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[2]The authors are research foresters with the Forest Service, U.S. Department of Agriculture. Haight is with the North Central Forest Experiment Station, 1992 Folwell Ave, St. Paul, MN 55108; Holmes is with the Southeastern Forest Experiment Station, Box 12254, Res. Tri. Park, NC 27709. The work was conducted while Haight was a member of the Southeastern Forest Experiment Station.

work has been conducted to test the efficiency of stock markets (see LeRoy 1989 for review), little has been done to test the efficiency of markets for capital assets such as stumpage. In a pioneering study, Washburn and Binkley (1990) examine the efficiency of loblolly pine (*Pinus taeda* L.) sawtimber markets across the southern United States. Their results depend on the time period in which prices are observed: while the markets are efficient for annual or quarterly price observations, markets did not pass the efficiency test using monthly price observations.

Market efficiency has an important implication for optimal harvest strategies. When past prices cannot be used to predict future price changes, there can be no gain in value from using past price movements to play the market in timing timber harvests (Washburn and Binkley 1990, p. 403). Clarke and Reed (1989) confirm this conjecture. They formulate harvesting as a continuous–time, optimal–stopping problem for diffusion processes. Prices are modeled as geometric Brownian motion. The properties of the model are consistent with an efficient market. When price is the only stochastic variable, the optimal harvest strategy for both single– and infinite–rotation models is based on a myopic–look–ahead rule: harvesting occurs when asset value is greater than the expected present value of the asset at an infinitesimal time later. [3] Further, this rule requires that the stand be harvested at a fixed rotation age, independent of the current price. If the price model is based on a logrithmic price transformation, then optimal rotation age and present value increase with increasing price variation. [4] With untransformed prices, uncertainty has no influence on optimum harvest age and present value. These results assume no fixed costs. Clarke and Reed conjecture that fixed costs would require that the optimal cutting rule depend on price and age.

Because the efficiency of southern pine stumpage markets depends on the interval of price observation (Washburn and Binkley 1990), these markets provide an opportunity to study the effects of market efficiency on stochastic price models and optimal harvest strategies. In the first part of this paper we construct time–series models for loblolly pine sawtimber in the Piedmont region of North Carolina using quarterly and monthly price observations between 1977 and 1988. In the second part, we numerically estimate optimal harvest strategies.

[3]Routledge (1980) shows that this rule is optimal for a discrete–time, infinite horizon harvest model in which price is a Martingale.

[4]In fact, optimal rotation age and present value may be computed with a deterministic model in which the discount rate is reduced as a function of the price variance.

The decision model is for a single rotation: the problem is to choose the optimal clearcut strategy for a mid–rotation stand that maximizes its expected present value. Revenue includes the value of harvested trees and the value of bare land, which is constant and independent of stumpage price and time. This single–rotation formulation is appropriate for a landowner who plans to sell the bare land for a known price and is faced with the problem of timing the clearcut. The model may also be appropriate for a timber manager who computes an expected present value for an infinite series of plantations (bare land value) that is independent of changes in stumpage price in the short term (less than, say, 5 years). The expected value of bare land is based on a long term (greater than 20 years) price forecast that is independent of monthly or quarterly price changes.

The results show that price models and optimal harvest strategies depend on market efficiency. Because the revenue equation includes a fixed, bare–land value, the optimal strategies are price–dependent; the form of the price dependence depends on the form of the price model. Using these price models and their associated harvest policies as baselines, the costs of suboptimal harvest strategies are estimated.

STUMPAGE PRICE MODELS

Time–series model of stumpage prices are developed using real loblolly pine sawtimber prices ($(1988)/Mbf, International) for the Piedmont region of North Carolina as reported in Timbermart South. Models are developed for quarterly and monthly time intervals. Price observations are available in monthly intervals between January 1977 and March 1988. A quarterly series of observations is obtained by aggregating the data.

Each time–series model is constructed under the assumption that the observed series of market prices $m(t)$, $t = 0, \ldots, T$, is generated by a stochastic process. The model describes the characteristics of the observed series' randomness in a manner that is useful for forecasting. Three steps are involved in contructing a model: identification of model form, estimation of model parameters, and examination of the random errors of the estimated model.

The model form is identified by determining whether or not the underlying stochastic process is stationary (i.e., the mean, variance, and covariance of the process are constant over time). If the process is stationary, it can be modeled as an equation with fixed coefficients that can be estimated from the past data.

If the data is not generated with a stationary stochastic process, the differenced price series $\Delta m(t) = m(t) - m(t-1)$, $t = 1, \ldots, T$ may have the desired properties.

The autocorrelation function for the observed time series is used to determine whether or not its underlying stochastic process is stationary. The autocorrelation function describes the amount of correlation between data points that are separated by a fixed number of time periods (lags). The autocorrelation function for a stationary series decreases rapidly as the number of lags increases. Conversely, the autocorrelation function for a non-stationary series does not decrease as the number of lags increases.

Plots of the autocorrelation functions for both the quarterly and monthly data indicate that neither series is generated with a stationary process. Both series are differenced once to obtain series that are generated with stationary processes. Therefore, autoregressive models of the following general form are identified for each series of price differences:

$$\Delta m(t) = \theta_1 \Delta m(t-1) + \ldots + \theta_p \Delta m(t-p) + \alpha + \varepsilon(t) \quad (1)$$

where α and θ_j, $j = 1, \ldots, p$, are the parameters to be estimated. The order of the autoregressive model is p, which refers to the number of lagged price changes that are used to estimate the current price change. The random component $\varepsilon(t)$ is assumed to be white noise: $\varepsilon(t)$ is normally distributed with zero mean and standard deviation σ, and $E[\varepsilon(t)\varepsilon(s)] = 0$ for $t \neq s$.

The order of the autoregressive model is determined using the partial autocorrelation function, which measures the correlation between observations at succeeding lags after the correlation at intermediate lags has been controlled. If the order of a process is p, the autocorrelation for all lags greater than p should be approximately zero. The partial autocorrelation function for the differenced quarterly data reveals no significant partial autocorrelation coefficients at any lags past lag zero (i.e., $p = 0$). The function for the differenced monthly data reveals a significant partial autocorrelation coefficient at the first lag only (i.e., $p = 1$).

Quarterly Price Model

Because the partial autocorrelation function suggests no lags in the process describing the quarterly price differences, the tentative model is

$$\Delta m(t) = \alpha + \varepsilon(t). \quad (2)$$

The parameter estimate for this model is

$$\hat{\alpha} = 0.04 \text{ with } t\text{–statistic} = 0.02.$$

Because $\hat{\alpha}$ is not significantly different than zero at the 0.05 level, it may be dropped from the equation without loss of precision. The standard deviation σ of the error term is 10.81.

The Box–Pierce Q–statistic is used to test the null hypothesis that the autocorrelation function for model errors is not different than a white noise autocorrelation function. The Q–statistic for the model errors is not significant at any lags indicating that the errors are white noise. Therefore, we conclude that the quarterly price differences are generated by an autoregressive process with zero lags.

Since $\Delta m(t) = m(t) - m(t-1)$, the stationary model for price differences (equation 2) may be tranformed into a non–stationary, random walk model for prices:

$$m(t) = m(t-1) + \alpha + \varepsilon(t) \quad (3)$$

where α is the drift parameter. When $\alpha = 0$, the price trend is horizontal.

The random walk model has implications for price forecasting (see, for example, Pindyck and Rubinfeld 1981). A forecast one period beyond period T depends only on the observed price in period T and the drift parameter:

$$\begin{aligned} \hat{m}(T+1) &= E[m(T+1) \mid m(T), m(T-1), \ldots, m(0)] \\ &= m(T) + \alpha. \quad (4) \end{aligned}$$

Likewise, the k–period forecast depends only on the current price: $\hat{m}(T+k) = m(T) + \alpha k$. This property is consistent with a necessary condition for an efficient market: all past information about stumpage price cannot be used to produce a better estimate of the future price than the capitalized current price. Further, there can be no gain in value from using past price movements to play the market in timing timber harvests.

Monthly Price Model

Because the partial autocorrelation function for the monthly price differences suggests one lag, the tentative model is

$$\Delta m(t) = \theta \Delta m(t-1) + \alpha + \varepsilon(t). \quad (5)$$

The parameter estimates for this model are

$$\begin{aligned} \hat{\alpha} &= -0.03 \text{ with } t\text{–statistic} = -0.04, \text{ and} \\ \hat{\theta} &= -0.30 \text{ with } t\text{–statistic} = -3.58. \end{aligned}$$

Because $\hat{\alpha}$ is not significantly different than zero at the 0.05 level, it may be dropped from the equation. $\hat{\theta}$ is significantly different than zero, and its value lies within the bounds of stationarity. The standard deviation σ of the error term is 11.81. The Q–statistic for the errors is not significant at any lags indicating that they are white noise. Therefore, we conclude that the model for monthly price changes is first–order autoregressive.

Since $\Delta m(t) = m(t) - m(t-1)$, equation (5) may be tranformed into a non–stationary model for prices:

$$m(t) = (1+\theta)m(t-1) - \theta m(t-2) + \alpha + \varepsilon(t) \quad (6)$$

where α is the drift parameter. When $\alpha = 0$, the price trend is horizontal.

Using $\hat{\theta}$, a forecast one period beyond period T is:

$$\hat{m}(T+1) = 0.70m(T) + 0.30m(T-1). \quad (7)$$

Equation (7) says that, when the current price is less (more) than the previous period's price, the price forecast is greater (less) than the current price. In other words, the forecast price change is inversly related to the price change in the previous period. Because the current and past price are used to predict the future price, the forecasting model is not consistent with the necessary condition for an efficient market. Further, the predictive power of past prices may be used to construct adaptive harvest policies that time timber harvests to periods of high prices and increase expected returns.

DYNAMIC PROGRAMMING FORMULATION

Similar to Norstrøm (1975), the dynamic programming model described below assumes that the stochastic price forecast depends only on the current price. Thus, the formulation is used with the random walk model for quarterly price changes (equation 3). The formulation is easily modified to incorporate the autoregressive model for monthly price changes (equation 5).

The state descriptor is a discrete variable representing the current market state. Let $m_k(t)$, $k = 1, \ldots, n$, represent n discrete sawtimber price classes (\$/Mbf, International) at the beginning of period t. For convenience, the period t equals the age of the stand. The random walk model (equation 3) is used to estimate discrete transition probabilities $p_{j,k}$ representing the probability of being in price class j in period $t+1$ given $m_k(t)$.

The revenue $R[m_k(t)]$ (\$/acre) obtained from clearcutting in period t depends on the current market state. Stand volume $v(t)$ (Mbf/acre) is a deterministic function of stand age. Bare land value L (\$/acre) is the selling price for bare land. The revenue function is:

$$R[m_k(t)] = m_k(t)v(t) + L. \quad (8)$$

For a given bare land value and time horizon T, the optimal harvest strategy is found by solving a recurrence relation for optimal stand value. Define $Z_t[m_k(t)]$ as the expected present value (\$/acre) of the stand in period t and market state $m_k(t)$. Assuming that the decision maker's real discount rate is r and the discount factor is $\delta = \frac{1}{1+r}$, the recurrence relation for optimal stand value is:

$$Z_t[m_k(t)] = \max\left\{R[m_k(t)],\ \delta \sum_j p_{j,k} Z_{t+1}[m_j(t+1)]\right\}. \quad (9)$$

The maximization problem is the choice between clearcutting and no action. Clearcutting is optimal when the revenue $R[m_k(t)]$ is greater than the expected present value of the stand in period $t+1$. The boundary condition in period T assumes that all trees are cut:

$$Z_T[m_k(T)] = R[m_k(T)]. \quad (10)$$

The recurrence relation for optimal stand value (equation 9) is solved backwards from period $T-1$ using the boundary equation (10). The recurrence relation ends in the earliest period in which the stand may be harvested. The solution is either a clearcut or no action decision for each market state in each period.

There is an important difference between the horizon T and the rotation age. The horizon T represents the maximum number of periods a stand is allowed to grow. If a stand reaches period T, it is clearcut. Clearcutting may take place in any period $t < T$. The rotation age depends on the market state and the probability distribution of future market states. The horizon T may be arbitrarily long; for computational efficiency it should be long enough that the likelihood of clearcutting before period T is high.

Optimal harvest strategies for the 30–year–old plantation are determined by solving the recurrence relation backwards from age 50. Harvest revenue is obtained for sawtimber; pulpwood has no value. The discrete variable for stumpage price ranges between \$0.00 and \$400.00/Mbf in \$5.00/Mbf intervals. Bare land value (L in equation 8) is \$550.00/acre and represents the rotation–start present value of an infinite series of plantations computed using a deterministic stumpage price equal to \$125.00/Mbf. Prices are in 1988 dollars. The real discount rate is 4 percent.

Monthly and quarterly sawtimber yields (International Mbf/acre) for a pure loblolly pine plantation are predicted with the second degree polynomial:

$$v(t) = -16.54 + 1.029t - 0.005220t^2 \qquad (11)$$

where t is stand age. The model is constructed with ordinary least squares applied to output from the North Carolina State University Plantation Management Simulator (Hafley and Buford 1985, Smith and Hafley 1986, 1987). The simulator is used to predict annual sawtimber yield from a 30-year-old plantation over a 20-year horizon. At age 30, the plantation has 100 trees/acre and 100 ft^2/acre basal area. The plantation is on site index 65 (25 year basis) land in the North Carolina Piedmont. The volume versus age model (equation 11) fits the data with $R^2 = 0.999$; all parameters are significant at the 0.05 level.

OPTIMIZATION RESULTS

The Quarterly Model

The optimal policy for the random walk model (equation 3) is to harvest when the observed price *is less than* an age-dependent reservation price. Reservation prices for the random walk model increase with age (Figure 1); the area under and to the right of the curve contains the price-age combinations when the stand should be harvested. Stands greater than 38.00 years are harvested regardless of price. In younger stands, harvesting is postponed when the observed price is high because the future price is expected to remain high and because the value of the growing stock and growth is high relative to the fixed value of bare land.

Using the optimal policy for the random walk model, the expected present value of the 30-year-old stand depends on the starting price (Table 1). As the starting price increases from \$80.00 to \$160.00/Mbf, present value increases from \$1,327.00 to \$2,163.00/acre. When $m(0) = \$125.00$/Mbf (the mean of the price series), the present value is \$1,800.00/acre.

For comparison, we computed optimal harvest policies for a deterministic price model and a stationary stochastic price model. With the deterministic model, the price forecast is the mean of the price series: $m(t) = 125,\ t = 0, 1, \ldots$. The optimal policy is to harvest when the stand is 34.25 year old. The present value is \$1,800.00/acre.

The surprizing result is that the expected present value of the optimal policy for the random walk model with $m(0) = \$125.00$/Mbf is the same as the present

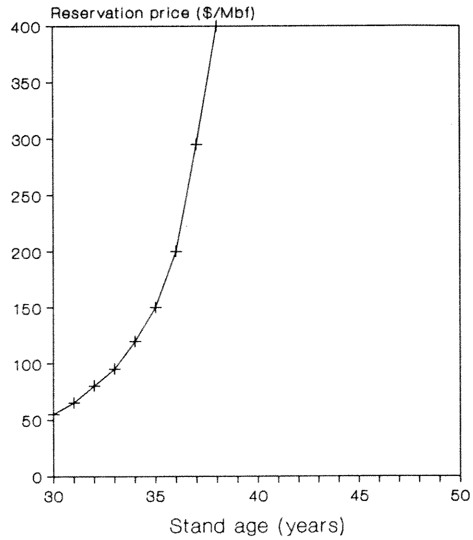

Figure 1.—Reservation prices for the quarterly random walk price model.

value computed with a deterministic price equal \$125.00/Mbf. With a random walk, the observed price in each period is the best estimate of the future price. Because the expected price change is zero, there can be no gain from waiting for a higher price. Furthermore, price variability has no effect on the expected present value of the optimal policy.

What is the cost of using the optimal fixed-rotation policy when prices are a random walk? The expected present values of the fixed rotation policy are listed in Table 1 for different starting prices. The cost is the difference in present value from the return obtained with the optimal policy for the random walk model. The cost depends on the starting price and is less than 1 percent of the value of the optimal policy for the random walk model.

Table 1.—Expected present values of harvest policies when price is a quarterly random walk model. Cost as a percentage of the expected present value of the optimal policy for the random walk model is listed in parentheses.

	Harvest policy for		
Starting price	Random walk price model	Deterministic price model	Stationary price model
\$/Mbf	———\$/acre———		
80	1,327	1,320 (.01)	1,138 (.14)
100	1,530	1,525 (.00)	1,385 (.09)
120	1,742	1,738 (.00)	1,631 (.06)
140	1,956	1,950 (.00)	1,884 (.04)
160	2,163	2,155 (.00)	2,115 (.02)

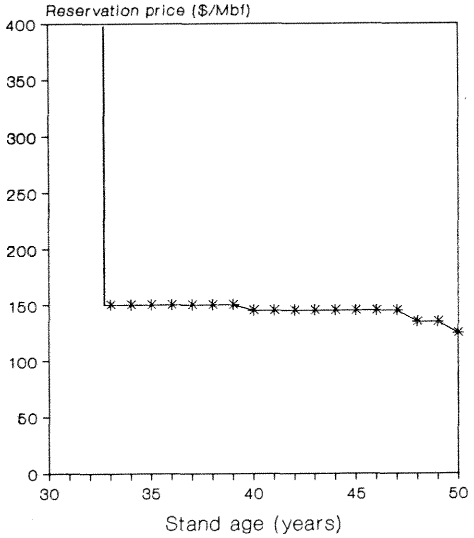

Figure 2.—Reservation prices for the quarterly stationary price model.

The stationary stochastic price model is based on the mean and variance of the price series: $m(t) = 125 + \varepsilon(t),\ t = 0, 1, \ldots$ [5] The random error is normally distributed with zero mean and standard deviation $17.158/Mbf. The optimal policy is to harvest when the observed price *is greater than* an age–dependent reservation price. Reservation prices for the stationary price model decrease with age (Figure 2) and approach the mean price ($125.00/Mbf). The area above and to the right of the curve contains the price–age combinations when the stand should be harvested. Harvesting is postponed when price is below $125.00/Mbf due to the expected future price increase. Harvesting takes place when the price is high (>$125.00/Mbf) due to the expected price decrease. Harvesting is postponed in stands less than 32.50 years old regardless of price.

Using the optimal policy for the stationary price model, the expected present value of the 30–year–old stand is $2,076.00/acre, which is 13 percent greater than the expected return from the optimal policy for the random walk model with $m(0) = \$125.00$/Mbf. [6] The present value of the stand is independent of the current price.

[5]The same model form is used in several other studies of timber harvesting with stochastic prices (Kaya and Buongiorno 1987, Brazee and Mendelsohn 1988, Haight 1990).

[6]The 13 percent gain in present value is an example of the general result for stationary stochastic price models that expected present value increases as the variance of the price model increases. As price variation increases, the likelihood of obtaining higher prices in the future increases. Thus, gains in present value can be obtained by postponing harvests until high prices are realized.

What is the cost of using the optimal policy for the stationary price model when prices are a random walk? The expected present values of the optimal policy for the stationary price model are listed in Table 1 for different starting prices. The cost decreases as the starting price increases and is between 2 and 14 percent of the value of the optimal policy for the random walk model. The cost comes from delaying the harvest of older stands (>35.00 years old) when price is below average and harvesting stands between 33.00 and 35.00 years old when price is above average (compare Figures 1 and 2).

The Monthly Model

The optimal policy for the autoregressive price model (equation 6) is to harvest when the observed price *is greater than* a reservation price that is conditioned on age and last month's price. For a given past price, reservation prices for the autoregressive model decrease with age and approach the level of the past price (Figure 3). The area above the curve for a given past price contains the price–age combinations when the stand should be harvested. Harvesting should be postponed when the observed price is less than the previous month's price because of the expected behavior of short–term price changes: when the observed price is less than the previous month's price, the expected future price change is positive. Thus, when price falls, the manager should postpone harvesting because price is expected to rise next period.

Using the optimal policy for the autoregressive price model, the expected present value of the 30–year–old stand depends on the price in the first two

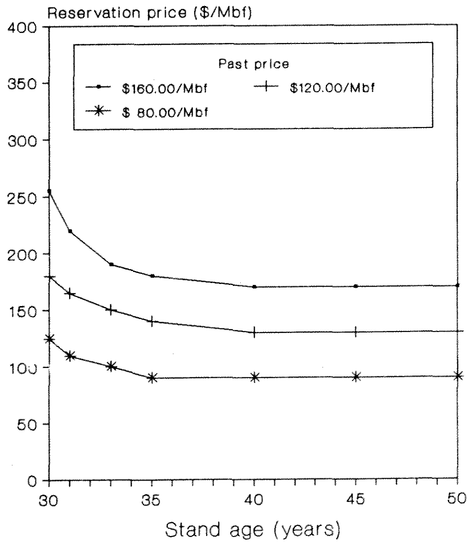

Figure 3.—Reservation prices for the monthly autoregressive price model for selected past prices.

months (Table 2). Expected present value increases as price in either month increases. When $m(0) = m(1) = \$125.00$/Mbf (the mean of the price series), the present value of the 30–year–old stand is $1,852.00/acre.

For comparison, we computed an optimal policy for the monthly random walk model (equation 3) where the random error has zero mean and standard deviation $10.81/Mbf. The reservation price policy is the same as that for the quarterly random walk (Figure 1).

Figure 4 compares harvest policies for the autoregressive and random walk price models for 33–year–old stands. The policy for the random walk model depends only on the current price, and harvests take place when the current price is relatively low. With the autoregressive model, harvest depends on both the current and past price. Harvests take place when the current price is greater than the past price because of the expected future price decrease. Harvests are postponed when the current price is less than or equal to the past price because of the expected future price increase.

What is the cost of using the optimal policy for the random walk model when prices follow the autoregressive model? The expected present values of the optimal policy for the random walk model are listed in Table 2 for different combinations of starting

Table 2.—Expected present values of harvest policies when price is a monthly autoregressive model. Cost as a percentage of the expected present value of the optimal policy for the autoregressive model is listed in parentheses.

Starting prices		Harvest policy for Autoregr. price model	Random walk price model	Stationary price model
$/Mbf		$/acre		
80	80	1,327	1,301 (.05)	1,213 (.12)
120	80	1,456	1,391 (.04)	1,314 (.10)
160	80	1,550	1,489 (.04)	1,424 (.08)
80	120	1,755	1,657 (.06)	1,618 (.08)
120	120	1,833	1,755 (.04)	1,725 (.06)
160	120	1,933	1,852 (.04)	1,836 (.05)
80	160	2,092	1,946 (.07)	1,930 (.08)
120	160	2,128	2,043 (.04)	2,037 (.04)
160	160	2,228	2,144 (.04)	2,141 (.04)

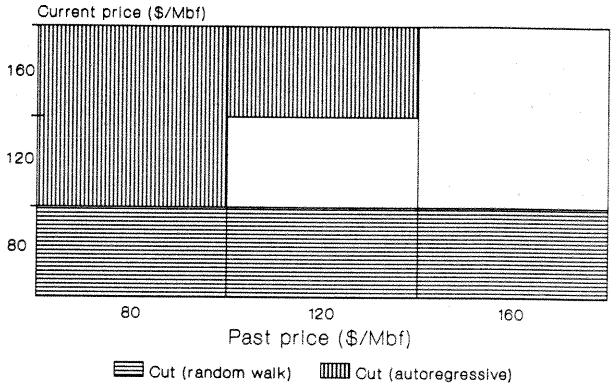

Figure 4.—Harvest policies for the monthly autoregressive and random walk price models as a function of selected past and current prices for a 33–year–old plantation.

prices. The cost depends on the starting price and is between 4 and 7 percent of the value of the optimal policy for the autoregressive price model. The cost is incurred by not taking advantage of predicted price changes that are conditional on past prices.

We also computed the optimal harvest policy for a stationary price model that is computed from the mean and variance of the monthly price series: $m(t) = 125 + \varepsilon(t),\ t = 0, 1, \ldots$. The random error is normally distributed with zero mean and standard deviation $18.48/Mbf. Due to the higher price variance, optimal reservation prices (not shown) are slightly higher than those for the stationary model with a quarterly decision cycle (Figure 2). Harvesting is postponed in stands less than 34.50 years old regardless of price. The expected present value of the 30–year–old stand is $2,076.00/acre.

The biggest difference in the policy for the stationary price model is that harvests are postponed in young stands; in older stands, harvest policies are alike. Figure 5 compares harvest policies for the autoregressive and stationary price models for 35–year–old stands. With the policy for the stationary price model, harvests take place when price is relatively high, similar to the policy for the autoregressive model.

What is the cost of using the optimal policy for the stationary price model when prices follow the autoregressive model? Costs depend on the current prices and are between 4 and 12 percent of the value of the optimal policy for the autoregressive model (Table 2). The cost is incurred by postponing harvests in young stands regardless of price and by postponing harvests in old stands when current and past prices are low relative to the historical average.

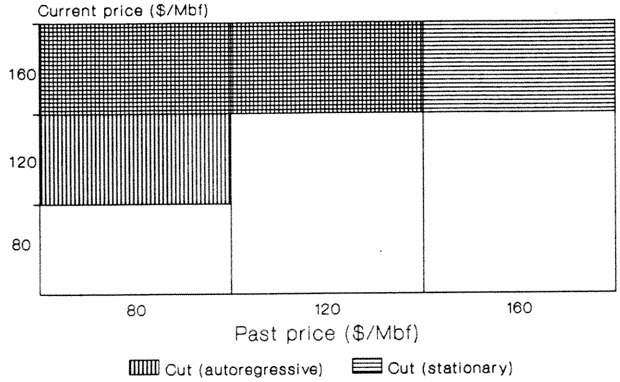

Figure 5.—Harvest policies for the monthly autoregressive and stationary price models as a function of selected past and current prices for a 35-year-old plantation.

CONCLUSIONS

Our analysis of loblolly pine sawtimber stumpage prices for the Piedmont region of North Carolina produces results that are consistent with earlier tests of market efficiency performed by Washburn and Binkley (1990). Quarterly prices are a random walk in which past prices cannot be used to predict future price changes. This property is a necessary condition for an efficient market. Monthly price changes are a first-order autoregressive process in which the expected price change is inversely related to the most recently observed price change. This result is consistent with Washburn and Binkley's finding that the monthly sawtimber market is not efficient.

Past forestry studies have focused on the determination of optimal harvest strategies for stationary stochastic price models with the implicit assumption that markets are inefficient. The optimal harvest policy is to cut only when price is above the historical average. The results for loblolly pine show that quarterly and monthly prices are not generated with stationary models and that their associated harvest policies are suboptimal. In our cases, the costs of employing strategies associated with stationary price models are up to 14 percent of the expected returns from the optimal policies for the random walk and autoregressive price models. Therefore, care should be taken in the analysis of historical prices and market efficiency before constructing adaptive harvest strategies.

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INCORPORATING LINEAR PROGRAMMING AND MONTE CARLO SIMULATION IN A SPREADSHEET-BASED HARVEST SCHEDULING MODEL[1]

Larry A. Leefers[2]

Abstract.--Harvest scheduling models have migrated from the mainframe to the microcomputer environment. This paper describes the structure of a microcomputer spreadsheet-based model, FORSOM (FORest Simulation-Optimization Model), and its application in forest planning in Michigan. Linkages with What's Best! (LINDO-based linear programming software) and @RISK (Monte Carlo simulation software) are presented.[3] A case study is used to illustrate the progression from simple user-defined harvest schedules to linear programming-based schedules and the inclusion of timber yield variability using Monte Carlo simulation.

Keywords: Optimization, risk, mathematical programming.

INTRODUCTION

Harvest scheduling is a traditional forestry problem that has been addressed using hand calculations, mainframe-based software and most recently, microcomputer-based software. Often, the software is developed exclusively for the harvest scheduling problem at hand. The purpose of this paper is to describe the use of commercial-off-the-shelf (COTS) software for harvest scheduling in the context of 3 modeling approaches. Specifically, applications are presented using simulation, optimization, and a combination of simulation and optimization.

HARVEST SCHEDULING

The Michigan Department of Natural Resources manages approximately 3.5 million acres of state forests. Two of 6 state forests are currently developing plans which include timber harvest scheduling considerations. To assist in these efforts, FORSOM (FORest Simulation-Optimization Model) is being used (Leefers and Robinson 1990). FORSOM is a spreadsheet-based harvest scheduling model created as a template for LOTUS 1-2-3 (Lotus Development Corp. 1985). For simulation modeling, planners change management assumptions and harvest patterns manually. Then they examine the implications on future forest age-class structure, acres harvested, volume harvested, and wildlife trends. Linkages between various forest types are modeled so that type conversion and natural succession can be included.

One benefit of modeling with popular COTS software is that other vendors create powerful add-in software. Two examples of software that enhance FORSOM's analytic capabilities are What's Best! (Savage 1991) and @RISK (Palisade Corp. 1988). By using What's Best!, FORSOM is converted into a type 1 linear programming model (Johnson and Scheurman 1977) which is solved with the LINDO-based algorithm. Cells are easily referenced to create constraints and the objective function. Results are presented in a copy of the original spreadsheet with decision variables adjusted for an optimal solution. @RISK, on the other hand, allows analysts to incorporate Monte Carlo simulation into FORSOM. This is accomplished by selecting a probability distribution (from 30 available) for variables of interest (e.g., timber yields, prices, costs, etc.), choosing the number of sampling/calculation iterations, and analyzing the compiled results.

For purposes of this paper, three harvest scheduling applications are presented. The first illustrates a simple simulation problem using LOTUS 1-2-3 and FORSOM. The second incorporates What's Best! to solve a common harvest scheduling problem. And the third uses @RISK and What's Best! to examine selected implications of timber yield variability on harvest scheduling results (see Hof et al. 1988 for a similar example). These are intended as examples from an array of more complex problems that can be addressed with this COTS software.

Simulation

Twelve forest type components (e.g., aspen, red pine, jack pine, etc.) can be combined to create FORSOM templates for various types of analyses. Each component has a common set of computer screens (or tables). These screens include: (1) management assumptions, (2) initial

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[1] Presented at the Symposium on Systems Analysis in Forest Resources, Charleston, SC, March 3-7, 1991.

[2] Associate Professor of Forestry, Michigan State University, East Lansing, MI 48824.

[3] Mention of commercial software does not imply endorsement of the software by the author or by Michigan State University.

Figure 1.--Simulated harvest schedule for 13,100 out of 115,686 acres of aspen.

Current Age	First Harvest Rotation Age						
Classes	40	50	60	70	80	None	Total
0-9	0	0	0	0	0	22150	22150
10-19	0	0	0	0	0	20096	20096
20-29	0	0	0	0	0	8785	8785
30-39	0	0	0	0	0	5958	5958
40-49	X	0	0	0	0	6447	6447
50-59	X	X	100	0	0	17398	17498
60-69	X	X	X	1000	2000	19689	22689
70-79	X	X	X	X	10000	2063	12063

acreage by 10-year age class, (3) simulated harvest, (4) projected acreage by age class for 5 decades, (5) a timber volume table, (6) a summary of volume and acres harvested for 5 decades, (7) calculations of present net value and undiscounted first decade net revenues, and (8) linkages to other components.

By manipulating management assumptions and the simulated harvest pattern, different projections are created. Management assumptions identify the forest type being modeled, appropriate rotation ages and harvesting systems, and conversion and successional pathways.

Figure 1 presents a harvest scheduling pattern applied to 115,686 acres of the aspen type from Michigan's Escanaba River State Forest. For the 50-59 year old age-class, one hundred acres are scheduled for harvest in the first decade (i.e., a 60-year rotation is selected). In the 60-69 age-class, a 70-year rotation is selected for 1000 acres, and an 80-year rotation is chosen for 2000 acres. In other words, the 2000-acre harvest is projected for the second decade. Finally, an 80-year rotation is selected for 10,000 acres of 70-79 year old aspen. The remainder of the acres are not scheduled for harvest. Based on the simulated harvest pattern and related assumptions, projected acres by age class are presented in figure 2. The 11,100 acres harvested in the first decade begin the second decade in the 0-9 age-class because no conversions are assumed. Natural succession assumptions, however, lead to a steady decline of the type over the projection period.

Optimization

The simulation approach provides a straightforward approach for creating projections with little formal knowledge of modeling required. However, the manual approach can be very tedious when a number of management constraints exist. In situations like this, it may be appropriate to use linear programming software, such as What's Best!, to solve constrained optimization problems.

Though very large problems (i.e., 16,000 constraints and 32,000 variables) can be solved using this software, a simple maximization problem is presented here. The problem is to maximize present net value associated with managing the aspen acreage identified in the preceding section. The following constraints are included:

1. Acres managed or unmanaged must equal inventory acres,
2. 8,000 acres of aspen currently over age 30 must be unmanaged (i.e., cannot be harvested),
3. At least 1,000 unmanaged acres must be in each of the 5 oldest age classes,
4. First decade harvest volumes cannot exceed 33 million cubic feet,
5. Harvest volumes cannot decline over the next 5 decades, and
6. Harvest volume cannot exceed long-term sustained yield.

Figure 2.--Current and projected acreage by age class for harvest pattern in figure 1.

Timber Age	Acres at Beginning of Decade:					
Classes	1	2	3	4	5	6
0-9	22150	11100	2000	0	0	0
10-19	20096	22150	11100	2000	0	0
20-29	8785	20096	22150	11100	2000	0
30-39	5958	8785	20096	22150	11100	2000
40-49	6447	5958	8785	20096	22150	11100
50-59	17498	6447	5958	8785	20096	22150
60-69	22689	17398	6447	5958	8785	20096
70-79	12063	21689	17398	6447	5958	8785
Total	115686	113623	93934	76536	70089	64131

Figure 3.--Linear programming solution for managing aspen.

Current Age	First Harvest Rotation Age						
Class	40	50	60	70	80	None	Total
0-9	0	22150	0	0	0	0	22150
10-19	0	18044	2052	0	0	0	20096
20-29	0	3038	5747	0	0	0	8785
30-39	0	0	1958	0	0	4000	5958
40-49	X	0	0	5447	0	1000	6447
50-59	X	X	0	6223	10275	1000	17498
60-69	X	X	X	7924	13765	1000	22689
70-79	X	X	X	X	11063	1000	12063

Figure 3 presents the optimal harvest schedule for this problem. The long-term sustained yield was approximately 38.7 million cubic feet per decade with a present net value of $3.9 million in 1989 dollars.[4] The pattern reflects the need to harvest higher-valued, older stands exclusively in the first 2 decades. Using What's Best! on a 386-based microcomputer, this problem was solved in less than 1 minute including file unloading and loading.

Simulation and Optimization

Several researchers have recently examined the effect of stochastic timber yield variables on linear programming results (Hof et al. 1988, Pickens and Dress 1988). A related example is presented in this section. Results in the preceding section are based on average yields for 40-, 50-, 60-, 70-, and 80-year old stands extracted from Michigan Department of Natural Resources' inventory data. Yields, however, are quite variable.

To assess the effects of yield variability, the following process was used:

1. Yield estimates from the timber database were extracted for different harvest ages,
2. Discrete yield distributions were then compiled for each harvest age,
3. 100 "sample" yield tables were created using Latin hypercube sampling, and
4. 100 linear programming problems were solved.

Latin hypercube sampling is a variation of Monte Carlo simulation which uses stratified sampling (McKay et al. 1979, Rubinstein 1981, Palisades Corp. 1988). This approach ensures that the entire range of yields will be represented in the 100 samples selected. @RISK was used for steps 2 and 3, and What's Best! was used for step 4.

The average of the 100 linear programming solutions is presented in figure 4. Clearly, a much wider range of rotation ages are selected when yield variability is considered. Different rotation ages are prescribed for 10,432 acres (highlighted in figure 4). The implications are particularly striking in the first decade where an additional 1,435 acres of 70-79 year aspen are not scheduled for harvest, and younger-aged stands are substituted. Focusing on broader parameters, such as present net value and first-decade net revenues, indicates less than 1 percent difference exists between the average of 100 solutions and the solution using average yields. Thus, interpretation of the similarities and differences hinges upon the key variables of interest.

[4] Cost, price and yield data supplied by Forest Management Division, Michigan Department of Natural Resources.

Figure 4.--Average of 100 linear programming solutions for managing aspen.

Current Age	First Harvest Rotation Age						
Class	40	50	60	70	80	None	Total
0-9	**1855**	19441	**855**	0	0	0	22150
10-19	**1086**	14145	4005	**860**	0	0	20096
20-29	0	3218	3810	**1650**	**107**	0	8785
30-39	0	**101**	2155	**2164**	**49**	1489	5958
40-49	X	**341**	**138**	4001	**553**	1414	6447
50-59	X	X	**683**	5623	9797	1395	17498
60-69	X	X	X	7108	14027	1554	22689
70-79	X	X	X	X	9628	2435	12063

The application of @RISK is fairly limited in this example. Other variations may include using simulation or optimization (as described in the preceding sections) to create harvest schedules and followed by Monte Carlo or Latin hypercube sampling of variables such as timber yields, prices, costs and discount rates. Resulting analyses would reflect other dimensions of risk.

DISCUSSION

This paper describes the use of FORSOM with LOTUS 1-2-3, What's Best!, and @RISK. By combining a spreadsheet template with COTS software, a variety of harvest scheduling questions can be addressed. Scheduling examples in this paper include a "manual" simulation problem, a common linear programming problem, and a problem involving risk and optimization. The COTS software, of course, is not limited to these problems.

The manual simulation approach has been adopted by 2 state forests in Michigan. Based on that experience and other applications of FORSOM, several strengths and weaknesses of modeling in the spreadsheet environment have emerged.

First and most obvious, harvest schedule modeling in a spreadsheet environment works. As with other abstractions, FORSOM or other spreadsheet models are simplifications of reality and must be judged accordingly.

Second, spreadsheet modeling tends to be very rigid. That is, detailed equations and formats are created which may be difficult to quickly adjust. For example, it is easy to adjust a traditional harvest scheduling model to include more rotation lengths. However, spreadsheet models may require extensive modification to accommodate these changes. On the other hand, most management strategies are well-defined and can be captured in a structured template. Then, consistent model structure becomes a strength.

Third, model size can be problematic in a spreadsheet environment. In FORSOM, screens with 20 rows are used regardless of whether all the space is needed. This allows easy movement (with Page-Up and Page-Down), but requires more rows. With availability of expanded and extended memory, few technical limitations exist. However, developing models with 20 to 30 vegetative components may be cumbersome for some users.

Finally, a strength of spreadsheets is that they are easy to use and facilitate communication. Spreadsheets are used extensively in public and private organizations. Therefore, constructing models in this environment should assist in their adoption. In addition, many people have the ability to create and modify spreadsheet equations; fewer are traditional programmers. Moreover, graphics and other spreadsheet features ease communication of analysis results.

Given the strengths and weaknesses of the spreadsheet environment and the availability of useful software add-ins, natural resources modelers should carefully explore this medium. It can provide a modeling framework that is well-structured, manageable and easy to understand while including sophisticated optimization and simulation options.

ACKNOWLEDGEMENT

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INCORPORATING PRICE UNCERTAINTY AND RISK AVERSION IN SHORT-TERM TIMBER HARVEST SCHEDULING DECISIONS[1]

Robert J. Lilieholm, Lawrence S. Davis, and J. Keith Gilless [2]

Abstract.--Tradeoffs between the expected net revenues of different short-term timber harvest schedules and the risk associated with those expected values can be considered using a MOTAD (Minimization of Total Absolute Deviations) model formulation to derive minimum-risk, expected-value frontiers. Significant reductions in risk may be achieved by accepting marginally lower expected values. The method, has particular applicability to trust management of lands.

Keywords: Linear programming, mathematical programming, mean-variance analysis, MOTAD programming, portfolio theory

INTRODUCTION

Mathematical programming models for long-term timber harvest scheduling have been widely adopted for the management of public and private forests. Many who contributed to the development of these models are now faced with the problem of how to reduce first period solutions to tactical, year-by-year, implementable harvest schedules. Uncertainty with respect to future stumpage prices is usually dealt with in this process by regarding forecasted revenues as expected values, and solutions to short-term harvest scheduling models based upon them as expected-value maximizing. An explicit or implicit assumption is therefore usually made of risk neutrality on the part of the forest owner (Lilieholm and Reeves, 1991).

Risk neutrality is, however, a problematic assumption for lands managed under some formal expression of trust responsibility (e.g., Native American tribal lands managed by the Bureau of Indian Affairs, pension and insurance fund holdings), as well as for lands managed under less formal notions of trust responsibility (e.g., limited partnerships, family or institutional trusts, or by arrangements with consulting foresters). Looking ahead, it is not difficult to foresee where heightened interest in ethical standards of conduct and current legal actions might well result in the development of risk-appropriateness standards for forest planners' recommendations much like those governing stockbrokers' recommendations. It is therefore an appropriate time for foresters to consider the potential for making tradeoffs between the expected net revenues for different short-term harvest schedules and the uncertainty associated with those expected net revenues.

For multi-species forests, modern stock portfolio theory provides a natural framework for incorporating data on the historical relationships between the prices of different species into short-term harvest schedules in a manner that permits the evaluation of such tradeoffs. In this paper, preliminary results are reported of an attempt to use Hazell's (1971) MOTAD linear programming technique to do such an evaluation. Working with a Sierra Nevada mixed-conifer case study (described below), this work indicates that significant reductions in risk may sometimes be obtained at the cost of minimal reductions from expected net revenues.

1/Presented at the 1991 Symposium on Systems Analysis in Forest Resources, Charleston, SC, March 3-7, 1991.

2/ Assistant Professor of Forest Management, Utah State University, Logan, UT 84322-5215; Professor of Forest Management and Associate Professor of Forest Economics, University of California, Berkeley, CA 94720.

MOTAD MODEL

A 5-year short-term timber harvest scheduling model was constructed that maximized net returns of first-period harvests from a mixed-species forest:

$$\text{Maximize } \Sigma_j \Sigma_s \Sigma_t (P_{st})(H_{jst})$$

where j, s, and t are stand, species, and time period indices, respectively, P denotes the forecasted net revenue per MBF of species s in year t, and H denotes the MBF harvest level for species s in year t from stand j. Constraints were placed on the model to ensure that stands were harvested only once over the planning horizon, and that only entire stands would be harvested in the first planning period. Additional constraints were placed on periodic net revenue flows (plus or minus 25% of that obtained in the first period) and on periodic harvest levels (plus or minus 30% of that obtained in the first period).

After solving this model to determine maximum possible first period expected net revenue, the model was converted to a MOTAD formulation in which time series net revenue deviations from an established trend were minimized subject to meeting a parametrically relaxed minimum net revenue constraint. Solutions to this MOTAD model trace out a minimum-risk frontier consistent with an underlying risk-averse quadratic utility function (Hazell and Norton, 1986).

CASE STUDY DATA

Data for the model came from a case study developed for a private forest ownership in the Sierra Nevada mixed conifer forest type. This forest type is characterized by highly variable mixtures of five commercial timber species -- ponderosa pine (Pinus ponderosa), sugar pine (P. lambertiana), incense cedar (Calocedrus decurrens), Douglas-fir (Pseudotsuga menziesii var. menziesii), and white fir (Abies concolor var. lowiana) (Tappeiner 1980). Stand descriptions for twenty 40-acre stands scheduled for harvest over the 5-year planning horizon were generated using the STAG model (Van Deusen and Biging, 1985). Growth and yield projections for the stands were made using the CACTOS model (Wensel et al., 1987).

Historical stumpage prices were obtained from publications of the California State Board of Equalization. These prices were deflated using the Producer Price Index for SIC 24. Harvesting costs were estimated from sales on the University of California's Blodgett Forest Research Station. Net revenues were calculated for each of the five species identified above. Deviations from the trended net revenue series (see Figure 1) were used to calculate mean absolute deviations.

RESULTS AND DISCUSSION

The MOTAD-derived set of minimum-risk harvest schedules is shown in Figure 2. The initial rate of tradeoff between 1st period expected net revenue and variance, moving leftward along the frontier from Solution A, is quite high. For example, a risk averse manager selecting Solution C would reduce the variance of expected net returns by over 34% while only lowering expected net returns by 0.7% (Table 1). Surprisingly, there was relatively little variation in periodic harvest levels or net revenues occurred over the planning horizon for Solutions A through D (Table 1).

The species breakdown of first-period harvests for the solutions along the minimum-risk frontier are given in Table 2. Examination of these results reveals how the variance of expected net revenue can be reduced in two ways moving along the minimum-risk frontier: (1) by favoring the harvest of species with low expected net revenue variances, and/or (2) by exploiting the historical covariance patterns in the fluctuations of past net revenues. (The net return variance-covariance matrix for the five conifer species is given in Table 3.)

Examining the minimum-risk solutions, it can be seen that ponderosa pine comprises half of the harvest in the net revenue maximizing Solution A. But as risk is reduced moving leftwards along the minimum-risk frontier, Douglas-fir displaces ponderosa pine in the species mix. This change results from the model diversifying the species mix to exploit the negative covariance between ponderosa pine and Douglas-fir, and to take advantage of the lower variance of net returns for the latter species. The relative stability of white fir and incense cedar in the species mix moving along the minimum-risk frontier, on the other hand, reflects the low variance of net returns to these species.

The negative covariances between the net returns associated with different species and differentials in the variances exploited by the MOTAD model used in this study are not limited to California conifers. Similar patterns and relationships can be observed in the net returns from different species, or even log grades, elsewhere from the same causes -- different end-product markets exhibiting different cyclical profitability and stability (Lilieholm, 1991).

CONCLUSIONS

The method briefly described in this paper has considerable promise for explicitly evaluating the tradeoffs between risk and expected net revenues in short-term harvest scheduling decisions in multiple species forests. Extensions considering various log grades and dimensions merit further examination.

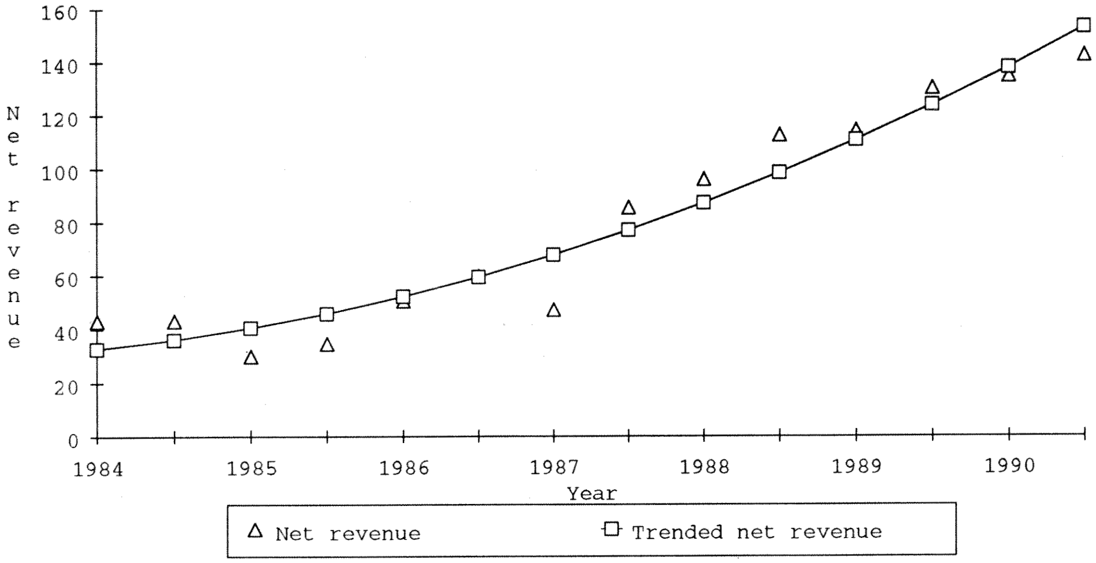

Figure 1.--Net revenue time series for ponderosa pine (1982 $/MBF).

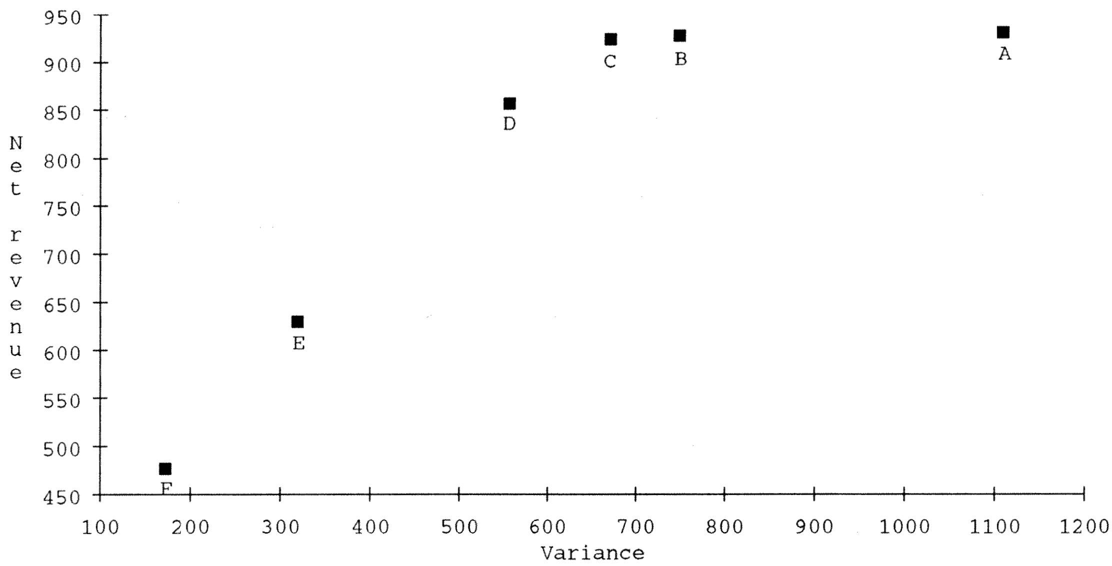

Figure 2.--Minimum-risk frontier: 1st period net revenue (10^3 1982 $) vs. 1st period variance (10^6).

Table 1.--Summary of model solutions along the minimum-risk frontier relative to solution A (1982 $).

Solution	1st period net revenue ($\$10^3$)	Percent reduction in 1st period revenue	1st period variance ($\$10^6$)	Percent reduction in 1st period variance	Present net worth	Percent reduction in present net worth
A	931.1	na	1108.6	na	3.47	na
B	928.2	-0.3	748.0	-26.6	3.46	-0.3
C	924.6	-0.7	669.9	-34.2	3.46	-0.3
D	857.6	-7.9	556.5	-45.4	3.47	0.0
E	630.5	-32.3	319.4	-68.6	2.86	-17.6
F	476.8	-48.8	172.7	-83.0	2.21	-36.3

Table 2.--Summary of 1st period harvest levels for selected model solutions on the minmum-risk frontier (MBF).

Solution	Ponderosa pine	Sugar pine	Incense cedar	Douglas-fir	White fir	Total 1st period harvest
A	2860	0	254	1060	1556	5734
B	660	0	492	3416	1464	6032
C	1352	0	396	2512	1656	5916
D	1532	0	0	2476	1284	5292
E	672	0	0	2476	776	3924
F	660	0	144	1816	368	2988

Table 3.--Net revenue variance-covariance matrix for five Califonia conifers.

	Ponderosa pine	Sugar pine	Incense cedar	Douglas-fir	White fir
Ponderosa pine	95.2	-	-	-	-
Sugar pine	93.9	102.0	-	-	-
Incense cedar	20.2	29.4	30.0	-	-
Douglas-fir	-12.1	-2.9	9.8	36.0	-
White fir	6.6	21.6	10.8	15.4	48.0

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A SYSTEMS APPROACH TO EVALUATING CAPITAL ALLOCATIONS IN AN INTEGRATED FOREST PRODUCTS FIRM [1)]

Ralph E. Colberg [2)]

ABSTRACT

The optimal allocation and use of limited capital is essential for business success. But as we enter this last decade of the twentieth century, these decisions become more and more complex. This paper describes in laymens terms a new and innovative approach that is being used by one major forest products firm.

Keywords: Hierarchical Planning; Integrated Planning; Operations Research.

The Problem Defined

A Forest Service friend of mine once suggested that we in industry are fortunate. Whereas his decisions required weighing a number of obtuse criteria collectively labeled "cost-benefit" ratios, we supposedly have a clearly defined profit motive. The dollars in and the dollars out can be compared, providing a clear-cut measure of financial success.

His point was well taken. Intangibles are indeed harder to measure. But this doesn't mean that traditional profit measures are a "piece of cake." We often find ourselves facing analytical difficulties that were never discussed in a graduate or undergraduate business course.

I lost my virginity shortly after graduate school when first instructed to develop a capital request yielding fifty-two percent. I was to do so because a competing manager was submitting one with a fifty percent return. I did my job well, and achieved a degree of notoriety to boot. The financial genius that I was, I managed to garner a full fifty-four percent.

Since then, I have watched the capital allocation process at work for more than a quarter century. This may not make me an authority, but longevity and a proven survival instinct provide the intellectual courage required to offer the first of three financial "axioms." I call them axioms because they do indeed fit Webster's definition. Each is a statement that needs no proof, because its truth is self evident. The first of these is simply this:

> Capital allocations are often driven by political motives that have nothing to do with financial realities.

In Washington, it's called "pork barrel;" in industry, it's often a power play. But for whatever the reason, when politics override financial integrity, capital is almost always allocated to uses that are less than optimal.

The problem is most prevalent in those firms that have decentralized to the extent that the left hand no longer knows what the right is doing. Decentralized operating decisions provide proven benefits, but capital allocations without proper controls can result in financial anarchy. Those of us who still cherish our "I like Ike" buttons have seen it happen more than once. Some senior manager with authority will personally endorse a capital expenditure, often with little or no quantitative support. If he or she is suitably persuasive, funds will no doubt be approved with or without financial merit.

All of this may be disagreeable to some of you. Surely, no project should ever be approved without the rigid financial review that an analyst can provide. While I would agree, I also know that there are those who will beat the system, no matter how diligent we may be. This brings me to the second of my three axioms:

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1) Presented at the Symposium on Systems Analysis in Forest Resources, Charleston, SC, March 3-7, 1991.

2) At the time this paper was presented the author was Manager, Woodlands and Wood Products Technical Services for Mead Coated Board. He now heads his own consulting firm as President, Decisions Support, located in Columbus, GA.

The analytical techniques used to evaluate financial worth are to some extent flawed, and easily manipulated to provide predetermined results.

A discounted cash flow analysis is the standard for evaluating investments with payback periods that extend over time. I have no quarrel with this approach; it does indeed provide a reliable comparison of two or more options if the same discounting criteria are used for each. My concern is not with the technique, but the underlying numbers, and how they are used.

Over the years, I have more than once said that if Operations Research had emerged before accounting, the accounting profession might not exist today. While said "tongue-in-cheek," there is perhaps some truth in all of this. Operations Research is a scientific discipline concerned primarily with planning, and its practitioners are "forward looking" in their approach. Accountants, on the other hand, are trained to keep score; to maintain a record of revenues and costs and tell us whether the results are positive or negative. Their perspective is historical. They can tell us what has happened in the past, but very little about what will happen in the future if we change things. Ask what manufacturing costs will be if we add a new machine center, and you will find that there is no good answer because there has been no prior experience. While the accounting profession can do a credible job telling us where we have been, they are less than reliable when asked to predict where we are going.

Transfer prices are one of the many tools an accountant will use to help him keep score. These are artificial dollar values assigned to resources that are produced and used internally. Chips that are transferred from a sawmill to an integrated pulp mill complex are assigned a value that supposedly equals market price. But if sawmill management can exercise sufficient strength in the negotiating process, they can often stretch the definition of "market value" to near incredulity. I have known companies with internal transfer prices that were at least twice any comparable market value.

No damage is done if transfer prices are used as an accounting tool alone. Here they record the internal movement of funds from one operating unit to another, and never appear on the bottom line for the business as-a-whole. I become concerned when these same values are used to plan capital expenditures, as they often are.

All of this represents a basic flaw in the capital review process. While the discounting criteria we use to evaluate the worth of a capital proposal has merit, the answer is no better than the underlying data. If the necessary information is lacking, or inaccurate, then there is ample opportunity to contrive whatever financial results you want.

Consider an example that I know many of you have encountered in the past. A mill manager submits a capital request for a machine upgrade that supposedly will perform wonders for the bottom line. You analyze the numbers, and sure enough there is a triple-digit after tax return. Somewhat skeptical, you ask for some backup that will verify expected gains. Management supplies you with the results from on-site studies and financial analyses prepared by the vendor. You see no reason why you should doubt these numbers, and so you lend your support. In the back of your mind, however, you wonder why it is that so many investment proposals appear favorable when the mill itself has not turned a profit for months.

The answer may lie in our failure to identify upstream or downstream constraints that will limit production. I could list dozens of examples, and many of you could list dozens more. There's the new plymill lathe that doesn't perform as expected because there is a previously unknown constraint on dryer capacity, or the new particleboard mill that cannot meet production goals because local raw materials supplies are limited. Each of these is a real-world example from my own experience, and each represents a major embarrassment for the managers who were involved.

A Historical Perspective

This brings me to the point where I'm ready to put forth my third and final axiom:

A suitable technique for evaluating capital projects must consider the financial aspects of interrelated resource allocations and manufacturing processes, unencumbered by artificial transfer prices or accounting mystique.

Now that's impressive. I've managed to use many of the better "buzzwords" in a single sentence. But I'm not trying to impress you, or confuse you. I am recommending a somewhat different approach to the capital review process; one that emphasizes the use of computer models to evaluate the interrelated "systems" aspects of major capital decisions.

Using computers and models to solve complex business problems is not a new idea, and in its simplest form it doesn't require an advanced degree in mathematics or Operations Research. The mill manager who develops a simple spreadsheet application is as much involved in building computer models as the corporate analyst, or the university researcher. We may even consider him a successful practitioner if his spreadsheet is used, while more sophisticated applications languish in the halls of academia.

And languish they have. Many of you may be surprised to learn that our industry was among the first to embrace the OR arts. Liner Programming was a powerful tool for scheduling west coast plywood operations, and twenty twenty-five years ago any firm that considered itself at all progressive had a battery of OR analysts running around the country conducting mill studies, and building models. But this early enthusiasm soon faded, and today it's difficult to find a substantial effort anywhere in the industry.

Why this early enthusiasm and subsequent demise? Many early associates content that the whole endeavor failed because senior management simply did not support us. I can't accept this argument. It isn't that management didn't back us, it's that we did not, and indeed could not deliver what was promised.

At the time, we were using first-generation computers that simply could not solve an LP model with more than a few hundred rows. To get something that would solve, we often simplified the problem to the point that it no longer existed. Processing time was relatively inexpensive, but it often took hours to solve a model and would cost thousands of dollars. While the potential returns might justify these costs, this was theory while the expenditures were real. Few managers were willing to accept the gamble.

There was a second problem as difficult as the first. Most models required a sizable amount of data preparation before they could be run, and management soon became disenchanted with this burdensome chore. Even successful applications with a sizable pay back would languish because it was too much trouble to maintain the necessary data.

All of this has changed. Today, we routinely solve on a personal computer problems that earlier we could not handle on a sizable mainframe, and with modern database languages we can develop and maintain the information required to support these systems. We now have access to a growing number of sophisticated decision-making tools, and none too soon at that. Our industry is challenged in a number of economic and environmental arenas, and how we respond to these issues will determine our financial well being for years to come.

Perhaps we were lulled in the belief that ours was indeed the "wood basket" of the world, and as such we didn't have to worry about our long term competitive position. For years, we had grown our trees, manufactured our products, and with few exceptions had sold our finished goods at prices that were profitable. But all of this complacency was shattered early in the past decade when we suddenly found ourselves unable to compete with overseas manufacturers. Scandinavian mills were selling pulp and paper products in US markets at prices that were less than our conversion costs, and fully half the lumber sold in Florida was made in Canada.

These events taught our industry a valuable lesson. Now, more than ever, we appreciate our role as but one of many players in a world market. If we are going to compete for overseas sales, or hold our own in domestic markets, then we must be cost-effective producers on a world-wide scale. We can do little to influence foreign exchange rates, or similar exogenous forces that to some extent control our financial destiny. We can, however, exercise greater control over those internal elements that determine our own costs and manufacturing efficiencies. For the past decade we have been modernizing our mills, and reducing our overhead. As a result, we enter this last decade of the twentieth century positioned to assume a new dominance in world trade.

Now we find ourselves being squeezed by a second market force. As manufacturers, we purchase raw materials and convert these into products that are sold in competitive markets. In our industry, we use trees to make the newsprint in your daily paper, and the lumber in your homes. The US has been blessed with abundant timber reserves, but in recent years this resource has been subjected to unrelenting pressures that restrict current and future availability. Whatever your views with regard to these issues, we must all agree that for industry, supplies are tightening, and costs are rising.

A New Analytical Approach

All of this has been said to set the scene for what I really want to talk about today. We sell our products in an unforgiving global market, using raw materials that are becoming increasingly scarce and costly. The only way we can remain competitive is to be among the most efficient converters on the world scene. No resource can be wasted, especially capital. When we invest funds in a new venture, there must be little doubt that the returns will be adequate.

As manufacturers, we have long ago learned that profit improvement results in part from the progressive removal of bottlenecks that limit mill performance. Our task is to concentrate on those measures that will eliminate the most costly of these first. But the removal of one will always result in identifying another. Optimal performance results from an ongoing program to improve mill productivity step by step until some break-even level is reached.

While all of this sounds fine in theory, in practice things seldom go as planned. Management may not have the information they need to identify or rank mill bottlenecks, and when they do they don't know what new restriction will emerge when existing constraints are removed. As a result, we too often overestimate the potential gains from a new capital expenditure because we cannot predict what will happen after the proposed changes are made.

Let me give you an example from my own experience. A few years ago I was asked to review a capital request from one of our sawmills. The mill had not been profitable for some time, and management offered as a solution a chip-n-saw rebuild that would result in improved throughput and recovery.

It didn't take much more than a brief walk through the mill to spot two potential problems. Downstream, there was an unscrambler that clogged when a series of larger logs produced a surge of lumber outturn. Upstream, the merchandising system could not provide adequate log supplies on a continuing basis.

Mill management was skeptical. They were aware of the unscrambler, but did not see the processor as a current or potential problem. Downtime was recorded daily, and what problems there were had always been at the headrig, not the merchandiser. We agreed to disagree, and take a second look.

We gathered additional data and built a model simulating green-end operations. Soon, even mill management was convinced that the processor was in fact a constraint. Much of the downtime that had previously been recorded at the headrig had indeed been due to a processor bottleneck.

These were good managers; they were in fact among the best in the Mead system. But when you are responsible for day-to-day mill operations, your attention is easily diverted from the big picture. In this case, management had simply not looked beyond the daily production reports. But because they had not, Mead was prepared to invest funds in a project that had little merit. The unscrambler was easily corrected, and additional maintenance was all that was required at the merchandiser. With these changes, a subsequent headrig upgrade paid off handsomely.

With this initial exposure, mill management acquired a new appreciation of what could be done using a "systems" approach to investment planning. They subsequently participated in developing and implementing a comprehensive linear programming model that simulated wood flows from stump to finished products markets. This proved to be a very powerful tool for evaluating investments ranging from stumpage purchases to major mill modifications.

The primary benefit derived from a model of this nature is the insight that it provides. With it, we can identify bottlenecks that limit mill outturn, and calculate what it is worth to remove them. We can also determine how much improvement there will be before a second bottleneck prevents further gains. This is important because it's this range that will determine the "real" returns from a proposed investment in added manufacturing capacity. These seldom approach what is calculated using traditional methods. A trimmer optimizer, for example, may indeed process a hundred boards per minute, but this is meaningless if the log mix and headrig capabilities will only supply fifty. It's this much smaller number that will establish financial returns.

Through a process that involved progressive removal of one constraint followed by another, in a little over two years mill outturn was increased more than half. All of this was accomplished with the knowledge that each investment was sound, and would provide the returns we had forecast.

While manufacturing applications have been our bread and butter, few of these can provide benefits equal to the recent work we have been doing to rationalize our core businesses. It's here that we consider how all the parts must fit together to optimize the whole; issues that are at the very heart of our success as an integrated forest products firm.

Mead Coated Board was established as a new operating division in 1988 when the old Georgia Kraft assets were split. We acquired a pulp and paper mill, two sawmills, and more than a half-million acres of southern pine timberlands. What we did not acquire was any preconceived notion with regard to how these land and timber assets should be managed.

With no prior "conventional wisdom" to guide us, we could develop a planning system that I had personally championed for a number of years. In addition to the standard accounting procedures that measure the performance of each business segment as a stand-alone unit, we would develop tools that could be used to measure their individual contribution to a combined bottom line for the enterprise as-a-whole.

Our woodlands and wood products organization is structured to accommodate three traditional functional areas: land and timber management, wood procurement, and wood products manufacturing. Like most of you, we tend to view these as separate operating units, with unique goals for each. We own land and invest in timber growth to strengthen our long-term fiber supply security, and we build sawmills to convert expensive sawlog material into higher valued lumber products. But what if we took a somewhat different approach? What if growing trees, cutting timber, and making lumber are all intermediate steps in a conversion process producing slush pulp for paper manufacturing? What if each of our three functional areas is but one step in a vertically integrated manufacturing process with a singular purpose:

> <u>To provide a secure supply of quality wood fiber for pulp manufacturing, delivered to the digestor at minimum "real" cost</u>;

with "real" costs represented by expenditures in which there is an actual "out-of-pocket" exchange of cash.

It's always pleasant when you learn that you and your peers are using a similar approach. Much has been said about hierarchical planning, and all that it offers. I didn't know that this is what we were doing until I came to this meeting, and I must thank a number of speakers for giving me a useful new buzzword. But seriously, the conceptual heart of our approach is a series of integrated models all linked together to optimize a single goal. At the top is a strategic model for the enterprise as-a-whole, linked to a number of more detailed tactical models for individual business units. At the very bottom is an operational model that provides data for a GIS system, and a tabular and visual display of recommended on-the-ground action.

Successful implementation of a system of this nature requires using a single objective function for all of our business units. Timberlands and wood products investments are evaluated in terms of their contributions to wood cost savings at the pulp mill. And why not? This is how we justified these expenditures in the first place. Our problem has not been the investment itself, but the tools we need to measure subsequent performance.

Consider, for example, the formula we use to evaluate a capital expenditure for added sawmill capacity. The traditional RONA calculation would compare net revenues from lumber and by-product sales with the amounts invested. But using our approach, the sawmill is little more than a chip-producing facility, with lumber revenues an offset against chip costs. A simple RONA calculation would look something like this:

$$\frac{FC_1 - FC_2}{NAV} \times 100 = RONA$$

Where: FC_1 = Pulp Mill Fiber Costs Without Sawmill
FC_2 = Pulp Mill Fiber Costs With Sawmill
NAV = Current Net Asset Value

The calculation is easily performed using a model, comparing solution results with and without the proposed investment. It can be a static analysis for a single year, or a discounted present value derived from a model with a planning horizon that spans more than one period.

A similar calculation is used for timberlands investments. This approach was in fact used by Mead to evaluate a recent purchase opportunity that involved a sizable acreage, and additional wood products capacity. The purchase was rejected because the asking price was higher than we could justify. We may not have made the same decision without the insight provided by a model.

In closing, I would once again stress what by now should be obvious. I'm convinced that the work we have been doing for the past three years offers great promise. While there is still more to learn, we've expanded our use of the management sciences to new horizons, offering insight that we have never had before.

MODEL FOR STRATEGIC PLANNING IN THE MANAGEMENT OF PINE INDUSTRIAL PLANTATIONS 1/

Ramiro Morales 2/
Andrés Weintraub

Abstract.-- A linear programming model for strategic decisions, such as silvicultural management policies, long range production levels and land acquisition was implemented in three medium sized timber industries in Chile. The model is currently being used routinely at higher executive levels to support decisions.

Keywords: Long Range Forest Planning, Linear Programming.

THE STRATEGIC PROBLEM

The strategic planning model is designed to assist in establishing long range policies for the acquisition and management of radiata pine plantations. In particular decisions of interest are:

a) Determining sustainable long range optimal rates of production.

b) Determining the technical and economic feasibility of supplying timber to the existing plants and defining investment in new facilities to transform raw timber into products.

c) Estimating potencial value (and maximum price to offer) of new timber lands to be acquired.

d) Selecting aggregate silvicultural management options.

The objective of the firm is to maximize the net present benefit subject to, among others, constraints of availability of resources, long range stability of the firm, supply commitments, silvicultural and technological considerations.

We consider a 45 year horizon divided into 15 three-year periods. In a hierarchical approach, the first three year period is disaggregated into a more detailed tactical model. In this form, using a rolling horizon procedure, coherence between tactical and strategic decisions is maintained. (Weintraub and Cholacky, to appear).

THE FOREST SYSTEM

To develop a strategic model, we define the following system characteristics:

Macro-Stands. Each macro-stand is composed of a set of stands spatially separate within a region but homogeneous in terms of age, site quality and initial structure. We consider two types of macro-stands: those with standing timber at present and those resulting after the final harvest of existing macro stands or through acquisition of new timber lands.

Typically, there are about 3500 stands over a radious of 60 miles. By considering up to 10 age ranges, 3 site quality classes, 3 density conditions and 4 pruning structures, we define all possible macro stand characteristics. This leads to 204 present macro-stands and 45 future macro-stands.

Silvicultural Prescriptions. We define silvicultural prescriptions as a program of actions on a given macro-stand during its existance. Typical practices are: planting, commercial and non commercial thinning, pruning and final harvest. Each of these practices can be applied in appropiate time periods.

For each macro-stand, a set of alternative prescriptions is defined. The

1/ Presented at the Symposium on Systems Analysis in Forest Resources, Charleston, S.C., March 3-7, 1991.

2/ Professor of Forest Management, University of Chile, Santiago; Professor of Industrial Engineering, University of Chile, Santiago.

model will choose among these an optimal subset. These management options are not actually meant to be implemented, but provide a framework for the strategic decisions described above, and as mentioned, those related to the first three-year period are used as a basis for a more detailed tactical model.

Timber Production. Future levels of log production capability are crucial in strategic planning. To determine sustainable levels of production it is necesary to estimate the future yields under different silvicultural prescriptions. Four basic types of products are considered, in order of increasing diameter and quality restrictions: timber for the pulp plant (P), for sawnmills (S), for export as logs (E) and logs of clearwood (C). To supply demand, it is possible to substitute timber in decreasing order of quality-diameter, C->E->S->P.

THE OPTIMIZATION MODEL

The following model contains the main characteristics used in the decision process: The model follows a type I format (Johnson and Scheurman, 1977).

Decision Variables

X_{ij} = Area of macro-stand i to be assigned to silvicultural prescription j (MHa)

W_{fj} = Area of macro-stand f to be planted in the future and managed with prescription j (MHa).

V_{kdt} = Volume of product k harvested (or thinned), in period t to be sent to destination d, k= C,E,S,P.

S_{st} = Area of site quality s to be acquired in period t (t=1,2,3,4), (MHa).

H = Value of standing timber at the horizon (MM $).

Constraints

a) Area constraints of existing macro-stands.

$$\sum_j X_{ij} \leq A_i \qquad \text{for all } i.$$

where A_i is the area of macro-stand i.

b) Area of future macro-stands

$$\sum_f \sum_j W_{fj} - \sum_i \sum_j X_{ij} - S_{st} \leq \begin{cases} A_{os} & t=1 \\ 0 & t=2,..,15 \end{cases}$$

f is a macro-stand of quality s.
j is such that harvest occurs in period t

i is of site site quality s.

where A_{os} is area of land of site quality s suitable for planting that belongs to the firm.

c) Land acquisition

$$S_{st} \leq \text{Max } st.$$

where Max st is the maximum area of site quality s that can be acquired in period t.

d) Value of standing timber at the horizon.

$$\sum_f \sum_j a_{fj} W_{fj} - H = 0$$

where a_{fj} is the value at the horizon of standing timber of macro-stand f if managed with alternative j.

e) Standing timber age requirements at the horizon

$$\sum_f \sum_j h_{fje} W_{fj} \geq \text{Min } S_e$$

where: macro-stand f has site quality s.

$$h_{fje} = \begin{cases} 1 & \text{If macro stand f managed with prescription j belongs to age class e at the horizon.} \\ 0 & \text{Otherwise.} \end{cases}$$

Min Se is the minimum required area at the horizon of site quality s with age class e. (Five age classes were defined).

f) Timber volume produced through harvests or thinnings is sent to destinations.

$$\sum_i \sum_j q_{kijt} X_{ij} - \sum_d V_{kdt} = 0$$

where q_{kijt} is the volume of product k produced in period t if prescription j is used in macro-stand i.

g) Satisfying demands for each product in each period.

$$\sum_{k \in P(k)} V_{kdt} \geq D_{dt} \qquad \text{for all d,t}$$

where P(k) is the set of products suitable for destination d (e.g. if d is pulp, any

product k can be used). D_{dt} is the demand in destination d, period t. These constraints avoid double accounting of timber production.
Other constraints include non declining income.

Objective Function

Maximize net discounted revenues.

$$\text{Max } Z = \sum_{t=1}^{15} \left(\sum_{k} \sum_{d} f_{kdt} \cdot V_{kdt} \right) + a_h \quad H$$

$$- \sum_{i} \sum_{j} g_{ij} \; X_{ij} \; - \sum_{t} \sum_{s} h_{st} \cdot S_{st}$$

where f_{kdt} is net discounted revenues of sales, a_h is the discount factor for standing timber at the horizon, g_{ij} is the net present cost of the management prescriptions and h_{st} is the discounted cost of land acquisitions.

THE COMPUTATIONAL IMPLEMENTATION.

The system was implemented using HyperLindo as the LP package. Data is inputed through an information system in dBase IV. Different files form the basis of the system. One set of files contains information on stands, such as site index, age, density, etc. Another set of files aggregates information for macro-stands. Other files define possible management prescriptions and yields. For each run, costs, revenues, demands and other parameters are introduced interactively.

The LP has typically dimensions of about 600 constraints and 1200 variables. It is run on a PC IBM 386 and takes about 2 hours for each run.

RESULTS OBTAINED.

The system is presently operating with succes in three firms, which own between 50 and 70 thousand hectares each.

Before implementing the described model, simulation was used as a planning tool, through projecting growth and yields in the plantations. The use of these simulation models was however not satisfactory, due to the difficulty in selecting adequate silvicultural prescriptions, satisfying non declining physical and monetary flow constraints, and satisfying the goal of gradually moving the forests towards regulated holdings. These problems are basically solved through the use of an optimization model. The present system presents, through adequate output formats, tables which show: optimal production amounts in the planning interval, and its distribution by type of product; the destination of this production, areas to be treated to different silvicultural practices, land to be acquired in the future, age and spatial distribution of plantations at the horizon, net monetary income in each three year-period and economic value of the firm.

The system has been used to analyze the technical and economic feasibility of supplying existing plants, make investments in new facilities and acquire new lands, already planted or suitable for planting. For these analysis the model is run with and without each project to determine its potencial contribution.

Results obtained showed that decisions were sensitive to the discount rate (8 to 14 percent), but given a discount rate, the model was not very sensitive to reasonable variations in the technical parameters.

The division of planning periods into three year intervals has been advantageous, as it allows an adequate aggregation of stands into macro-stands without loosing an important level of precision in spatial location, which is essential for smaller intervals.

In relation to silvicultural prescriptions, the basic results obtained agree with general economic evaluations. Intensive management is concentrated in high quality sites, while lower quality sites are oriented towards a higher proportion of pulp timber. And, in spite of the high requirement firms have for fiber wood, they prefer to use sawnmill quality timber for pulp rather than have short rotation forests to obtain pulp production or products of reconstituted wood.

Border constraints, to impose a regulated forest at the horizon, are active and lead to a relatively small loss in objective value (at worst, 6 percent). There was one exception; in one firm, given the irregular distribution of stand ages, site quality and past silvicultural treatment, it was more complex to find a compromise between maximizing net total income and establishing a regulated forest

CONCLUSIONS

The model shown has been accepted at strategic level in all three firms. After a year in development it has substituted with clear advantages the simulation models used in the past. One important element in its succes has been the structure of the system, which is user friendly for input requirements and generates easy to interpret results. This model is complemented with a tactical one, which deals in detail with decisions in a three year horizon.

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CAPACITY EXPANSION & STRATEGIC BEHAVIOR IN THE NORTH AMERICAN NEWSPRINT INDUSTRY[1/]

Thomas W. Steele and Jeffrey C. Stier[2/]

Abstract.--A dynamic dual model of capacity expansion in the North American newsprint industry is developed. The model integrates micro-economic analysis with explicit consideration of strategic behavior. Agents maximize an intertemporal value function by selecting optimal levels of variable and quasi-fixed factor inputs. Within this setting, agents' decisions are interdependent, endogenous, and time-variant. The result is a theoretically consistent analytical model of dynamic behavior in an oligopolistic setting.

Keywords: Dynamic optimization, oligopoly.

INTRODUCTION

In general, traditional investment models have not been able to identify the determinants of investment behavior within the pulp and paper sector very well. This problem may be traced to two sources. First, the majority of research has proceeded under the naïve assumption of perfect competition. Most segments of the pulp and paper industry are not characterized by a perfectly competitive market, but rather by an oligopolistic environment in which agents' profits are interdependent and optimal behavior is contingent upon rivals' actions. Second, investment models may be misspecified due to the manner in which investment dynamics have traditionally been modeled.

In this paper we develop a dynamic model of capacity change and variable factor demand for the North American newsprint industry. The model is constructed at the micro level and attempts to capture firm interdependence while imposing minimal structure on the form and extent of oligopolistic competition. In contrast to traditional models of capacity investment, the problem is cast within a framework of dynamic optimization in which firms maximize an intertemporal value function by selecting optimal levels of variable factor inputs and an optimal path of capacity expansion. This optimization framework endogenizes firms' capacity decisions, making them time-variant, and provides theoretical consistency lacking in many traditional investment models.

Recent applications of this approach to capital investment analysis include the energy (Berndt *et al.*, 1981), agriculture (LeBlanc and Hrubovcak, 1986), dairy (Howard and Shumway, 1988; Weersink and Tauer, 1989), and food processing sectors (Lopez, 1985). These studies draw extensively from the theory of adjustment costs and dynamic firm behavior first posited by Eisner and Strotz (1963) and later extended by Lucas (1967), Gould (1968), and Treadway (1971). We build upon this research by applying the optimization framework to oligopolies. Implicit throughout our analysis is the

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[2/]Natural Resources Manager, Kemp Natural Resources Station, Minocqua, WI; Professor of Forestry, University of Wisconsin-Madison, Madison, WI.

ssumption that firms are profit aximizers which are able to observe the apacity decisions of rivals, but are nable to distinguish between their pponents' strategic and non-strategic ehavior.

The choice of the North American ewsprint industry is for illustrative urposes only. The model can be eneralized to any oligopoly.

HE THEORETICAL MODEL

The manufacture of newsprint can be lescribed by the production function

$$(1) \quad q_j(t)=f_j\big(x_j(t);k_j(t),\dot{k}_j(t),\tau_j(t)\big).$$

This expression represents the efficient combination of variable inputs (x) and quasi-fixed capacity (k) that can be used to produce output (q) by firm j at time t. The impact of technological change on newsprint production is captured via the index $\tau_j(t)$.

Capacity levels are regulated via the control variable $\dot{k}$ (the time derivative of k) such that capacity evolves as

$$(2) \quad k_j(t)=\int_0^t \dot{k}_j(t)dt$$

$$=\int_0^t dk_j(t).$$

Assume the production function is well behaved; that is $f(\cdot)$ is twice continuously differentiable and strictly concave in x, k, and $\dot{k}$ over the relevant range of production. Further, assume $\frac{\partial f}{\partial \dot{k}}<0$. This inequality, which arises from the diversion of resources from newsprint production to changing capacity stock, reflects the internal costs of adjusting quasi-fixed capacity. It is the existence of endogenous and transitory adjustment costs which drives the intertemporal nature of firms' capacity decisions. The fact that such costs increase with increasing expansion; i.e., the concavity of $f(\cdot)$ in $\dot{k}$, leads to recurring capacity investment rather than bang-bang controls. Moreover, if a firm could adjust instantaneously and costlessly to changes in the market environment, the intertemporal nature of the model would collapse leaving a simple problem of static optimization (Meese, 1980).

To capture the oligopolistic nature of the newsprint industry and permit alternative pricing behaviors, price is expressed as an endogenous function of the output and capacity of all m firms in the industry

$$(3) \quad p(t)=P\big(q_1(t),q_2(t),\ldots,q_m(t),\,k_1(t),k_2(t),\ldots,k_m(t)\big).$$

This specification recognizes the impact of capacity utilization, both at the firm and industry level, on newsprint price; yet, it is sufficiently general to model a number of market environments. The effect of excess capacity on price depends upon industry structure, market conditions, and the strategies followed by individual firms. In a perfectly competitive industry, only *aggregate* behavior determines price because no single firm can influence the market. Excess capacity occurs when exogenous factors shift demand to the left or short-run marginal costs to the right; hence, price falls as surplus capacity rises (Masson and Shaanan, 1986).

In an oligopoly characterized by a dominant firm and a competitive fringe, the dominant firm may use excess capacity (whether strategic or non-strategic) as a barrier to entry or mobility in order to fix a high price. Since barrier height increases with the amount of surplus capacity, greater surplus implies that the dominant firm can set a higher market price. The competitive fringe possesses insufficient power to impact the market. Alternatively, the dominant firm could elect not to use excess capacity strategically, but rather lower price in order to increase its level of capacity utilization.

Under barometric price leadership, no single firm dominates the industry. The price leader is unable to coerce rival firms into accepting its price and merely announces an industry price which has recently developed or will develop under oligopolistic competition. Given excess capacity, an individual firm may be tempted to undercut a non-cooperative oligopoly price in hopes of garnering a larger share of industry demand and increasing its capacity utilization at the expense of rivals. The desire to cut price must be tempered, however, by the threat of an ensuing price war which could erode any short-run gains in sales, and ultimately could lead to reduced revenues for all firms (Green and Porter, 1984; Brock and Scheinkman, 1985; Rosenbaum, 1989). Thus, a firm's incentive to cut price depends upon its "fighting reserves" - the amount of excess capacity that it can operationalize relative to that of its opponents (Scherer, 1980: 370, 371). The deterrent to price cutting is the threat of major retaliation of rival firms, which in turn, depends upon the magnitude of their excess capacity.

Implicit in the endogenous price expression is the presumption of instantaneous price adjustment. Such a model structure conflicts with statistical evidence which indicates that newsprint firms avoid price wars by gradually adjusting price to target levels in response to changing market conditions. Indeed, recent work by Booth *et al.* (1989) revealed protracted lags of 1.9 to 3.3 years depending on the particular pricing rule followed. Ideally one would like to endogenize the speed of price adjustment within a dynamic optimization framework; however, this would impose offensive and implausible restrictions on firm and industry output. Therefore, we are forced to adopt a more parsimonious model of inverse demand, and to draw empirical support from the frequency of changes in list price and from the prevalence of off-list price concessions that characterize the newsprint industry.

Dropping the time notation, firm j's single period restricted profit function is

$$(4)\quad \Pi_j\left(P(\cdot), q_j, x_j, w_j, k_j, \dot{k}_j, \tau_j\right) = \max_{q_j, x_j} P(q_1, q_2, \ldots, q_m, k_1, k_2, \ldots, k_m) q_j - w_j' x_j$$

subject to $q_j(t) = f_j\left(x_j(t); k_j(t), \dot{k}_j(t), \tau_j(t)\right)$,

where w_j' is a transposed n-dimensional vector of variable input costs faced by firm j.

Inserting the production function $f_j(\cdot)$ for q_j in Equation (4) and solving the first order necessary conditions yields

$$(5)\quad \frac{\partial \Pi_j}{\partial x_j^i} = \frac{\partial P(\cdot)}{\partial Q} \frac{\partial Q}{\partial f_j(\cdot)} \frac{\partial f_j(\cdot)}{\partial x_j^i} f_j(\cdot) + P(\cdot) \frac{\partial f_j(\cdot)}{\partial x_j^i} - w_j^i = 0 \quad \forall\, x_j^i.$$

where x_j^i is quantity and w_j^i is per unit cost of the ith factor employed by firm j.

Like the endogenous price expression, the restricted single period profit function is sufficiently general to model a number of market environments depending on firm j's conjectural industry output variation - $\frac{\partial Q}{\partial f_j(\cdot)}$ (Varian, 1984: 102, 103).

Specifically, $\frac{\partial Q}{\partial f_j(\cdot)} = 0$ denotes a competitive setting in which firm j exhibits price taking behavior and chooses its output level accordingly. In contrast, Cournot behavior is implied by $\frac{\partial Q}{\partial f_j(\cdot)} = 1$ because it implies that firm j makes output decisions under the belief that rival firms will not adjust their production. Consequently, a change in firm j's output results in an equal and identical change in industry output. Collusion (tacit or otherwise) is indicated by $\frac{\partial Q}{\partial f_j(\cdot)} = \frac{Q}{f_j(\cdot)}$ as firms attempt to achieve in aggregate the monopoly outcome.

And finally, $\frac{\partial Q}{\partial f_j(\cdot)}$ equalling none of the above implies some form of Stackelberg behavior where $\frac{\partial Q}{\partial f_j(\cdot)}$ gives the opponents' aggregate response to firm j's choice of output.

Using the first order necessary conditions and the implicit function theorem and assuming an interior solution, we can solve for firm j's short-run variable factor demands conditional on factor price, quasi-fixed capacity, capacity change, level of technology, and rivals' output and capacity

$$(6)\quad x_j^* = \theta_j\left(w_j; k_j, \dot{k}_j, \tau_j, q_{i \neq j}, k_{i \neq j}\right).$$

Substituting these demands into the production function gives

$$(7)\quad q_j^* = f_j\left(\theta_j\left(w_j; k_j, \dot{k}_j, \tau_j, q_{i \neq j}, k_{i \neq j}\right), k_j, \dot{k}_j, \tau_j\right)$$

which is similar to the reaction functions of oligopoly theory, the only difference being the inclusion of rivals' capacity.

Replacing x_j^* and q_j^* in Equation (4) by Equations (6) and (7), respectively, we obtain firm j's short-run indirect, or dual, profit function conditional on factor costs, capacity, capacity change, technology, rivals' output, and rivals' capacity:

(8) $\Pi_j\left(w_j;k_j,\dot{k}_j,\tau_j,q_{i\neq j},k_{i\neq j}\right)=P\left[f_j\left(\theta_j\left(w_j;k_j,\dot{k}_j,\tau_j,q_{i\neq j},k_{i\neq j}\right),k_j,\dot{k}_j,\tau_j\right),q_{i\neq j},k_1,k_2,\ldots,k_m\right]f_j\left(\theta_j\left(w_j;k_j,\dot{k}_j,\tau_j,q_{i\neq j},k_{i\neq j}\right),k_j,\dot{k}_j,\tau_j\right)-w_j'\theta_j\left(w_j;k_j,\dot{k}_j,\tau_j,q_{i\neq j},k_{i\neq j}\right)$.

As structured, Equation (8) captures the interdependent nature of firm behavior via the endogenous price expression. More specifically, rivals' production and capacity decisions affect market price which, in turn, impacts firm j's profitability and influences behavior. By endogenizing newsprint price and dealing with its reduced form, it is possible to develop a complete and consistent model of firm interaction while avoiding the contentious issues of off-list price concessions and inaccuracy of list price data.

Now assume firm j acts to maximize the intertemporal value function

(9) $V_j(0)=\max_{x_j,\dot{k}_j}\int_0^\infty e^{-rt}\left\{\Pi_j\left(w_j;k_j,\dot{k}_j,\tau_j,q_{i\neq j},k_{i\neq j}\right)-m_jk_j-a_j\dot{k}_j\right\}dt$

where r, the discount rate, is assumed to be constant over the time horizon; m_j is the unit cost of maintaining productive capacity at installed levels; a_j is the unit cost of capacity acquisition; and all other variables are as previously defined. Thus, the problem facing firm j is deciding when, what type (i.e. strategic or non-strategic), and how much capacity it should add in order to maximize $V_j(0)$.

Maximization of the objective functional requires that the Euler differential equations hold (Gould, 1968); that is, the first order necessary conditions for static profit maximization (Equation 5) must be satisfied at all points in time and $\frac{\partial V_j}{\partial k_j}-\frac{\partial^2 V_j}{\partial t\,\partial \dot{k}_j}=0$.

Solving the second of the Euler equations yields

(10) $\Pi_{k_j}+r\Pi_{\dot{k}_j}-\Pi_{\dot{k}_j\dot{k}_j}\ddot{k}_j-\Pi_{\dot{k}_jk_j}\dot{k}_j=ra_j+m_j$,

where $\Pi_{k_j}\equiv\frac{\partial\Pi(\cdot)}{\partial k_j}$, $\Pi_{\dot{k}_j}\equiv\frac{\partial\Pi(\cdot)}{\partial \dot{k}_j}$, $\Pi_{\dot{k}_j\dot{k}_j}\equiv\frac{\partial^2\Pi(\cdot)}{\partial \dot{k}_j^2}$, $\Pi_{\dot{k}_jk_j}\equiv\frac{\partial^2\Pi(\cdot)}{\partial \dot{k}_j\partial k_j}$. and $\ddot{k}_j=\frac{\partial \dot{k}_j}{\partial t}$. Equation (10) is predicated on the assumption of static expectations about factor input costs, technology, opponents' outputs, and opponents' capacities. This assumption is necessary to motivate the existence of a long-run equilibrium toward which firm j is moving. Restated, static expectations imply that firm j's target capacity is not moving over time unless there are changes in factor prices, technology, rivals' output, or rivals' capacity change. The problem, then, is not one of optimal control characterized by a single maximization with strict observance of a unique investment path to some pre-determined target. Rather, Equation (10) is the result of an open-loop control policy in which firm j re-evaluates its capacity decisions as current market conditions change. Thus while the assumption of stationary expectations represents an inherent weakness of the model, its offensiveness may be mitigated by the observation that firms periodically adjust their investment plans in response to changing market conditions.

In long-run equilibrium $\dot{k}_j=\ddot{k}_j=0$ and Equation (10) becomes

(11) $\Pi_{k_j}\left(w_j,k_j^*,\dot{k}_j=0,\tau_j,q_{i\neq j},k_{i\neq j}\right)+r\Pi_{\dot{k}_j}\left(w_j,k_j^*,\dot{k}_j=0,\tau_j,q_{i\neq j},k_{i\neq j}\right)=ra_j+m_j$

where k_j^* is the long-run optimal capacity level and $r\Pi_{\dot{k}_j}(\cdot)$ represents the costs of capacity adjustment. Equation (11) is a mathematical expression of the familiar optimization result that marginal revenue equal marginal cost; or more specifically, that the marginal return to capacity less the amortized cost of capacity adjustment equals the rental cost of capacity investment plus the annual cost of capacity maintenance.

In the neighborhood of the long-run equilibrium Equation (11) can be linearly approximated (Treadway, 1971) as

(12) $\Pi_{\dot{k}_j\dot{k}_j}\ddot{k}_j + \left(\Pi_{\dot{k}_j k_j} - \Pi_{k_j\dot{k}_j} - r\Pi_{\dot{k}_j\dot{k}_j}\right)\dot{k}_j - \left(\Pi_{k_j k_j} + r\Pi_{\dot{k}_j k_j}\right)\left(k_j - k_j^*\right) = 0.$

Solving for the stable root, Treadway obtained

(13) $\dot{k}_j = B\left(k_j^* - k_j\right)$

where B, the speed of adjustment variable, is equal to

$$(14) \quad B = -\frac{1}{2}\left[r - \left(r^2 + 4\Pi_{k_j k_j}/\Pi_{\dot{k}_j\dot{k}_j}\right)^{\frac{1}{2}}\right]$$

Equation (13) is the flexible accelerator model of partial adjustment that has been widely used in numerous studies of capacity expansion. Traditional application of the model requires that the researcher impose some ad hoc time structure of firm investment. Within a dynamic setting, however, capacity decisions are explicitly based on dynamic optimization which incorporates the costs of adjusting quasi-fixed capacity. The implications of this property, as identified by Berndt *et al.* (1981), are (1) speed of adjustment of quasi-fixed capacity to its long-run equilibrium is endogenous and time variant, (2) short-run variable factor demands depend on factor costs, quasi-fixed capacity, level of technology, and in the case of oligopoly, rivals' output and capacity, (3) the dynamic path of adjustment is based on economic optimization at each point in time, and (4), the transition from short- to long-run for variable factor inputs incorporates adjustments in quasi-fixed capacity and variation in the optimal rate of capacity utilization. Thus, there appear to be real gains from both a theoretical and empirical standpoint to casting the problem within a dynamic framework.

Using Equations (8), (13), and (14), it is possible to specify a theoretically consistent model of firm j's short-run factor demands which recognizes the interdependency of firm behavior. The model is comprised of the following system:

$$(15.1) \quad \dot{k}_j = -\frac{1}{2}\left[r - \left(r^2 + 4\Pi_{k_j k_j}/\Pi_{\dot{k}_j\dot{k}_j}\right)^{\frac{1}{2}}\right]\left[k_j^* - k_j\right]$$

and

$$(15.2) \quad x_j^i = -\frac{\partial\Pi\left(w_j, k_j, \dot{k}_j, \tau_j, q_{i\neq j}, k_{i\neq j}\right)}{\partial w_j^i} \quad \forall\, x_j^i.$$

THE EMPIRICAL MODEL

To make the theory tractable, we must specify an explicit functional form for the short-run indirect restricted profit function. Based on its desirable inherent properties, the normalized quadratic function is used:

$$(16) \quad \tilde{\Pi}_j = \alpha_0 + \sum_{h\neq n}\alpha_{w_j^h}\tilde{w}_j^h + \alpha_{k_j}k_j + \alpha_{\tau_j}\tau_j + \sum_{i\neq j}\alpha_{q_i}q_i +$$
$$\sum_{i\neq j}\alpha_{k_i}k_i + \sum_{h\neq n}\beta_{w_j^h k_j}\tilde{w}_j^h k_j + \sum_{h\neq n}\beta_{w_j^h\tau_j}\tilde{w}_j^h\tau_j +$$
$$\sum_{h\neq n}\sum_{i\neq j}\beta_{w_j^h q_i}\tilde{w}_j^h q_i + \sum_{h\neq n}\sum_{i\neq j}\beta_{w_j^h k_i}\tilde{w}_j^h k_i + \chi_{k_j\tau_j}k_j\tau_j +$$
$$\sum_{i\neq j}\chi_{k_j q_i}k_j q_i + \sum_{i\neq j}\chi_{k_j k_i}k_j k_i + \sum_{i\neq j}\gamma_{\tau_j q_i}\tau_j q_i +$$
$$\sum_{i\neq j}\gamma_{\tau_j k_i}\tau_j k_i + \sum_{i\neq j}\sum_{i\neq j}\varphi_{q_i k_i}q_i k_i + \frac{1}{2}\left(\sum_{h=1}^{n}\alpha_{w_j^h w_j^h}\tilde{w}_j^{h2} +\right.$$
$$\left.\alpha_{k_j k_j}k_j^2 + \alpha_{\dot{k}_j\dot{k}_j}\dot{k}_j^2 + \alpha_{\tau_j\tau_j}\tau_j^2 + \sum_{i\neq j}\alpha_{q_i q_i}q_i^2 + \sum_{i\neq j}\alpha_{k_i k_i}k_i^2\right)$$

where $\tilde{\Pi}_j$ is short-run profit normalized by the price of variable factor x_j^n, $\tilde{w}_j^h$ is an hx1 vector of normalized variable factor prices, and α , β , χ , and φ are vectors of parameters to be estimated.

Economic theory dictates that the short-run profit function satisfy regularity conditions in factor prices (Varian, 1984: 46): Namely, $\tilde{\Pi}_j$ should be nonincreasing, homogeneous of degree one, convex, and continuous in $\tilde{w}_j$, at least when $\tilde{w}_j >> 0$. Further $\tilde{\Pi}_j$ should be strictly concave in k_j; strictly concave and decreasing in $\dot{k}_j$; monotonic; and symmetric. As well, the speed of capacity adjustment should lie in the interval (0,1].

Having specified a functional form, it is possible to derive an explicit representation of the complete model. Long-run optimal capacity, derived from Equations (11) and (16), is written as

$$(17)\quad k_j^* = \left[r a_j + m_j - \alpha_{k_j} - \sum_{h \neq n} \beta_{w_j^h k_j} \tilde{w}_j^h - \chi_{k_j \tau_j} - \sum_{i \neq j} \chi_{k_j q_i} q_i - \sum_{i \neq j} \chi_{k_j k_i} k_i \right] \Big/ \alpha_{k_j k_j} .$$

Substituting (17) into Equation (15.1) yields:

$$(18.1)\quad \dot{k}_j = -\frac{1}{2}\left[r - \left(r^2 + 4\alpha_{k_j k_j}/\alpha_{\dot{k}_j \dot{k}_j} \right)^{\frac{1}{2}} \right] \left[\left(\left(r a_j + m_j - \alpha_{k_j} - \sum_{h \neq n} \beta_{w_j^h k_j} \tilde{w}_j^h - \chi_{k_j \tau_j} \tau_j - \sum_{i \neq j} \chi_{k_j q_i} q_i - \sum_{i \neq j} \chi_{k_j k_i} k_i \right) \Big/ \alpha_{k_j k_j} \right) - k_j \right].$$

Variable factor demands are calculated using Equation (16) and Hotelling's lemma to yield

$$(18.2)\quad x_j^h = -\alpha_{w_j^h} - \beta_{w_j^h k_j} k_j - \beta_{w_j^h \tau_j} \tau_j - \sum_{i \neq j} \beta_{w_j^h q_i} q_i - \sum_{i \neq j} \beta_{w_j^h k_i} k_i - \alpha_{w_j^h w_j^h} \tilde{w}_j^h$$

where x_j^h are the derived demands of those factors whose price was normalized by the price of factor x_j^n.

Equations (16), (18.1), and (18.2) represent a theoretically consistent model of profits, capacity change, and variable factor demands for a single firm. Replicating these equations for dominant and co-dominant firms and the competitive fringe results in a comprehensive model of firm dynamics within the North American newsprint industry. The model is sufficiently general to accommodate a number of market environments while capturing the interdependence of firms' decisions. This was accomplished using a generalized expression for the endogenous price equation rather than specifying an exact functional form. Consequently, a dialogue is established with the data, allowing it to drive the analysis rather than imposing structure *a priori*.

Tests of oligopolistic behavior and strategic capacity can be conducted via examination of regression coefficients. In a competitive setting $\frac{\partial P}{\partial q_i} = 0$ and rivals' output decisions would have no impact on firm *j*'s variable factor demands or capacity change. Thus, coefficients $\beta_{w_j^h q_{i \neq j}}$ that are significantly different from zero suggest an oligopolistic industry structure. Likewise, non-zero values for $\chi_{k_j q_{i \neq j}}$ and $\chi_{k_j k_{i \neq j}}$ imply strategic capacity in the sense that rivals' capacity directly influences the optimizing behavior of firm *j*. More specifically, $\chi_{k_j k_{i \neq j}} < 0$ indicates a strategy of accommodation; conversely, $\chi_{k_j k_{i \neq j}} > 0$ reflects an aggressive or predatory stance in which firm *j* responds positively to rivals' investment behavior. Moreover, comparison of coefficients among firms permits assessment of firm power on a firm by firm basis.

Throughout model development we assumed the existence of a stationary state toward which all firms are moving. The intent was never to prove the existence of an oligopolistic equilibrium, but rather to model firm behavior assuming one exists. While some may consider this a serious flaw, it is one that we are forced to live with until a single and robust theory of oligopoly is developed. In the absence of such a unifying theory, we have posited a general model that emulates a variety of oligopolistic behaviors.

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FOREST PLANNING AND MODELING BASED ON ECOLOGICAL LAND STRATIFICATION[1/]
A Case Study of the Umpqua National Forest

William J. Connelly[2/]

Abstract.--In the development of the Umpqua National Forest Plan, several ecoclass groups were used to stratify the planning model. These stratifications were used to estimate timber production, timber management methods, habitat for management indicator species and economic stratifications of costs and values. Better management of national forests can result from a shifting emphasis from output production to managing forest vegetation for multiple uses.

Keywords: Ecology, Analysis, National Forest

INTRODUCTION

From the very beginning of its forest planning process under the National Forest Management Act (NFMA), the Umpqua National Forest structured planning and modeling based on the forest's ecology. Stratifying the forest based upon its ecology was expected to lead to a better representation of timber productivity, timber management appropriate to the vegetative potential of the land, wildlife relationships based upon associated vegetation and economics sensitive to the costs and benefits of particular vegetative communities. Focusing a large emphasis of the planning effort on ecological land classification also meant that other major issues (primarily recreation opportunities, watershed conditions, and road management) not related to ecological information, needed other land stratifications to represent their response to forest management activities.

THE UMPQUA NATIONAL FOREST

The Umpqua National Forest (See Figure 1) consists of nearly a million acres (983,890) on the western slopes of the Cascade Mountains in southwestern Oregon. It ranges in elevation from about 1500 to 9000 feet at the summit of Mount Thielsen on the crest of the Cascades. However most of the Forest ranges in middle elevations between 2000 and 5000 feet. The land can be characterized as having predominantly moderate to steep slopes forming the Umpqua River watershed. Small portions of the forest also drain into the Willamette and Rogue river basins.

The forest's climate is generally characterized by cool,wet winters with substantial accumulations of snowfall above 4000 feet, and warm, dry summers. The forest is a transition zone as parts of the forest further south tend to have warmer drier conditions, similar to conditions in northern California, while the northern part of the forest is colder and wetter, similar to conditions of the western Cascades of Washington and Oregon. "This area is the southern limit for the range of Pacific silver fir, Alaska cedar, and noble fir, and the northern limit for coast redwood, Jeffrey pine, tanoak, and Shasta red fir... Species from different geographical areas are continuing to mix and develop." [3/]

The forest is overwhelmingly dominated by coniferous forest vegetation. At the lower elevations Douglas Fir predominates with a number of other species including western red cedar, western hemlock, white fir, incense cedar, sugar pine(world record tree), and western white pine. Moving towards higher elevations, the vegetation transitions to include Shasta and Pacific silver fir eventually leading to timber stands dominated by mountain hemlock and lodgepole pine at the highest elevations (above 5000 feet). There is deciduous vegetation, although most is found in the understory of dominant conifers.

As timber harvest activity grew on western forests in the post war period, the Umpqua was one of the last forests to be harvested heavily. It is still characterized as a forest comprised primarily of mature and old growth forests and it currently ranks second or third as compared to all other

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2/ Program Analyst, USDA Forest Service, Roseburg, OR

3/ Atzet and Mcrimmon, Preliminary Plant Associations of the Southern Oregon Cascade Mountain Province, 1990.

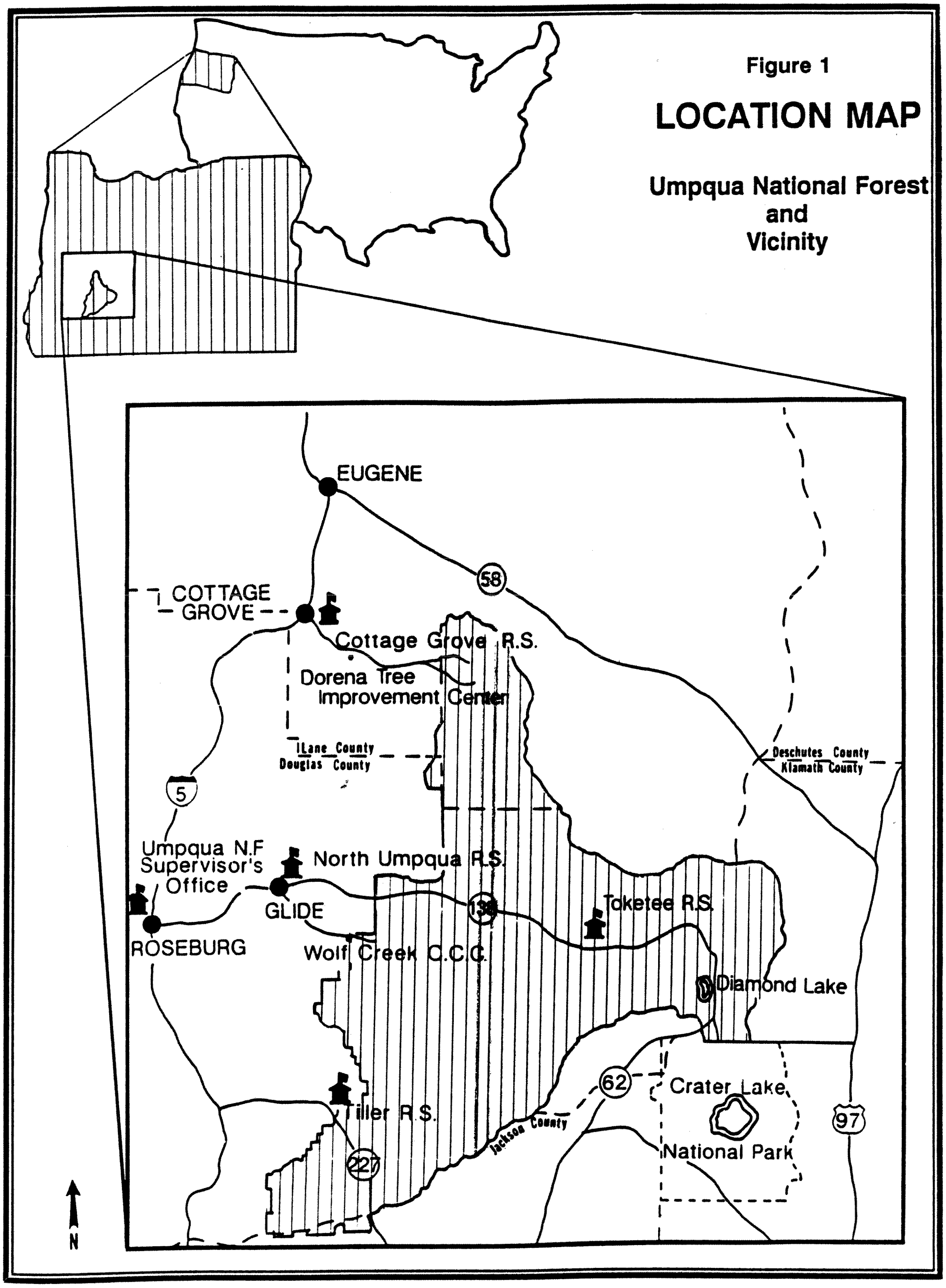
Figure 1
LOCATION MAP
Umpqua National Forest
and
Vicinity
EUGENE
58
COTTAGE
GROVE
Cottage Grove R.S.
Dorena Tree
Improvement Center
Lane County
Douglas County
Deschutes County
Klamath County
5
Umpqua N.F
Supervisor's
Office
North Umpqua R.S.
GLIDE
138
Toketee R.S.
ROSEBURG
Wolf Creek C.C.C.
Diamond Lake
62
Crater Lake
National Park
97
Jackson County
Tiller R.S.
227
N

national forests in its level of timber volume produced. It provides raw material for an economy specialized in the manufacturing of forest products.

The Umpqua's stands are highly productive, with estimates of potential growth as high as 140 cubic feet per year. However, this productivity is believed to vary across the forest with the most productivity in the lower elevations of the northern part of the forest, lesser productivity in the southern part and middle elevations (3500-5000 feet), and very low productivity in high elevations. There are also known difficulties in the ability to regenerate timber stands, especially in the southern part of the forest on south facing slopes and at higher elevations. It was expected that ecological stratification of the forest would capture these differences in productivity and regeneration potential.

STRATIFICATION OF ECOCLASS GROUPS

The ecological stratification of southwestern Oregon forests begins with the definition of the ecological series based on the climax tree species in the forest overstory. In most situations the response of vegetation is more similar within a series than between series. Within each series are a number of plant associations. Plant associations are classified based on the climax species associated with the tree, shrub and/or herb layers. Plant response within an association is expected to be fairly consistent. The number of associations within a series can provide an indication of both the amount of land in the series and the relative variety of plant response within the series.

Similar to most other national forests, the Umpqua developed a FORPLAN model to support its land management planning effort. In stratifying analysis areas for the FORPLAN model the primary ecological series based on the dominant climax vegetation was used. The series were grouped together where the grouped series were perceived to have similar characteristics. The groups (hereafter called ecoclass groups) identified in the stratification are as follows:

Western hemlock/White fir (CH-CW): This ecoclass group is expected to contain the identified species in a climax condition. Presently, the climax species generally occupies an understory condition with Douglas Fir predominating in the overstory. This group tends to be found at lower to middle elevations throughout the forest where moist conditions exist. The western hemlock series occurs more in the northern part of the forest while the white fir series is found more in the southern part of the forest. It was expected that this was the most productive ecoclass group. Although there were known to be some situations of regeneration failure, it was felt that active reforestation could produce desired results. Since the initial stratification was developed, 20 plant associations have been identified for the western hemlock series and 18 for the white fire series; a total of 38 different plant associations for the entire ecoclass group.

Douglas Fir (CD): This series is expected to contain Douglas Fir in a climax condition. They occur on southerly aspects throughout the forest, but become more common further south. The drier conditions are expected to be sufficient to support Douglas Fir and some pines with slower growth. Research papers and field experience suggested that the forest needed a separate recognition of this strata with different management. Regeneration was expected to be more difficult even with active reforestation efforts. Six plant associations have been identified for this series.

Shasta fir/Pacific Silver fir (CF-CR): These stands are expected to climax with either shasta or pacific silver fir, summarized as true fir climax. They occur along the ridgetops at higher elevations (above 3500 feet) where there is more moisture, heavier snowpack, and colder temperatures. Douglas fir also makes up a substantial number of the trees found in this ecoclass group. Field experience suggested that this group was less productive than the CH-CW group. Five plant associations have been identified with this ecoclass group.

Mountain hemlock (CM): The mountain hemlock group occurs in conditions of short growing seasons at high elevations (generally above 5000 feet). Mountain hemlock comprises a majority of the trees found in this ecoclass with Shasta and Pacific silver fir also found. Field experience suggested that these stands were very slow growing. Mountain hemlock is not a very desirable commercial species and experience indicated that regeneration of these stands to more desirable species was difficult. More likely harvest activity would be followed by initial natural regeneration of lodgepole pine. Five plant associations have been identified with this group.

Lodgepole pine (CL): Although lodgepole pine is usually associated as a pioneer species following disturbance, the Umpqua has some areas where lodgepole is a climax species. These situations occur at high elevations in frost pockets or where moisture rapidly drains deeply into the soil. These soils usually consist of volcanic ash or pumice deposited after the eruption of Mount Mazama (Crater Lake). These lands were considered to be quite unproductive. There are 2 plant associations within this series.

Table 1.-- Inventory Information for Each Ecoclass Group[a/]

Abbreviation: Ecoclass Group	Area	Standing Volume in Old Growth	Mean Annual Increment
	Acres	MCF/Acre[b/]	CF/Acre[c/]
CH-CW: W. Hemlock/W. Fir	654,998	8.03	40.15
CD: Douglas fir	123,705	5.51	32.41
CF-CR: True Fir	19,801	10.07	43.78
CM: Mountain hemlock	79,924	5.23	23.24
CL: Lodgepole pine	14,449	.86	.86

a/ Data from USDA Forest Service, Final Environmental Statement Land and Resource Plan Umpqua National Forest, 1990.
b/ MCF represents thousand cubic feet; CF represents cubic feet
c/ Mean annual increment measures average growth over a rotation.

Nonforest: There were also a number of nonforest ecological series recognized in the model design. These generally fit into four groups: rock, meadow, water, and roads. Rock included all vegetation situations dominated by rocky soils severely limiting vegetation, such as rock outcrops, talus slopes, cinders, and lava flows. Meadows included dry or wet situations where grasses or shrubs were considered to dominate. One interesting separation from "true" stratification based on potential vegetation, classified powerline corridors as meadows; since they were actively planted with grasses and shrubs and managed to suppress the development of trees. Water represented permanent water situations. Roads represented all logging roads and other permanent conversions of land to other uses. It was estimated that approximately 2.5% of the total forest was contained in roads.

INVENTORY RESULTS BASED ON THE ECOCLASS GROUPS

In the early stages of its planning process, the ecoclass groups were structured as the basis of the timber inventory. Developing this inventory involved two parallel processes. The first was mapping the ecoclass groups through aerial photography to provide the basis for delineating the various strata. Each of the ecoclass groups were also stratified by age class. Once these strata were identified, inventory plots were established and measured for each stratum. For some of the smaller strata, there was difficulty in measuring an adequate number of plots to establish appropriate statistical reliability. This limited reliability has surfaced as an issue in appeals. Inventory results for the ecoclass groups are displayed in Table 1.

The results of this inventory obviously brought some surprises. The major surprise was how small the CF-CR ecoclass group was in terms of acres and also the information which indicated that it contained both the largest volume and greatest productivity of all the ecoclass groups.

On the other hand, this left the CH-CW group comprising nearly 2/3 of the entire forest. This raised the possibility that too much discrete information was being washed together in the large CH-CW ecoclass group. To deal with this problem, the planners considered separating the White fir (CW) and the western hemlock (CH) ecoclasses into two separate groups. However, when the plots in the CH-CW group were stratified in this manner, there was less than a single point difference in the estimated site index. This suggested that even if the two ecoclasses involved were separated in the analysis, it would make little difference in the model solution. When considering the costs in time and money involved to make the separation, it was concluded that the separation was not needed. Despite this, the relative homogeneous treatment of such a large acreage remains a continuing problem in both modeling and plan implementation.

WILDLIFE RELATIONSHIPS

Generally, the CH-CW, CD, and CF-CR ecoclass groups become commonly referred to as the Douglas Fir forest type and the CL, CM, and CF-CR as the high cascades forest. The inclusion of the CF-CR in both types recognizes its transitional nature. This distinction remains a issue in determining the appropriate habitat for management indicator species, especially the northern spotted owl.

The Douglas Fir forest types are considered to be primary habitat for the northern spotted owl and the pileated woodpecker. For the spotted owl, primary habitat is considered to be old growth conditions. For the pileated woodpecker, primary habitat is considered to be mature forest or old growth conditions. For the pine marten, primary habitat is considered to be mature or old growth habitat in the high cascade forests. These three management indicator species and their habitat are tracked over time in the FORPLAN model as a consequence of the changes in the vegetative stages in their habitat range.

Although found throughout the forest, populations of big game indicator species (Roosevelt elk and blacktail deer) were modeled as a function of the management of inventoried winter range. Appropriate mixes of forage and cover on inventoried winter range were assumed to be the critical factor influencing the forest's capability to support these animals. Winter range habitat was inventoried as occurring generally at low elevations below 3500 feet on southern or western exposures. This inventoried winter range was associated with the CH-CW and especially the CD ecoclass groups. Where meadows occurred in inventoried winter range areas, the their forage production was recognized.

There was also management for cavity nesting birds and animals. Habitat for these species could be provided by any of the forested ecoclass groups, but needed to be widely distributed across the forest.

A number of nonforest ecoclasses (meadows, rock outcrops, etc) were recognized as "unique" wildlife habitats. These inventoried habitats and their forested periphery were considered for special management prescriptions to protect these unique wildlife values.

PRESCRIPTION DESIGN

The Umpqua developed a large number of written prescriptions (56). The number of prescriptions developed to respond to each major issue area were as follows: recreation (12), riparian and watershed issues (12), specially designated areas (7), wildlife (18), timber (5) and custodial management (2). Of these 56 written prescriptions, 11 had a direct tie to the ecoclass groups, and all of these related to the wildlife issues previously discussed. This left 45 other prescriptions which did not relate to the ecoclass groups. A substantial amount of additional spatial information had to be introduced into the model to recognize specially designated areas, riparian and watershed issues, winter ranges, recreation areas and roadless areas.

Ecoclass groups also served as an important link in developing timber management intensities and their associated yields. Timber management was generally divided into two types of intensities referred to as managed or unmanaged. Of the five timber prescriptions 3 are classified as managed regimes and 2 as unmanaged regimes. Managed regimes are characterized by intensive management practices, specifically precommercial thinning and stocking control to produce optimal levels of growth and economic return. Planting and gains from use of genetic stock, control of competing vegetation, application of fertilizer, and commercial thinning also characterized managed regimes. Unmanaged regimes relied on natural regeneration or planting, if natural regeneration was not considered reliable, followed by either commercial thinning or regeneration harvest without any other intermediate treatments.

Managed yields were developed for the Douglas Fir forests using the DP-DFSIM yield simulator[4/] based on the original DFSIM yield simulator[5/]. For mountain hemlock stands, regenerated yields were estimated by extrapolating height-growth curves from research on mountain hemlock[6/]. Unmanaged yields developed for all ecoclass groups were developed from growth relationships based on empirical yield data. Generally managed yields were estimated to produce twice the volume of unmanaged yields even without the use of commercial thinning (See Figures 2 and 3). This difference between the managed yields developed with DP-DFSIM and growth relationships in the empirical yields has become a significant issue in appeals of the plan.

A summary of the management practices associated with each ecoclass group is presented in Table 2. The intensities prepared for CH-CW and CD groups assumed active reforestation followed with the intensive management practices shown in the table. The CD, CF-CR and CM ecoclass groups were scheduled for shelterwood harvest with overstory removal following ten years after the initial entry. For the CF-CR group, regeneration could be done either by planting with genetically improved stock to produce a regenerated stand consisting primarily of Douglas Fir or use of natural regeneration with an unmanaged intensity.

For the CM group, intensities were initially developed with the same types of regimes as the CF-CR group, although genetically improved stock was not considered to be available. One problem was that with an assumption of active reforestation, the per acre present net value of an acre in timber management (including the value of removing the existing stand) was quite negative. With further review, it was determined that regeneration with natural seeding following a shelterwood could be considered to be sufficiently reliable to permit a managed timber regime without active reforestation. Thus, both the managed and unmanaged regimes relied upon natural regeneration.

4/ Johnson and Sleavin, DP_DFSIM -- Overview and Users Guide, 1984

5/ Curtis, Clenden, and Demars, A New Stand Simulator for Coast Douglas-fir: DFSIM Users Guide, 1981.

6/ Johnson, Site Index Equations for Mountain Hemlock on three Habitat Types in the Central Oregon Cascades, 1981.

Figure 2

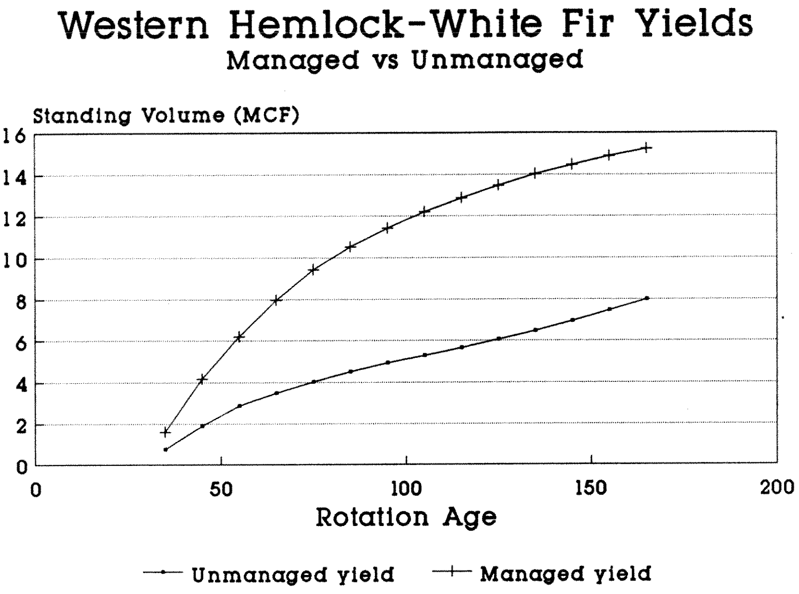

Figure 3

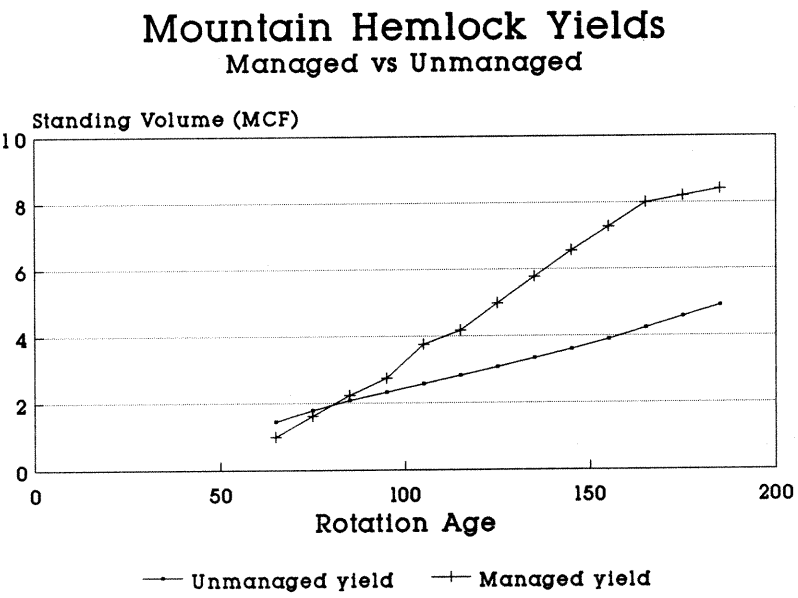

Table 2.-- Modeled characteristics of Ecoclass Groups[a/]

	Ecoclass Group Hemlock/Fir CH-CW	Douglas Fir CD	True Fir CF-CR	Mtn. Hemlock CM
Intensive Practices				
Genetic Stock	Yes	Yes	Yes	No
Vegetation Control	Yes	Yes	Yes	Yes
Precommercial Thinning	Yes	Yes	Yes	Yes
Fertilization	Yes	Yes	No	No
Commercial Thinning	Yes	Yes	Yes	Yes
Regeneration Method	Clearcut	Shelterwood	Shelterwood	Shelterwood
Natural Regeneration	No	No	Yes	Yes
Managed Rotation Age (Based on 95% CMAI)[b/]	65	85	95	165
Unmanaged Rotation Age (Based on 95% CMAI)[b/]	65	125	75	165
Present Net Value[c/]	8033	1590	6107	-4

[a/] Data from USDA Forest Service, Final Environmental Statement Land and Resource Plan Umpqua National Forest, 1990.
[b/] 95% CMAI represents 95% of the culmination of mean annual increment of growth in cubic feet.
[c/] Present Net Value is based on the most efficient regime and includes the costs and values of harvesting the existing stand, including road access. PNV is based on a 4% discount rate.

Economic information was also related to ecoclass groups. The value of timber was based on transaction evidence of the actual price paid for each species of timber harvested on the forest over a 6 year period. For each ecoclass group, the stumpage value of each species was weighted (based on share of standing volume) to form an average stumpage value. When the CF-CR was planted, the mix of species was assumed to be changed from the existing mix and values were adjusted accordingly. Since Douglas Fir is the premium species on the forest, the value of timber in the ecoclass groups varies according to the share of Douglas Fir.

Cost information also varied somewhat by ecoclass group. A separate cost of reforestation was established for each ecoclass group based on the difficulty of reforestation as indicated by an analysis of earlier reforestation efforts. The CD-CP lands were the most expensive and the CM and CF-CR lands were the least expensive when natural regeneration was used. Other costs generally varied as a function of harvest method. Since shelterwood harvest required two entries, the ecoclass groups which used shelterwood harvest were more expensive to log.

MODELING RESULTS

In the model's selection of intensities for timber management and scheduling of land for timber harvest, the results are relatively predictable. The FORPLAN model generally assigns the intensities with the highest PNV if using PNV objective functions, and usually also assigns the intensities with the highest PNV when maximizing timber in the objective function. Since there is a general association of high volume with high PNV, this is fairly predictable. However, there were a number of other important patterns present in the model results which required consideration and often adjustment through the addition of constraints.

For the CH-CW group, two intensities were usually selected. The first featured intensively managed short rotations without any commercial thinning. The second featured a rotation which was approximately two decades longer, but included two commercial thinning entries prior to regeneration. In terms of PNV, the two regimes were nearly identical, but the commercial thinning intensity produced substantially more volume over the entire rotation than the short rotation.

In nearly all runs, both of these intensities were selected to some degree, whether timber or PNV was maximized in the objective function. Scheduling constraints were important in influencing the intensity selection. Short rotations were needed in nondeclining flow runs, usually to provide replacement volume as soon as possible. In departure formulations and when maximum timber (over all periods) objective functions, the rotation with thinning was more often selected. The thinning intensity removed volume in the thins which reduced overall productivity for the rotation, as compared to another thinning intensity which maximized volume over the entire rotation. This later intensity was rarely if ever selected by the model, even in maximum timber runs. Since it contributed minimum volumes in early thins, it was not useful in meeting scheduling constraints and did not contribute to increasing PNV or first decade timber volume.

For the dry site Douglas Fir (CD) group, the managed intensity with commercial thinning was usually selected. The managed short rotation, was not short enough to make a better contribution to meeting scheduling constraints than the longer rotation with thins. Volume produced by the thins did contribute to meeting scheduling constraints. In relatively unconstrained runs, other intensities were rarely selected.

For the CF-CR group, the selection of intensity varied between the one with the highest PNV (natural regeneration in an unmanaged intensity) and the most timber production (reforestation with genetics followed by intensive management with commercial thinning). Usually, the regime selected matched the objective function. The earlier age of 95% CMAI for the unmanaged intensity contributed to its selection. There was also a tendency to select the managed intensity for first and second decade harvests and existing plantations.

Intensities selected for the mountain hemlock (CM) generally varied between either no timber management or the unmanaged intensity. Both harvesting intensities produced volume so late in the planning horizon that they could not affect the solution. Since the unmanaged intensity avoided the costs of precommercial thinning it was preferable in PNV formulations. Curiously, the use of nondeclining flow constraints with PNV objective functions usually assigned all of the mountain hemlock to the timber base. When nondeclining flow constraints were relaxed in departure formulations, substantial acres of this ecoclass group drop out of the timber base. This occurs because harvesting the mountain hemlock in later decades allows harvesting more Douglas Fir volume in the early decades as a result of constraint. With the constraint removed, there is no economic need to harvest the mountain hemlock.

In harvest scheduling, the model sequentially harvested all of the mature volume of the most efficient ecoclass group (CH-CW) first, followed by a complete harvest of mature volume on the ecoclass groups of intermediate efficiency (CF-CR and CD), and last by the least efficient group (CM). This was perceived as unacceptable to the Forest ID team. As a result, upper limits were placed on the share of each ecoclass group which could be harvested in each decade. For some alternatives, there were even minimum constraints which forced a share of each ecoclass group to be harvested in each decade.

The addition of constraints modified the pattern of sequential harvesting in order of the most efficient ecoclass group, but the pattern persisted up to the levels permitted by the constraints. When requirements for minimum harvest were introduced for the mountain hemlock group, acreage was once again removed from the timber base in nondeclining flow runs with PNV objective functions. When an objective function of maximizing volume was used, nearly all of the mountain hemlock was included in the timber base, but volume was not increased appreciably.

Some other types of constraints also affected the types of intensities selected for the various ecoclass groups, although they did not have a substantial impact on the level of timber volume. When either tighter constraints limiting acres harvested or objectives for larger trees in the future were applied, the acres of CH-CW assigned to the short rotation prescription diminished and the longer rotation with commercial thinning increased. Limits on acres harvested in viewsheds had a similar effect and in some cases selected the thinning intensity which maximized timber volume over the long term.

There were also a number of special prescriptions where the variation in the response of ecoclass groups based on efficiency considerations was relatively predictable. One of these was a prescription (Snag habitat) which partially harvested lands to leave residual trees for snag habitat. Constraints in the model required certain levels of snag habitat, for which the snag patch prescription provided the highest level. In unconstrained runs, the snag patch prescription tended to be assigned to the least efficient ecoclass groups (CM and CD). Since this was not spatially feasible, constraints also had to be added to require an appropriate minimum share of each ecoclass group to be assigned to the snag patch.

Another unique prescription was the four part winter range prescription which intensively managed winter range areas to maintain an optimal mix of forage and cover conditions. The four parts consisted of two long rotations (one of 100 and one of 200 years) each applied to 20% of the prescription area; a very short rotation (50-60 years) applied to 50% of the prescription area, and permanent openings from either existing meadows or created openings which applied to 10% of the prescription area. The four part winter range prescription was the only way in which the dry site Douglas fir (CD) lands could be harvested with clearcutting. As a result, the four part prescription tended to be assigned relatively more frequently to dry site Douglas fir lands than other timber intensities. This prescription also permitted the shortest rotations for both the CH-CW and CD ecoclass groups. With this scheduling flexibility the four part prescription was selected in nearly all runs, even those which used maximum timber objective functions in unconstrained situations. Within the prescription, long rotations for cover were usually assigned to the CD ecoclass group, while the shorter rotations were assigned to the more efficient CH-CW ecoclass group. In order to avoid the high costs of reforestation, when permanent openings were created they were more often created out of the CD ecoclass group than the CH-CW group.

REMAINING PROBLEMS

As the Umpqua has moved from plan formulation to plan implementation, there are a number of problems created by the modeling of the ecoclass groups which are becoming an issue in plan implementation. Most often these problems result from the sweeping assumptions made about the ecoclass groups. They also occur as a result of the relatively soft science of ecological mapping and vegetation management. Finally, there is tension between management by ecology versus management for other resources.

Of these the homogeneous classification and management problem is probably the most serious. This is especially true for estimates of timber volume and management practices associated with the CH-CW ecoclass group.

There is a widespread concern that the estimates of standing volume and projections of future volume are incorrect. While most internal and environmental concerns suggest that volume estimates are inflated, industry appellants have argued that the volumes are underestimated. Reviews of site specific estimates of standing volume exhibit so much variation that they are not useful in determining if there is an over or under estimation. Since these volumes form the basis for estimating allowable sale quantity and timber targets, they are a particularly important factor in directing forest management. The greatest concern is that an overestimation of timber volume leads to a situation where more acres are harvested than projected by the model. Plan standards and guidelines cannot be met and future ability to sustain production levels is threatened.

The other problem is the determination of harvest methods. A basic sequence of harvest methods was assumed in modeling each ecoclass group. It is now clearly emphasized that the determination of harvest methods must be made in a site-specific project analysis. The Forest Service is also moving to reduce the magnitude of clearcutting. Already, there are indications that the sequences of harvest methods programmed in FORPLAN for each ecoclass group are not appropriate. A mixture of several methods would be more appropriate. On the other hand, the modeling of each ecoclass group defines an "implicit" guideline for selection of harvest method since it is the basis of calculating allowable sale quantity. Changing the harvest method from that modeled in FORPLAN will require added documentation and effort. Also since clearcutting removes the total amount of standing volume, use of any other harvest method which harvests less tends to impose on the District a need to harvest more acres to make up for the reduction of volume.

Identification of ecological land units remains as much an art as a science. The Umpqua relied on interpretation of aerial photography to map its ecoclass groups. Identifying the ecoclass groups in this manner relies on professional judgement. Determining climax ecoclass while the area is occupied by transitional vegetation relies even more heavily on this judgement. More subtle characteristics of ecological land units contained in the vegetative understory may be very difficult to identify through aerial photography and site specific evaluations may be needed. The mapping of the Umpqua by ecoclass groups has been questioned by a number of outside reviewers. Mapping of the Umpqua by ecological series and plant association has begun. This promises to be a substantial and expensive undertaking, likely to be subject to critical review.

While management through ecological land units was one of the basic building blocks for developing the Umpqua's land management plan, its importance was limited in dealing with other resource questions. At the outset of the planning process, the forest sought to relate most of its central resource questions to the ecoclass groups. It simply did not work. Recreation, watershed, fisheries, and big game resource questions did not relate well to situations related to ecoclass groups. These resources required identification of other land parameters (recreation areas and viewsheds, soil types and drainages, riparian areas, and winter ranges) in order to address their issues. Only timber management intensities and tracking of habitat for wildlife indicators related well to the ecoclass groups.

Since the primary focus of the model has been on vegetative management with an emphasis on determining the highest level of ASQ, emerging changes since the initial formulation of the model are not represented in the model. At the outset of the planning process, recommendations from resource specialists for modeling their resources tended to avoid reducing timber harvest levels. Actual resource constraints introduced into the model have become standards and guidelines in the Forest plan. However, specialists are also preparing recommendations for site specific project evaluations which go beyond the plan standards and guidelines. Often the effects of these recommendations have never been estimated with the model. District personnel, aware that their project analyses are likely to be reviewed in court are reluctant to select projects which are inconsistent with these recommendations even if they are consistent with plan standards and guidelines. This situation is likely to lead to a systematic underachievement of timber outputs relative to the assumptions of the plan.

RECOMMENDATIONS FOR THE FUTURE

The central tension in national forest management focuses on production of commodity outputs (primarily timber) and conservation or preservation of forest vegetation central to other resource uses. Recent modeling of national forests has focused on maximum commodity production subject to a defined set of environmental constraints. Forest plans now serve as the basis for determining timber targets, but the harvest methods and resource effects on which they are based must be revaluated on a site specific basis. Rather than resolving or reducing this central tension, this approach further exacerbates it. As long as the predominant direction from Congress focuses on the quantity of timber to be sold, while ignoring the consequences of the practices needed to produce this timber, this central tension will persist.

A more balanced approach focuses on more carefully defining a set and quantity of vegetative practices and other management activities needed to produce the full set of multiple use benefits. Congress then focuses on funding these levels of activities with feedback and evaluation of the results produced. Forest plans can serve as the mechanism to define the level of these practices, with flexibility for amendment and revision. Current forest plans are not very far from serving as a basis for this future. The primary change is an added emphasis on vegetative management practices and a reduced emphasis on quantifying timber volume.

An emerging view of the analysis in the first round of national forest planning is that FORPLAN models were too complex and produced unworkable solutions. As FORPLAN results are disaggregated, these problems become apparent. One paper presented at this conference demonstrated this problem for several forests in the Pacific Northwest.[7/] Another paper indicated that the exploitation of allowable cut effect over time, leads to a systematic overestimation of timber outputs.[8/] Yet timber volumes remain the most meaningful result of FORPLAN models, as they provide the basis for determining the "hard" timber target. Only a softening or elimination of the timber target is likely to create a situation where proper vegetative management comes first, and getting the cut out comes second.

Use of ecological land units offers promise as a basis for developing vegetative management practices appropriate to particular ecological communities. Greater understanding and accuracy can result in identifying the effects of these practices. However, we have a long way to go in developing information which is meaningful and scientific. While ecological series and plant associations have been identified for southwest Oregon, they need to be mapped. All that presently exists in estimating the response of these associations to vegetative management, is the recommendations of ecologists and general data such as that used by the Umpqua. Information measuring the effects of vegetative practices with links to these associations needs to be compiled and analyzed to provide a scientific basis for better forest planning and management. Developing such information will take years, if not decades to clearly establish.

If this type of information can be collected, models will be needed which can simulate the response of a wealth of indicators to activities on a large number of detailed land units. With data for each plant association, watershed, viewshed, soil type, etc., better estimations and determinations can be made of future outputs and forest conditions. The general view of the first round of national forest planning was that the analytical capabilities of FORPLAN were far beyond the data available for the model. The next round of forest planning is likely to change this by having more detailed data than can currently be analyzed by models available today. As this paper clearly shows, the introduction of more detailed land data into FORPLAN also requires the addition of more constraints to control how the model schedules vegetative practices for each land stratum. Adding more detailed stratifications

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[7/] Merznich, Spatial Disaggregation Process and map display of feasible harvest schedules for small drainages, 1991

[8/] Daugherty, Dynamic Inconsistency in Forest Planning, 1991 will only lead to more complex linear programming models.

Alternatives are to develop analytical tools capable of simulating the effects of a program of vegetative management on all of the identified strata or the establishment of a hierarchical system for planning. This kind of a hierarchical system captures the site-specific detailed information at a project or planning area level, then collapses this detail for consideration at a higher level.[9/]

The promise of the science of ecology, is that national forests can do better in meeting multiple use demands while avoiding the destruction of important plant and animal communities. Ecology represents a system for understanding forest interactions over long periods of time. Much additional research is needed to complete this system for even a single forest. Even with such information, forest planners and managers will continue to face difficult decisions in meeting demands for forest uses. A change in emphasis, to manage vegetative communities, rather than produce outputs may help to reduce the central tension straining our national forest system.

9/ Connelly, Area Based Forest Planning, 1988.

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INTEGRATION OF ECOLOGICAL CLASSIFICATION AND VEGETATION MANAGEMENT INVENTORY SYSTEMS FOR ANALYSIS AND PLANNING [1]

James B. Hart, Jr.
Larry A. Leefers
David T. Cleland[2]

Abstract.-- Ecological land maps with interpretations and forest type maps with associated data were integrated for a 10,033 acre area comprised of extensive red pine plantations, native upland hardwoods and aspen, and minor acreages of swamp conifers. Experiences integrating ecological and type maps, and developing integrated information for analysis are discussed.

Keywords: ECS, VMIS, Area Analysis, Opportunity Area

INTRODUCTION

Historically, forest land management relied on forest cover type maps, forest inventory data, county soil survey maps and silvicultural prescriptions for timber management planning. Management decisions were made concurrently for the other multiple use values. Over the last decade greater emphasis has been placed on integration of information and analysis to prepare forest wide management plans, particularly within the USDA Forest Service. The greater availability of computers coupled with ecological data analysis, systems analysis and geographic information system (GIS) techniques are important factors that coincide with public demand for new perspectives in management.

The Huron-Manistee National Forests, North Central Forest Experiment Station and Michigan State University have been involved in utilizing these new techniques and analysis approaches since 1983. The 3 basic initiatives to which this paper relates are 1) Ecological Classification System (ECS), and associated mapping and interpretations, 2) Vegetation Management Information System (VMIS) and associated type mapping and inventory information, and 3) integration of maps and information for analysis of a 10,033 acre area. These 3 initiatives were used by an interdisciplinary team on the Cadillac Ranger District to conduct systems analysis at a more comprehensive level than done historically.

[1] Presented at the Symposium on Systems Analysis in Forest Resources, Charleston, SC, March 3-9, 1991.

[2] Associate Professors of Forestry, Michigan State University, East Lansing, MI; and Forest Ecologist, Huron-Manistee National Forests, Cadillac, MI.

Land management agencies are now involved in forest resource planning and systems analysis over a range of scales including stands, compartments, opportunity areas, districts, forests, states and regions. Several questions arise regarding systems analysis at these scales including: 1) what technologies can be effectively used to handle information and perform analyses, 2) what technologies and information will be useful at various scales, 3) how can existing maps and information databases be combined for analysis, and 4) what will be the time and costs for integration of maps and databases.

Specific objectives of this paper are to briefly describe the ECS and VMIS systems, document techniques used to prepare an integrated map and database of current and potential conditions, present results, and discuss how this technique can be used for planning and management of forestlands.

ECOLOGICAL CLASSIFICATION SYSTEM (ECS)

The Forest Service ECS evaluates, classifies, maps and interprets ecological information on forestlands that are useful for management. Important characteristics of ECS include 1) use of multiple factors, 2) incorporation of regional climate effects, 3) recognition of geomorphic landform geology, physiology and hydrology influences on local ecology, 4) use of natural vegetation, 5) incorporation of soil and groundwater information to ecologically classify local ecosystems, and 6) provision for mapping landscape ecosystems at large to small scales for planning as well as stand prescriptions.

Forest management is increasingly being based on biotic and abiotic evaluations at multiple scales. The ECS, since it maps forestlands based on potential natural vegetation and abiotic land characteristics, is effective for predicting changes in vegetation, animal habitat and animal populations over time intervals of decades and probably centuries (Bailey 1982).

The ECS is a hierarchical system (Miller 1978). Climate has uniform influences at a relatively broad scale (Bailey 1988, Denton and Barnes 1988), with hydrology influences at a moderate scale. Local systems are further characterized by the ecosystems' components of vegetation and soils at scales of 5 acres or more, and are called Ecological Land Type Phases (ELTP) (USDA Forest Service 1982).

An ELTP is best described as a delineated area of land with predictable climatic, geologic and hydrologic relationships (Hart 1988) and with known potential natural vegetation and soils (Cleland et al. 1985, 1988). These units also have predictable successional pathways (Host et al. 1987), and are the map unit of appropriate scale for integration with stand maps. Therefore, they provide a useful building block for ecologically-based analyses (Barnes et al. 1982, Leefers et al. 1987).

VEGETATION MANAGEMENT INFORMATION SYSTEM (VMIS)

This system is a computerized database used by the Forest Service Eastern Region to manage information routinely collected on compartments and stands. It is part of a program which primarily evaluates, classifies and maps forest overstory vegetation types and contains important information for stand silvicultural decisions. The delineated stands reflect areas of uniform current vegetation. This current condition occurs due to recent management as well as natural ecological processes. Periodic re-evaluations and updates are made to the stand maps and inventory so that they always map current conditions and supply information reflecting past management and stand growth effects. The VMIS is unconcerned with climate, geology, soils, hydrology, or many ecological characteristics.

INTEGRATION OF ECS AND VMIS INFORMATION

Interdisciplinary planning requires integration of various types of data and information. To provide a basis for sound ecologically-based forest planning, VMIS and ECS information must be integrated. This can be accomplished in a rudimentary fashion by visually comparing separate maps and tabular summaries or by systematically combining both sets of information on a map and in a database. Then the information is more fully integrated and accessible.

By integrating this information, it is possible to define subunits of the forest (e.g., stands) and their current condition, and to predict vegetative changes and possible future conditions. This, of course, provides a foundation for analyzing various management alternatives for that subunit.

In the Eastern Region, national forests have delineated opportunity areas (OAs) which generally range from 5,000 to 10,000 acres in size. These OAs are contiguous areas for which an integrated resource analysis is performed. The remainder of this section presents characteristics of the Kellogg Block OA, methods used to develop an integrated VMIS/ECS map and database, and results of the integration work. These results would be followed by the OA analysis.

Kellogg Block Opportunity Area

The OA upon which this report focuses is known locally as the Kellogg Block. It is located in the Cadillac Ranger District of the Huron-Manistee National Forests. Much of the area was forested with mixed hardwood stands prior to the turn of the century. Following a period of intense harvesting, a large portion of the area was briefly used for agriculture, abandoned, and then planted to red pine during the Civilian Conservation Corps era. Other portions of the area have regenerated to natural hardwood stands following the turn-of-the-century harvesting. The Kellogg Block has been managed under multiple use objectives since the late 30's.

Initial 1988 data for the OA of 10,033 acres indicated the Kellogg Block had 21 different forest type classes, 16 different ELTP classes, and 361 delineated stands. Current vegetation consisted of second growth native upland hardwoods, aspen, significant areas of planted red or jack pine, and minor acreages of swamp conifers. A unique feature of the Kellogg Block is the large acreage with red pine which was planted by the Civilian Conservation Corps.

Methods

The chronological approach used was as follows:

A. STAND TYPE AND ELTP MAP RECONCILIATION

1. Procure USFS compartment/stand maps (black on white copies, 2"/mi).
2. Procure ECS Ecological Land Type Phase (ELTP) maps (on 4"/mi CIR photos).
3. Prepare composite ELTP maps at 4"/mi and reduce to 2"/mi acetate transparencies.
4. Systematically overlay ELTP transparency on stand maps and ocularly estimate percentages of stand areas on various ELTPs. Up to 5 ELTPs were identified for a stand. Estimates were made to 5 percent using dot grids and soil mottling charts as guides. Time required and characteristics of each compartment were recorded.

B. DEVELOP ELTP DATABASE ON MICROCOMPUTER

5. Enter compartment, stand, ELTP codes and ELTP percentages into a microcomputer database.

C. DEVELOP CURRENT VEGETATION (VMIS) DATABASE ON MICROCOMPUTER

6. Perform VMIS queries of appropriate stand and management history fields on the USFS Data General computer system and obtain ASCII text file output.
7. Download the stand and history query files in ASCII format to a mini-computer and use a BASIC program to remove blank lines, remove comment lines, rejoin word-wrapped lines, and write the file to a reformatted ASCII file. This process took approximately 45 minutes for 10 compartments, 361 stands, 10,033 acres.
8. Import the VMIS ASCII file into a separate database table.

D. COMBINING OF VMIS AND ELTP MAPS AND DATABASES

9. Database procedures were used to systematically compare the ELTP and VMIS databases.
10. Compartment and stand VMIS data were reconciled with the ELTP data using the VMIS data as a base. Stand number assignments to roads were checked.

11. Updated silvicultural examination data for 70 stands were obtained and entered into the VMIS database. This was necessary because the updating was not completed on the USFS Data General System prior to running the original query.

12. Database procedures were used to sort, list and analyze the stands with 2,3,4 or 5 ELTPs to determine which stands had very different ecological types. Areas of distinctly different ecological types less than 5 acres were ignored. Areas with similar ELTP were retained and recoded with a conservative assignment of ecological type.

13. A database procedure was used to transfer ELTP data and ELTP adjustment notes to the VMIS database table.

14. Database procedures were written to compare VMIS forest type and site indices to stand ELTP data. Those stands with major discrepancies (e.g. forest cover type impossible for a given ecological type) were reviewed by USFS personnel to resolve differences.

15. The combined VMIS-ECS database was restructured into 1 information source.

E. INTERROGATIONS AND LISTINGS OF VMIS/ELTP DATA

16. Summaries of acres by ELTP and Forest Service type were prepared.

17. Sorted listings of stand condition by Forest Service type, ELTP, basal area, age and DBH (Diameter Breast Height) were prepared for use in developing stand management alternatives.

18. Groups of forest cover types and ELTPs were developed for analyses.

Original plans were to utilize microcomputer and/or mainframe geographic information system (GIS) programs to perform the spatial analysis of ELTP and stand maps (i.e., reconciliation). Due to the developmental nature of the project and unavailability of previously digitized data, the decision was made to not use GIS techniques on this relatively small area of 10,033 acres with 361 stands. However, this technology is developing rapidly and GIS analyses would be very applicable for future efforts of this type.

Results

The 18 steps listed above were completed at widely interspersed times over a several month period as time permitted and the information needs were defined in the interagency interdisciplinary planning and analysis effort.

The first 4 steps were relatively simple to perform and required a minimum of time once the maps and overlays were obtained. The actual time spent performing step 4 for the 10 compartments in the 10,033-acre opportunity area was 5 hours.

Of the 361 stands tabulated in step 5,

98 were areas with 2 ELTPs,
15 were areas with 3 ELTPs, and
2 stands had areas of 4 ELTPs.

Sixty-eight percent (246) of the stands were delineated on 1 ecological type (over 95 percent of stand area and less than 5 acres of ELTP inclusion). Of the 31 percent with 2 or 3 ecological types, many stands occurred on ELTPs which would perform similarly with management.

Following input of the VMIS query into a database (steps 6-10), the joint interrogation of the 2 data bases indicated that some stands existed in VMIS but were not identified on the maps. Discussions with District personnel determined some stands were roads while other discrepancies were due to data updates. These were corrected in step 11.

A listing of all the 115 stands with more than 1 ELTP for the stand was prepared and reviewed with District personnel. The result was a set of 49 changes to be made in the VMIS database. Changes involved splitting some stands because the ELTPs were very different and significant acres were involved, correcting some ELTP assignments based on field observations and professional knowledge, and ignoring small areas of similar ELTP or small acreages within a stand. During steps 12-15, changes can be summarized as follows:

6 new stands delineated and stand data entered
7 stands enlarged in size
15 stands decreased in size
3 stands assigned new Forest Service types
23 stands assigned new ecological types
6 stand adjustments involved roads.

The total area involved in the adjustments was 502 acres, or 5 percent of the OA. Adjustments between 2 stands involved 289 acres (2.8 percent of OA). Most changes involved 5-20 acres per stand. These changes include both VMIS/ECS integration and VMIS data updating effects. Table 1 presents the areas, number of ELTPs and stands, and stand sizes for compartments of the Kellogg Block.

Based on planning process decisions, the Forest Service cover types were grouped, the ELTPs were grouped, and a cross-tabulation between Forest Service cover type and ELTP groups was prepared (table 2). These tabular data and age class listings were the basis for preparing cover type-ELTP-age clas groups to be used in the OA planning and analyses portion of the project. The principal information made available from VMIS and ECS for planning are presented below:

Source	Information
VMIS	Compartment number
	Stand number
	Size of stand in acres
	Land use code
	Forest Service cover type
	Size density class
	Total basal area
	Mean DBH
	Operability
	Primary species code
	Site index for primary species
	Productivity growth for primary species
	Year of origin
ECS	Land type association (larger ECS map unit)
	Ecological land type phase (ELTP, detailed ECS map unit)
	Remarks noted during VMIS/ECS reconciliation and integration
	Potential natural vegetation types
	Mean annual tree increment (cf/ac/yr)
	Composition of regeneration in unmanaged stands

Site index of major commercial species
Understory plant community types
Coverage and frequency of understory and ground flora
Probable successional pathways
Soil series and soil interpretive information
Presence of textural substratum
Presence of subirrigation
Slope class

Table 1.--The area, number of ELTPs and stands, and stand sizes in compartments of the Kellogg Block Opportunity area.

COMPARTMENT	TOTAL AREA	ELTPs	STANDS	STAND SIZE MEAN	STAND SIZE MAXIMUM
		Number		Acres	
96	869	4	18	48.3	354
97	1843	4	54	34.1	422
101	967	5	52	18.6	131
102	1361	6	62	22.0	229
103	1985	4	26	76.3	732
106	922	8	53	17.4	76
107	536	6	30	17.9	53
109	407	4	20	20.4	79
110	202	6	13	15.5	45
111	941	3	39	24.1	182
10	10033	16	367	27.3	732

Table 2.--Summary of acres for U.S. Forest Service cover type groups occurring on ELTP Groups for the Kellogg Block OA.

ELTP GROUP	Types: Aspen-2 Birch	Jack Pine	Oak-Pine	Red-Wh. Pine	Spruce-Heml.	North Hdwd.	Oak	Low Wet Hw-Con	Non-Forest	TOTAL ACRES
	--------Area by Forest Service cover type (acres)--------									
Codes:	91,93[a]	1	48,49	2,3	4,5,16	81,82 84,85	53,55 59	14,18 76,71	97,98 99	
20,21,22[b]	890	646	49	4810	4	12	241		177	6829
23,25	10			68					2	80
33,35	871			413		254	274		31	1843
37	48									48
40	88	69		290		63			3	513
43						2		2		4
45	131	16		64		280	20		20	531
61,62								11	1	12
64						6		5		11
74	75							68	4	147
81									15	15
TOTAL	2113	731	49	5645	4	617	535	86	253	10033

a/ Numbers are Forest Service codes for cover type.

a/ Numbers are Forest Service codes for ecological land type phases.

CONCLUSIONS

During interdisciplinary team analysis of the Kellogg Block area, it was not difficult or time consuming to obtain compartment/stand maps, VMIS information, ELTP maps, and ECS information. Reconciliation of stand type boundaries and current condition VMIS information with ELTP delineations and ecological potential information was also relatively easy and not time consuming. The 18 step reconciliation and integration procedure used in this study could be implemented on larger analysis areas using GIS capabilities. The combined map and associated database give location, size, current characteristics and projected future conditions of lands.

The 367 stands, 16 ecological land type phases, and 21 Forest Service types occurring in this 10,033-acre area were sufficiently complex to define the procedures, relative times required and magnitude of changes resulting from reconciliation and integration of VMIS and ECS information. Twenty-seven percent of the stands occupied lands with 2 ELTP classes, 4 percent had 3 ELTP classes and 1 percent had 4 ELTP classes. Relatively few of the stand delineations were revised. By grouping ELTPs judged to have similar ecological potentials, and accepting boundary slivers which were less than 5 percent of stand size, only 49 changes were made in the stand maps and associated VMIS database. The reconciliation process identified several errors in type assignments in the VMIS database, and the VMIS database identified several stands which were mapped with incorrect ecological types. Some "stands" were roads. In most instances, stand boundaries were in close agreement with ecological landtype boundaries and map and database revisions were not made because boundary differences involved less than 5 acres.

The process resulted in a single map with 1 linked database of pertinent information for management. The map and linked database include information on current conditions and greatly increased information for projecting future conditions with management alternatives. The information was used for developing and analyzing management alternatives.

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LATLONG[1]

John W. Armstrong[2] and Gerald C. Franc[3]

LATLONG is a commputer program that allows natural resource managers to easily convert township, range, section and quarter section to latitude and longitude in degrees, minutes and seconds.

The square system of public land survey found throughout most mid-western and western states originated as a recommendation by a committee on the subject chaired by Thomas Jefferson. The recommendations of the committee became law with the passage of a Public Land Survey Bill in 1784. Modifications to the original law were made in 1796 and 1800. Since then the basic provisions of the law have remained virtually unchanged.

Following the procedure specified in the public land survey law, a north-south principle meridian is established for each state. At some convenient point near the center of the state, the meridian is intersected by an east-west running baseline. In Idaho, the principle meridian is identified as the Boise Meridian. North-south running Auxilliary Guide Meridians are established at 24 mile intervals east and west of the Principle Meridian. Similarly, east-west running Standard Parallels are established at 24 mile intervals both north and south of the Baseline.

The 24 mile squares deliniated by the meridians and parallels are further sub-divided into squares, 6 miles on a side, called Townships. Townships are numbered consecutively from the intersection of the Principle Meridian and the Baseline and are further identified by their direction north or south of the Baseline and east or west of the Principal Meridian.

Townships are divided into 36 squares, 1 mile on a side, called Sections. The Sections are numbered in an east-west direction starting with 1 in the northeast corner and continuing in a serpentine pattern to 36 in the the southeast corner. Each section is 640 acres in size. Sections are futher subdivided into half sections, quarter sections or even halves or quaters of quarter sections by describing the appropriate coordinates; ie, north 1/2, NE 1/4, SE 1/4 of the NW 1/4 and so on. Section and quarter section corners are monumented on the ground as a part of the original public land survey. A particular spot on the ground is defined by Township # N or S, Range # E or W, section #, and Quarter Section with additional descriptive subdivision as necessary.

Irregularities in the square pattern are created when offset corners are established to correct for curvature of the earth. Errors in the ground surveys also result in irregular section lines.

While the implementation of the Public Land Survey system may seem a bit involved and although some errors have been made in surveying and monumenting the corners, the system has been a huge benefit in that ownership patterns are much more uniform and systematic than is the case in the original 13 colonies where the system of metes and bounds was used to survey land.

A disadvantage of the Public Land Survey system is the irregularity caused by having the system implemented state by state, by numbering townships in all four directions from the intersection of the Principle Meridian and the baseline, and by numbering the sections in a serpentine manner. Such a system makes it difficult to define one point on the ground in relation to another point, or to other points, on the ground. This causes problems in tree improvment work where breeding is done within biologically defined breeding units and where material may be moved among states or even among foreign countries.

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2/ John W. Armstrong, Computer Programmer Analyst, USDA-Forest Service, 1221 South Main St. Moscow, ID 83843

3/ Gerald C. Franc, Selective Breeding Specialist, USDA-Forest Service, 1221 South Main St., Moscow, ID 83843

A more suitable method of locating points on the ground, and one that is recognized world wide, is to use Angular Projection. This system is based on the fact that there are 360 degrees in a circle and that the earth is round. Any point on the earth can be uniquely defined in terms of degrees, minutes and seconds by determining its vertical and horozontal angle with the center of the earth. These vertical and horozontal angles are called Latitude and Longitude.

On a map, latitude lines are a series of lines circling the earth that are parallel to and north or south of the equator. They are numbered from the equator to the poles with the equator being 0 degrees and the poles being 90 degrees. Longitude lines are a series of lines perpendicular to the equator and running from pole to pole. Zero degrees longitude is a line running through Greenwich, England. Longititude lines are numbered from 0 to 180 degrees in both an easterly and westerly direction from Greenwich.

Forest and District maps used for field work incorporate the public land survey system. Sections lines are marked on the ground. Most field work is tied very closely to the public land survey system. As a result, the locations of plus-trees and other sources of genetic material for tree breeding programs in the Northern Region are defined in terms of section, township and range. It would be very beneficial, on occasions, to be able to conveniently and quickly convert section, township, and range to latitude and longitude. Other natural resource management disciplines would also benefit by such a capability, but an extensive pole of State and Federal agencies in our area of work failed to turn up anything more than just a few localized efforts towards this end.

Enter "LatLong", the program to do township/ range/section conversion to latitude/longitude. This program, developed by the R-1 Tree Improvement staff at the Forestry Sciences Lab in Moscow, Idaho, translates the values via a resident datafile of township midpoints plotted in terms of latitude/ longitude.

Each dataline in the resident datafile consists of a township and range, and the latitude and longitude of its midpoint in degrees, minutes and secondse. When a particular location is described by the public land survey system, Latlong matches the township with the latitude and longitude of its center point and then adds or subtracts degrees of latitude and longitude to move the pointer to the section and quarter section described.

To make Latlong operational for a particular geographic area, such as a national forest for example, one must first develop the resident datafile of township midpoints. This can be done by hand by using the latitude and longitude scales on the margin of a forest map, but the job is faster and simpler if a digitizer is used.

Latlong has accuracy to the quarter-section at best, if the user specifies it; otherwise, the pointer goes to the middle of the section specified. Currently, it does not translate the other way around; that is, from lat/long to township/range/section.

Input for this program can be interactive (one translation at a time) or batch (from a datafile in the operating system). Output is screen-displayed, in report form, or as a datafile for SAS MapGraphics.

Currently, it runs only on Data General equipment but is written in generic Fortran (largely hardware free) so that it can be micro ported in the future.

MULTIVARIATE STOCHASTIC SIMULATION

WITH SUBJECTIVE MULTIVARIATE NORMAL DISTRIBUTIONS[1]

Peter J. Ince[2]
and
Joseph Buongiorno[3]

Abstract.–In many applications of Monte Carlo simulation in forestry or forest products, it may be known that some variables are correlated. However, for simplicity, in most simulations it has been assumed that random variables are independently distributed. This report describes an alternative Monte Carlo simulation technique for subjectively assessed multivariate normal distributions. The method requires subjective estimates of the 99-percent confidence interval for the expected value of each random variable and of the partial correlations among the variables. The technique can be used to generate pseudorandom data corresponding to the specified distribution. If the subjective parameters do not yield a positive definite covariance matrix, the technique determines minimal adjustments in variance assumptions needed to restore positive definiteness. The method is validated and then applied to a capital investment simulation for a new papermaking technology. In that example, with ten correlated random variables, no significant difference was detected between multivariate stochastic simulation results and results that ignored the correlation. In general, however, data correlation could affect results of stochastic simulation, as shown by the validation results.

INTRODUCTION

Generally, a mathematical model is used in stochastic simulation studies. In addition to randomness, correlation may exist among the variables or parameters of such models. In the case of forest ecosystems, for example, growth can be influenced by correlated variables, such as temperatures and precipitations. Similarly, in complex forest product technologies, predicted production, or returns, may depend on several engineering and economic variables, some of which may be correlated. However, in most applications of Monte Carlo simulation in forestry or forest products, data correlation has been largely ignored (e.g., Engelhard and Anderson, 1983).

Stochastic simulation is a practical approach to prediction because estimating a likelihood distribution for many variables in a model is often easier than estimating their precise values. In this paper we shall first review classical stochastic (Monte Carlo) simulation techniques, then suggest a method to take into account the subjective correlations among variables, validate the method, and apply it to a specific case study.

MONTE CARLO TECHNIQUE

The Monte Carlo simulation technique utilizes three essential elements: (1) a mathematical model to calculate a discrete numerical result or outcome as a function of one or more discrete variables, (2) a sequence of random (or pseudorandom) numbers to represent random probabilities, and (3) probability density functions or cumulative distribution functions for the random variables of the model.

The mathematical model is used repetitively to calculate a large sample of outcomes from different values assigned to the random variables. The sequence of random numbers is generally drawn independently from the uniform distribution on the unit interval (0, 1) and thus represents a sequence of so-called uniform deviates. The "distribution" of a continuous random variable refers to the probability of its occurrence over its domain or "distribution space."

The distribution of a random variable is represented mathematically by its probability density function, which gives the probability that the random variable will occur within any subspace of the distribution space. Examples of probability

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[2] USDA Forest Service, Forest Products Laboratory, Madison, WI 53705.
[3] Department of Forestry, University of Wisconsin, Madison, WI 53706.

density functions include the uniform, triangular, exponential, gamma, beta, Weibull, lognormal, and normal distributions (e.g., see Fishman, 1973, pp. 200-214). Probability density functions for multivariate distributions cover the case in which two or more random variables are correlated with one another, including for example the multivariate normal distribution (Hogg and Craig, 1978, p. 409).

The distribution function (or cumulative distribution function) for a continuous random variable is the probability that the random variable will be less than or equal to a given value, x, within the distribution space (Hogg and Craig, 1978, p. 31). The cumulative distribution function is the integral of the probability density function over the interval from negative infinity to x.

Because all probabilities range from 0 to 1, the cumulative distribution function is bounded by the unit interval (0, 1). Based on this observation, one can transform a sequence of independent uniform deviates into a sample of pseudorandom variates that correspond to a specified probability distribution.

For example, the method of Box and Muller (1958) transforms independent uniform deviates U into standard normal variates z of mean zero and variance 1 by the formula

$$z = (-2 \log U)^{1/2} \cos 2\pi U \tag{1}$$

In addition, techniques are available for transforming standard normal variates into random variates that correspond to a specified multivariate normal distribution; i.e., with a specified vector of mean values and specified variance-covariance structure (Scheuer and Stoller, 1962).

In summary, in Monte Carlo simulation, a pseudorandom number generator is used to produce a sequence of independent uniform deviates, the uniform deviates are transformed into random variables or "sample data" for random variables in a mathematical model, and the "sample data" are then used in the model to compute a corresponding "sample" of outcomes from which the simulated outcome distribution can be inferred.

SIMULATIONS BASED ON MULTIVARIATE NORMAL DISTRIBUTION

Few studies deal with multivariate stochastic simulation with correlated variables. Such studies include methodological reports (e.g., Oren, 1981; Shachter and Kenley, 1989) and some applications, including those by Kaya and Buongiorno (1989), Bianchi et al. (1978), Van der Knoop and Hooijmans (1989), and Schwert (1989). There appear to be few published examples of multivariate Monte Carlo simulation techniques in risk analysis studies or decision theory (Hertz and Thomas, 1983 and 1984; Merkhofer, 1987) or in the areas of forestry or forest products. Nevertheless, techniques have been described in the literature that consider covariance or joint probability distributions among random normal variables in Monte Carlo simulation. The introduction of correlation significantly increases the complexity of generating random variates. Instead of generating each variate independently as in the conventional simulation, sample vectors of pseudorandom data must be generated such that all the variates exhibit the appropriate covariance structure.

An early multivariate simulation technique, based on the multivariate normal distribution, was developed by Scheuer and Stoller of the Rand Corporation (Scheuer and Stoller, 1962). The Scheuer and Stoller algorithm presupposes estimates of (1) the covariance matrix Σ containing the variance and covariances of the normally distributed random variables (e.g., see Hogg and Craig, 1978, pp. 408-409) and (2) the vector of their means μ. The algorithm is based on the theorem (Anderson, 1958, p. 19) that if $\mathbf{x}$ is an n-component vector of variables with a multivariate normal distribution (i.e., $\mathbf{x}$ is distributed as $N(\mu, \Sigma)$, where μ is the vector of mean values and Σ is the covariance matrix), then a vector of variates $\mathbf{x}$ that correspond to the multivariate normal distribution of $\mathbf{x}$ is given by

$$\mathbf{x} = \mathbf{C}\mathbf{z} + \mu \tag{2}$$

where $\mathbf{C}$ is the Cholesky Factor of Σ and $\mathbf{z}$ is an n-component vector of independent standard normal variates. The matrix $\mathbf{C}$ is the unique lower-triangular matrix such that

$$\mathbf{CC}' = \Sigma \tag{3}$$

Thus, finding $\mathbf{C}$ (Cholesky factorization) is equivalent to finding the "square root" of the covariance matrix.

For the purpose of Monte Carlo simulation, a pseudorandom vector $\mathbf{z}$ can be derived by the method of Box and Muller from a sequence of uniform deviates, as from Equation (1), such that $\mathbf{z}$ corresponds to independent pseudorandom variates drawn from the standard normal distribution $\mathbf{N(0, I)}$, having a mean vector of $\mathbf{0}$ and covariance matrix equal to the identity matrix $\mathbf{I}$.

Thus, once the Cholesky matrix $\mathbf{C}$ has been derived from the covariance matrix Σ, repeated application of Equation (2) to successive random vectors $\mathbf{z}$ yields a large sample of independent pseudorandom data vectors, each vector corresponding to an independent observation of the variables from the specified multivariate normal distribution. Computer programs are available to obtain the Cholesky Factor of a matrix, such as the programs in IMSL MATH/LIBRARY (IMSL, Inc., 1987).[4]

Requirement of Positive Definiteness

The algorithm of Scheuer and Stoller requires that the matrix $\mathbf{C}$ in Equation (3) be computable. Previous authors have noted that this Cholesky factorization or triangular decomposition of the symmetric matrix Σ is possible if and only if Σ is positive definite (see Farebrother and Berry, 1974). This may not be the case for a covariance matrix that has been established by judgement rather than from real data. Consider, for example, the covariance matrix

$$\begin{vmatrix} 1.0 & 0.99 & 0.99 \\ 0.99 & 1.0 & -0.99 \\ 0.99 & -0.99 & 1.0 \end{vmatrix}$$

This matrix is symmetric, and it might seem to be an acceptable covariance matrix for a three-dimensional set of variables (x_1, x_2, and x_3). The matrix would indicate that x_1 is very highly correlated with x_2 and x_3, while x_2 is strongly negatively correlated with x_3. However, if the vector $\mathbf{a}$ is defined as (-1, 1, 1) and the variable $\mathbf{y}$ is defined as $\mathbf{y} = \mathbf{a'x}$ (a linear combination of random variables, itself a random variable), then var(y) = $\mathbf{a'}\Sigma\mathbf{a}$. But this leads to a negative variance: var(y) = -2.94, and thus the matrix Σ cannot be a representation of the covariance structure of $\mathbf{x}$. For the quadratic form $\mathbf{a'}\Sigma\mathbf{a}$ to be positive, for any non-negative $\mathbf{a}$, Σ would have to be positive definite, by definition (Searle, 1971, p. 34).

This requirement of positive definiteness creates a problem for multivariate stochastic simulation whenever distributional parameters are obtained subjectively (e.g., from expert opinion or from various sources via statistical inference) because it is possible to propose a subjective "covariance"

[4] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

matrix that seems reasonable but that is actually not a true covariance matrix because it is not positive definite. As the number of correlated variables increases, the problem tends to become more severe. At the same time, the requirement of positive definiteness provides a natural test of the proposed covariance matrix. Once positive definiteness is satisfied, one is confident that the covariance matrix used in the simulation does indeed represent a relationship that would be possible among real data.

Subjective Definition of Multivariate Normal Distributions

As we have indicated, the key problem in doing multivariate stochastic simulation with judgmental data is to define a covariance matrix Σ that is positive definite. Oren (1981) provided one method (conjugate directions) for solving the problem. Oren's method was based on construction of a matrix of the means and conditional means of the variables of interest. In the process, he suggested a way of ensuring that the covariance matrix of the variables would be positive definite.

Though insightful, Oren's method seems difficult to apply because of the lack of a practical method to estimate all the conditional expectations needed. Shachter and Kenley (1989) did offer a systematic approach to estimating conditionality parameters (the method of the "Gaussian influence diagram") that could then be used to derive a covariance matrix, but the technique seems complicated and requires the estimation of parameters that cannot be explained easily to non-statisticians.

Nevertheless, one aspect of Oren's approach was extremely useful from a practical standpoint, when combined with the Scheuer and Stoller technique. Oren's method of restoring positive definiteness to a "covariance matrix" (by increasing the variance of certain parameters while keeping the conditionality or covariance structure constant) provided the basis for the modified Scheuer and Stoller technique.

Modified Scheuer and Stoller Technique

The Modified Scheuer and Stoller technique begins with estimates of the familiar partial correlation coefficient statistics. The complete matrix of correlation coefficients for n random variables is

$$\mathbf{P} = \begin{bmatrix} 1 & p_{12} & p_{13} & \cdots & p_{1n} \\ p_{21} & 1 & p_{23} & \cdots & p_{2n} \\ \vdots & & & \ddots & \\ p_{n1} & & \cdots & & 1 \end{bmatrix} \qquad (4)$$

where p_{ij} are the partial correlation coefficients between random variables x_i and x_j

$$p_{ij} = p_{ji} = \sigma_{ij} / \sigma_i \cdot \sigma_j \qquad (5)$$

where σ_{ij} is the covariance and σ_i and σ_j are the standard deviations (Hogg and Craig, 1978, p. 73).

In practice, the meaning of a partial correlation coefficient is easy to communicate because it varies between -1 and +1 depending on the degree of negative or positive correlation between two variables. Also, the meaning of different values of the correlation coefficient can be readily communicated with scatterplot diagrams. Thus, subjective estimates of partial correlation coefficients are reasonably easy to obtain.

The only other data required by the modified technique are estimates of the means and standard deviations of the variables of interest. In our method, these are derived simultaneously from estimates of the 99-percent confidence interval for the expected value of each random variable.

Given the normal distribution assumption, the midpoint of the 99-percent confidence interval provides an estimate of the unconditional mean value of each variable (μ_i). In addition, the width of the 99-percent confidence interval for each variable is about 5.15 standard deviations. Thus, an estimate of the standard deviation of each variable is

$$\sigma_i = \left(x_{i\text{high}} - x_{i\text{low}}\right) / 5.15 \qquad (6)$$

where $x_{i\text{high}}$ and $x_{i\text{low}}$ refer to the upper and lower bounds of the 99-percent confidence interval for the variable x_i.

Given the estimated **P** matrix and the estimated standard deviations, an initial or "preliminary" estimate of the covariance matrix is given by the following equation (Morrison, 1967, p. 80):

$$\Sigma = \mathbf{D}(\sigma_i)\,\mathbf{P}\,\mathbf{D}(\sigma_i) \qquad (7)$$

where the matrix $\mathbf{D}(\sigma_i)$ is the diagonal matrix of estimated standard deviations of the variables. Still, there is no assurance at this point that Σ is a positive definite matrix, corresponding truly to a possible covariance structure. Nevertheless, following Oren's technique for restoring positive definiteness, the Scheuer and Stoller algorithm (or Cholesky factorization) itself provides the means by which a matrix Σ can be tested for positive definiteness and can be modified, if necessary, to achieve positive definiteness. The method is based on the following observations.

First, a symmetric matrix is positive definite if and only if it can be written as **BB'**, for a nonsingular matrix **B** (see Searle, 1971, p. 36, Lemma 4 and proof). Since the Cholesky factor is defined as the unique lower-triangular matrix **C** such that **CC'** = Σ (Equation 3), then Σ is positive definite if and only if the Cholesky factor **C** is nonsingular. In addition, a square matrix such as **C** is nonsingular if and only if the determinant of the matrix is not equal to zero (e.g., see Isaak and Manougian, 1976, p. 186). Also, the determinant of a triangular matrix such as **C** is equal to the product of all the entries on its main diagonal (e.g., see Isaak and Manougian, 1976, p. 181). Thus, the lower-triangular matrix **C** (the Cholesky factor) will be nonsingular if and only if the product of all the entries on its main diagonal (the c_{ii} elements) are not equal to zero.

Furthermore, the c_{ii} elements of the Cholesky factor **C** are computed by the Scheuer and Stoller algorithm (Figure 1). Formula 1a gives the c_{i1} element, and formula 2a gives the c_{ii} elements for $i > 1$. The requirement that the product of the c_{ii} elements be nonzero (for **C** to be nonsingular) is equivalent to each of the c_{ii} elements being positive. This occurs if and only if the term under the square root in formula 2a (Figure 1) is a positive real number. In summary, the matrix Σ is positive definite if and only if the term under the square root sign in formula 2a for each of the c_{ii} elements of the Cholesky factor of Σ is a positive real number.

Finally, it can be observed that whenever the term under the square root sign in formula 2a is negative or zero, then increasing the corresponding variance factor (σ_i^2) by

$$\Delta_i = \sum_{k=1}^{i-1} c_{ik}^2 - \sigma_i^2 + \varepsilon_i \qquad (8)$$

where ε_i is an arbitrarily small number, can restore positive definiteness to the covariance matrix Σ. Thus, the Scheuer and Stoller algorithm provides a simple way of testing if the matrix Σ is positive definite and of restoring positive definiteness if needed.

As shown by Equation (5), the effect of increasing the variance of one variable while keeping the covariance fixed is to cause any related correlation coefficients to decrease.

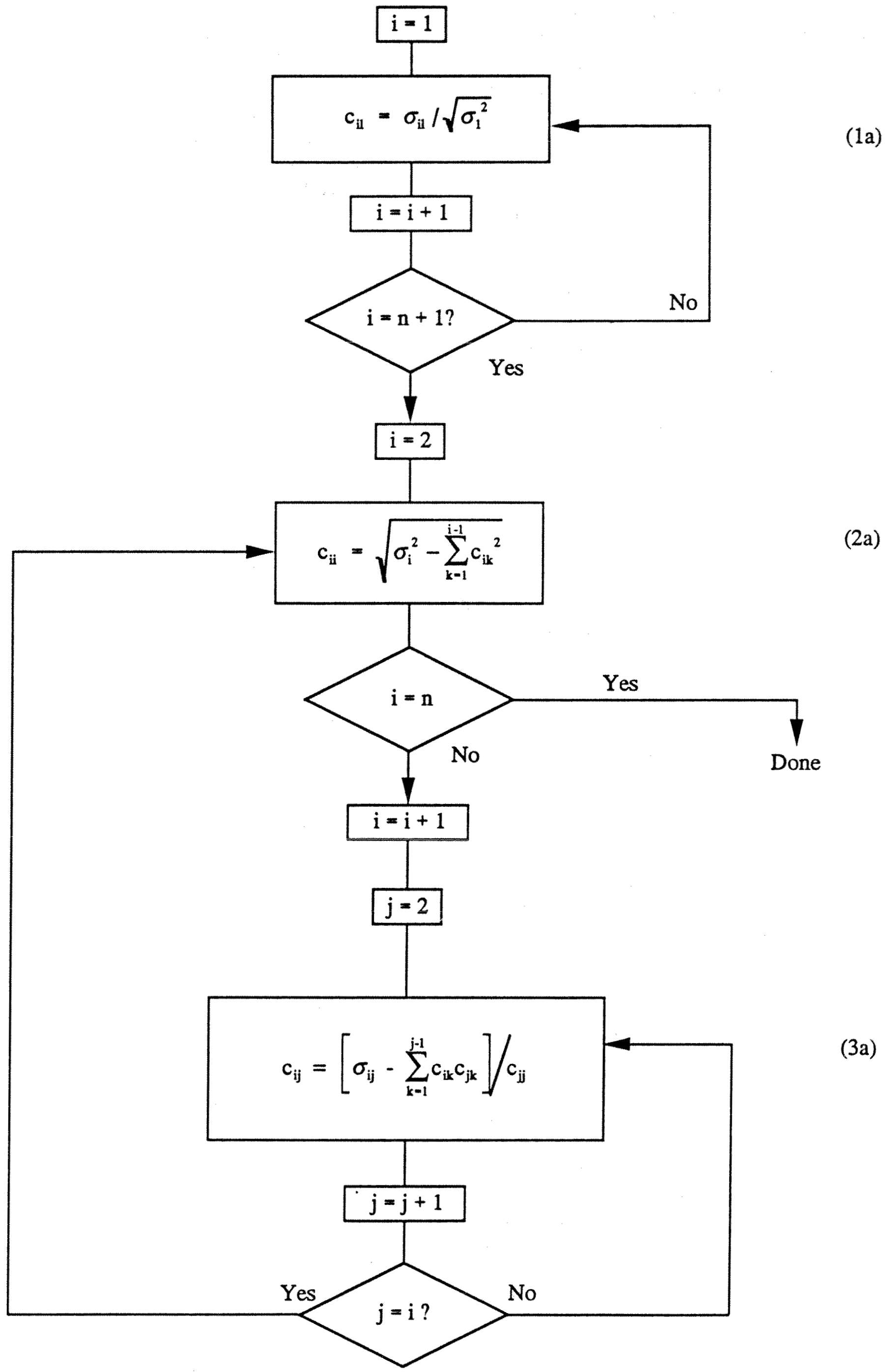

Figure 1. Scheuer and Stoller algorithm for deriving elements c_{ij} in the Cholesky factor C of the matrix Σ with elements σ_{ij}.

Essentially, when the initial variance and correlation structure is not acceptable because the implicit "covariance matrix" is not positive definite, the technique finds an adjusted variance and correlation structure that meets the positive definiteness requirement, while preserving the covariance terms. This may also be interpreted as a situation in which the originally specified variance of one or more variables is "too small" in relation to the larger specified variances of other variables and the specified covariance structure (see Oren, 1981, p. 34).
If the revised variance and correlation structure is not acceptable—i.e., if the revised variances are judged to be too large—or if the revised correlation coefficients are too small, the entire process can be repeated, starting with revised initial estimates of the correlation coefficients and confidence intervals for the variables; i.e., with smaller initial correlation coefficient assumptions or larger initial variance assumptions, or both, resulting in different covariance terms.

Clearly, the order in which variables are entered in the matrix **P** can affect which variance is adjusted and the extent of adjustment required. However, in practice, changes in the order of the variables seem to have little impact on results of simulation. In principle, one could refine the technique further to find the order of variables in the **P** matrix that minimizes the required adjustments in variance parameters to restore positive definiteness.

Summary of Method

The Monte Carlo simulation technique with subjective specification of a multivariate normal distribution consists of the following steps:

1. Obtain subjective estimates of 99-percent confidence intervals of unconditional expected values for each random variable in the simulation model. (This is approximately equivalent to asking for the lowest and highest possible values that each random variable may take.) Use this 99-percent confidence interval to derive the estimated unconditional mean, variance, and standard deviation of each random variable (Equation 6). Arrange the mean values in a vector μ and the standard deviations on the diagonal of a diagonal matrix $\mathbf{D}(\sigma_i)$.
2. Obtain subjective estimates of the partial correlation coefficients between each pair of random variables. The elicitation of these subjective estimates from experts can be facilitated by using scatterplot diagrams to illustrate various values of positive and negative correlation coefficients. Arrange the partial correlation coefficients in the correlation matrix **P**.
3. Derive a preliminary estimate of the covariance matrix Σ from the correlation matrix and the diagonal matrix of standard deviations (Equation 7).
4. Use the modified Scheuer and Stoller algorithm to derive the Cholesky factor **C** of the matrix Σ. The modified algorithm will stop if the term under the square root sign of formula 2a (Figure 1) is found to be negative on any iteration. In that case, the corresponding variance (σ_i^2) will need to be increased by the amount given by Equation (8).
5. If any variance term has been revised in Step 4, compute the revised correlation matrix **P** from the revised covariance matrix Σ, using Equation (7), and examine the revised partial correlation coefficients in **P** and the revised variance terms in Σ to verify that they are still acceptable. If the correlation coefficients have been decreased too much or if the variance terms have been increased too much, go back to Steps 1 and 2, and start over with revised subjective estimates for all the statistics (specifically, widen some confidence interval assumptions or decrease the absolute magnitude of some correlation coefficients, or both, and repeat the subsequent steps).
6. Use a pseudorandom number generator and Equation (1) to generate a sequence of independent standard normal variates, and arrange the sequence in *n*-dimensional vectors, denoted **z**.
7. For each **z** vector, calculate a corresponding multivariate random vector **x**, using the vector of estimated means μ, the Cholesky matrix **C** derived from Step 5, and Equation (2).
8. Repeat Steps 6 and 7 to generate a large number (e.g., ≥1,000) of independent vectors of multivariate normal variates.
9. Use the sample data generated in Step 8 to calculate a large sample of results predicted by the model, and examine the distribution of these results. The sample distribution can be used to infer the range and distribution of outcomes and the probability that various subsets of outcomes will occur.

An interactive microcomputer program, STOCSM, was written in FORTRAN by Ince to facilitate Steps 3 through 8 (Ince, 1990). Very recently, commercial software to do risk analysis with subjective multivariate distributions has become available (Market Engineering Co., 1991). The software, called Crystal Ball, uses rank correlation to correlate variables. This loses some information, but it permits the use of other marginal distributions besides the normal distribution. Like STOCSM, Crystal Ball starts from estimates of the marginal distribution of variables, and of the correlations between variables. Crystal Ball also revises the correlation matrix, when marginal distributions and correlations are inconsistent.

VALIDATION OF METHOD

To test the performance of the method, results of formulas for the expected values of products and quotients of pairs of correlated random variables were compared with simulated results obtained from the STOCSM program. These results also serve to illustrate how correlation assumptions may affect results of stochastic simulation.

The expected value of the product of two correlated continuous random variables X and Y is

$$E(XY) = \mu_X \mu_Y + \sigma_{XY} \tag{9}$$

The expected value of the quotient of two random variables is

$$E(X/Y) \approx \frac{\mu_X}{\mu_Y} - \frac{1}{\mu_Y^2}\sigma_{XY} + \frac{\mu_X}{\mu_Y^3}\sigma_Y^2 \tag{10}$$

(See Mood and Graybill, 1963, pp. 180–181.) Two pairs of random variables (X_1, Y_1) and (X_2, Y_2) were used in the tests. All variables had 99-percent confidence bounds of 10 and 20 and were normally distributed. Thus, they all had means of 15 and variances of 3.767 (Equation 6). X_1 and Y_1 had a correlation of -0.9, whereas X_2 and Y_2 had a correlation of +0.9. From these variances and correlations, the covariance could be obtained by Equation (5), and Equations (9) and (10) could be used to compute, analytically, the expected values of products and quotients of (X_1, Y_1) and (X_2, Y_2).

The results appear in Tables 1 and 2. The tables show that the expected value of the product of positively correlated variables (228.39) is about 3 percent higher than that of the negatively correlated variables (221.61). Instead, the expected value of the quotient of the positively correlated variables (1.002) is 3 percent lower than that of the negatively correlated variables (1.032).

The results in Tables 1 and 2 also show that the expected values computed by the STOCSM simulator in 1,000 replications were very close to those predicted by the analytical formulas. This supports the validity of the method embodied in STOCSM, at least for these admittedly simple cases.

APPLICATION OF METHOD

In a recently completed study at the Forest Products Laboratory (FPL), we applied the multivariate Monte Carlo technique to simulate the economic performance of a hypothetical paperboard mill with a new pulping and papermaking technology (Ince, 1990). The simulation was designed to assess the probability of investing in a 500 t/day mill producing linerboard with a new technique called CTMP-press-drying. This technique resulted from research at FPL, and a mathematical model of a CTMP-press-drying linerboard mill was developed (Ince, 1990). However, because the technology had yet to be applied commercially and because there was general uncertainty about the values that should be assigned to many technical and economic variables, eighteen variables were treated as random variables. Furthermore, we recognized that ten of those variables would be correlated and that the assumption of normality would be generally applicable. The nature of the distribution function and the magnitude of the uncertainties (standard deviations and correlations) were

Table 1: Comparison of STOCSM results with those obtained from analytical formulas: Product of variables.

Random variable	Mean	Variance	Correlation	Expected Value of XY	
				Analytical	Simulated
X_1	15	3.767	-0.9	221.61	221.46
Y_1	15	3.767			
X_2	15	3.767	+0.9	228.39	227.92
Y_2	15	3.767			

Table 2: Comparison of STOCSM results with those obtained from analytical formulas: Quotient of variables.

Random variable	Mean	Variance	Correlation	Expected Value of X/Y	
				Analytical	Simulated
X_1	15	3.767	-0.9	1.032	1.033
Y_1	15	3.767			
X_2	15	3.767	+0.9	1.002	1.001
Y_2	15	3.767			

obtained by interviewing scientists, engineers, and economists at the FPL (Ince, 1990). Figure 2 shows the correlation matrix that was obtained for the ten correlated variables in the model.

The STOCSM program was then used to predict the distribution of the internal rate of return (IRR) and net present value of the mill, given this subjective assessment of the distribution of the stochastic variables. Two simulations were done. In one simulation, the full multivariate normal distribution was considered, including the correlation coefficients shown in Figure 2. In the other simulation, variable correlations were ignored; thus, all the variables were regarded as random but independently distributed.

The results of the simulation experiments, with 1,000 observations each, appear in Table 3. The IRR for the hypothetical CTMP-press-drying paperboard mill is expressed in real dollars, after taxes. The most striking aspect of the results is that they differ so little. The means of the IRR were almost identical in the two cases, although the standard deviation was 8 percent smaller when the correlation of variables was taken into account. Thus, although ignoring the correlations would lead to exaggerating the risk of the investment, the difference between the results obtained by the simulations is quite small. Still, one should not make broad generalizations from this example. In other cases, it is conceivable that larger differences could occur between multivariate stochastic simulation and conventional Monte Carlo simulation, depending on the distributional assumptions. This was in part demonstrated earlier by the experiments with the products and quotients of highly correlated variables (Tables 1 and 2).

CONCLUSIONS

Generally applicable techniques for subjective assessment of a multivariate normal distribution were developed and demonstrated in the context of Monte Carlo simulation. The techniques were based on subjective specification of the 99-percent confidence intervals and partial correlation coefficients for the random variables. The technique combines the modified Scheuer and Stoller algorithm for Cholesky factorization and the variance-adjustment technique suggested by Oren, for ensuring a positive definite covariance matrix. The technique provides the means for assessing a subjective multivariate normal distribution—starting from the 99-percent confidence intervals and partial correlation coefficients, checking the covariance matrix for positive definiteness, and restoring positive definiteness, if necessary, by adjusting the variance assumptions while preserving the covariance terms. The method was validated by showing that simulated expected values of products and quotients of highly correlated variables were very close to those obtained from analytical formulas.

The method was applied to predict the internal rate of return of an investment in a new papermaking facility, with ten

		1	2	3	4	5	6	7	8	9
		.4	.7							
1	.4							.3	.3	.8
2	.7									
3					-.7	-.5	-.7			
4				-.7		-.5	.7			
5				-.5	-.5					
6				-.7	.7					
7		.3							.5	.5
8		.3						.5		.5
9		.8						.5	.5	

1.Specific gravity of pulpwood
2.Price of pulpwood ($,1986/cord)
3.Chipping energy requirement (kWh/ton)
4.Pulp yield (percent)
5.Chemical charge in chip pretreatment (lb/ton)
6.Electric energy in refining (kWh/ton of chips)
7.Cost of pulping effluent facilities ($,1986)
8.Price of electricity ($,1986/MCF)
9.Price of linearboard ($,1986/ton)

Figure 2. Matrix of correlation coefficients for ten correlated random variables in simulation experiment.

Table 3: Mean and standard deviation of internal rate of return for hypothetical CTMP-press-drying paperboard mill.

	Internal rate of return	
Monte Carlo simulation	Mean	Standard deviation
Multivariate normal distribution	8.55	1.28
Conventional	8.53	1.39

correlated random variables. The results showed that recognizing the correlation among variables had no effect on the expected internal rate of return, although it decreased its variance. The difference was small, in this particular case. Additional experiments are needed to determine under what circumstances correlations among variables in Monte Carlo simulations should be recognized explicitly.

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TIMBER SUPPLY ANALYSIS

A PROBABILISTIC APPROACH TO BLM PLANNING[1]

Kent P. Connaughton, James F. Cathcart[2]

Abstract.--The USDI Bureau of Land Management is in the process of completing Resource Management Plans for forested lands within western Oregon. Given declining timber availability on private lands, and reduced sale quantities on National Forests, the question facing BLM decision makers is what kind of an effect will a change in the BLM allowable sale quantity (ASQ) have on local timber economies? We address this question by applying a private timber supply logit model that provides the probability of harvest given certain stand conditions. We calibrate the logit model for changes in price, and link changes in the BLM ASQ to private timber supply using a downward sloping demand curve. Results are discussed in the context of a case study assessing the effect of a proposed ASQ increase within Lane County, OR.

Keywords: BLM, timber supply, planning.

INTRODUCTION

Forested lands of the USDI[3] Bureau of Land Management account for 15 percent of the 13,667,000 acres of timberland in western Oregon[4] (Gedney 1982). This is an important resource in meeting western Oregon's raw material needs for lumber and plywood production, which accounted for 17% and 29% of U.S. production respectively (1980-89 average). If western Oregon is broken into subregions, the importance of the BLM timber harvest increases as one looks north to south (fig. 1). Furthermore, declining timber availability on private lands intensifies the need for public timber, of which the BLM is a secondary supplier in relationship to USDA[5] Forest Service National Forest lands. However, recreation, wildlife, preservation, and water define competing demands for the forest resource, especially on public lands.

BLM: Planning for the 1990s

The BLM is preparing Resource Management Planning (RMP) for its six western Oregon Districts: Coos Bay, Eugene, Medford, Roseburg, Salem, and the Klamath Falls Resource Area of Lakeview (USDI 1988). In contrast to the consolidated ownership of the National Forest system, the BLM manages a checkerboard ownership intermingled with private lands.

Eighty-seven percent of the BLM ownership is revested Oregon and California (O&C) railroad land grant holdings managed under the O&C Act of 1937: The act stipulates that:

> timberlands ... shall be managed ... for permanent forest production ... in conformity with the principal (sic) of sustained yield for the purpose of providing a permanent source of timber supply ... contributing to the economic stability of local communities and industries.

The O&C Act also provides the same management direction for reconveyed Coos Bay Wagon Road

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[2] Research Forester and Forester, Pacific Northwest Research Station, P.O. Box 3890, Portland, OR 97208.

[3] U.S. Department of Interior.

[4] That portion of Oregon west of the Cascade Range divide.

[5] U.S. Department of Agriculture.

lands which represent three percent of the BLM ownership; and are locally important within the South Coast and Roseburg subregions. The remaining balance (ten percent) represent public domain lands. Since 1962 management of the public domain has been coordinated with the O&C for the purposes of calculating allowable cuts and for timber investment financed from O&C harvest receipts (BGRS 1968).

While the RMP process, directed by the *Federal Land Policy and Management Act of 1976*, applies directly to the management of the public domain, the BLM has chosen to consider all of the lands under its jurisdiction in the development of the new plans. The preferred alternative will be developed from 5 common alternatives evaluated by each district. These alternatives, addressing A) maximum timber production, B) riparian management, C) biodiversity, D) northern spotted owl conservation, and E) old-growth preservation, will differ in terms of the allowable sale quantity (ASQ) of timber and their market-related effects on timber supply from private owners in western Oregon.

BLM Policy Environment

Historically, the proportion of harvest originating on western Oregon's private forestlands has been greater than the proportion of forestland in private ownership. The harvest of timber in mature age classes and the subsequent establishment of young forests has created a temporary supply deficiency on private lands. Beuter and others (1976) and Sessions (1990) conclude that timber availability on private lands will decline in the north Willamette, mid-Willamette, Eugene, Roseburg, and Medford subregions (fig. 1).

Beuter and others (1976) identify increases in federal harvest as a solution to declining private timber availability. The potential supply of timber from nonindustrial land is not large enough to offset the reduced timber availability on federal and industrial ownerships (Sessions 1990, Greber and others 1990). It would seem that the pressure to harvest would fall on the National Forests due to their size and visibility within western Oregon. And it has. But because National Forest planning in western Oregon is nearing completion, and BLM planning is beginning, BLM inherits the timber supply effects of adopted National Forest policy with respect to the northern spotted owl, old-growth preservation, and an ecological focus in forest management.

How the BLM approaches timber supply is significant because BLM harvest receipts have proportionally greater financial consequences for western Oregon counties than National Forest receipts. The O&C lands are unique in that 50% of gross timber harvest receipts are returned to the general funds of the 18 counties containing O&C lands. In contrast, only 25 percent of gross National Forest timber receipts are returned to counties - earmarked specifically for roads and schools (BGRS 1968)[6].

OBJECTIVE AND APPROACH

Our objective was to answer a key policy question facing BLM decision-makers: "What kind of an effect will a change in BLM ASQ have on local timber economies?" The forest policy environment is frustrating for BLM managers; they are called to carry out their charter to stabilize local communities even though the tide has turned against increasing public harvest as an instrument to deal with declining private timber availability. With the exception of Alternative A, which is evaluated as a point-of-reference, the BLM ASQ will likely decline under alternatives B-E.

Our approach was to prepare a model of the local timber economies in western Oregon that we used to calculate variables that were critical to question facing BLM managers. Those variables were: private (industrial and nonindustrial) harvest, national forest harvest, other public harvest, and log consumption by subregion. The model was designed so that it: 1) simulated the supply and demand for timber within and between western Oregon's subregions, 2) addressed the BLM planning period (1991-2000), (3) distinguished effects between the BLM common alternatives, and 4) separated out those effects attributed directly to BLM planning action and those effects due to macroeconomic conditions.

Unlike previous analyses that examine timber availability as a biophysical process driven by a sustainability objective (Beuter and others 1976, Sessions 1990, Greber and others 1990), our approach treated private timber supply as an economic process responding to the price effects associated with the different BLM alternatives and to macroeconomic conditions that are outside the control of the BLM. We assumed that National Forest and BLM supply, which are determined outside the marketplace in the political arena, were unaffected by macroeconomic conditions.

We present an example of the analysis for the Eugene subregion. The effect of implementing Alternative A on the Eugene District is analyzed relative to current management direction under existing 1980 plans (henceforth referred to as No Action). We conclude with a discussion of the results and an interpretation pointed at BLM planning.

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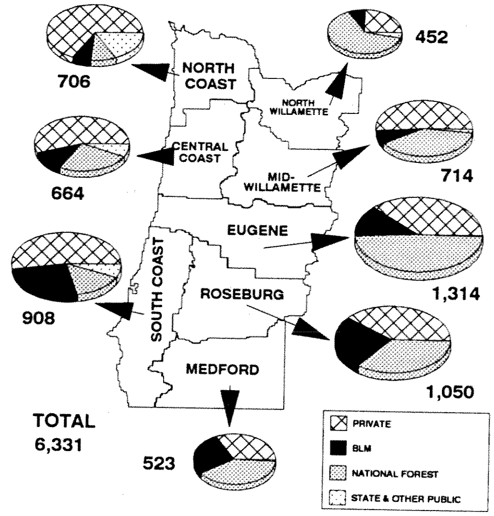
[6] Timber receipts from Coos Bay Wagon Road lands are returned to specific taxing authorities within the county based on the property tax value of the land if it were privately owned. Public domain lands return four percent of net receipts to counties (Hackworth and Greber 1988).



SOURCE: ODF (1985-1990).

Figure 1.--Western Oregon timber harvest, 1984-88. (Annual average, million board feet per year).

MODEL DESIGN

We made several assumptions concerning demand, and federal and private timber supply that allowed us to model key features of the western Oregon timber economies while avoiding some of its complexities.

We assumed that all of the federal timber offered for sale would be harvested. This assumption allowed us to focus on the differences in ASQ by alternative. The assumption implied that federal harvest would not fluctuate as a function of demand. The assumption is an important simplification, because historical federal harvest (not necessarily ASQ or quantity offered for sale) has fluctuated--with the greatest fluctuations accompanying peaks and troughs associated with prevailing macroeconomic activity affecting the demand for wood products in domestic and international markets.

We assumed that private harvest would respond to price changes associated with changes in the BLM ASQ, and that the private harvest would be conditioned on assumptions concerning macroeconomic activity.

Implications

Taken together, these assumptions allowed us to simulate harvest as an equilibrium quantity made up of a fixed federal supply that varied only by alternative, a price-responsive private supply that varied by macroeconomic conditions, and a relationship between stumpage price and the quantity of timber demanded by western Oregon's mills. By holding the National Forests and other public ownerships constant, the analysis quantified the private industrial and nonindustrial harvest response to a change in the BLM ASQ.

CASE STUDY

To demonstrate the approach we focus on the Eugene subregion (Lane County) of western Oregon. The Eugene subregion includes portions of the Siuslaw National Forest along the Coast Range to the west, and portions of the Willamette National Forest along the Cascade Range to the east (fig. 2). BLM lands, principally of the Eugene District, are located in the interior valleys and slopes located between the Coast and Cascade Ranges. Private lands, the majority industrial, are located in this interior region as well. The major forest industry processing center is located within the Eugene-Springfield metropolitan area. The 1984-1988 harvest level[1] was 247 million cubic feet per year; National Forest (48%), private industrial (34%), BLM (14%), nonindustrial private (3%), and other public (1%). Processing within the subregion was 1.5 billion board feet per year in 1988 (Howard and Ward [In press]); 1.1 billion board feet per year in 1982.

Recent projections of timber availability indicate that the Eugene subregion will experience declining National Forest timber availability over the next 10 years due to reduced ASQs in proposed forest plans (Sessions 1990, Greber and others 1990). Sessions concludes there will be no decline in private timber availability relative to 1983-87 harvest level of 95 mmcf/year, while Greber and others project a modest increase to 105 mmcf/year, primarily as a result of a projected increase in nonindustrial harvest.

METHODS: MODEL IMPLEMENTATION

Figure 3 displays the structure of the model we formulated. The major components of the model were: relationships between quantity demanded and price, fixed public supply, the spatial portrayal of log flows by macroeconomic conditions, and the incorporation of macro-

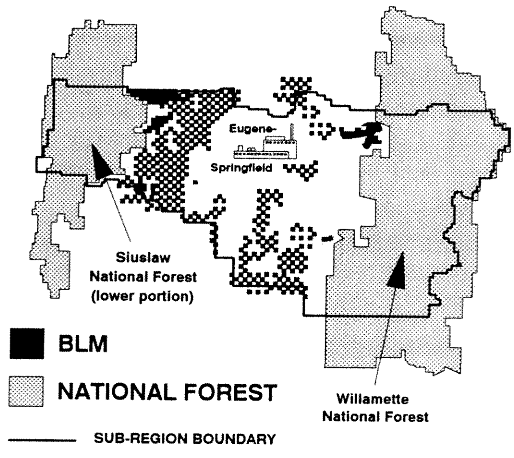


Figure 2.--Eugene sub-region (Lane County, OR).

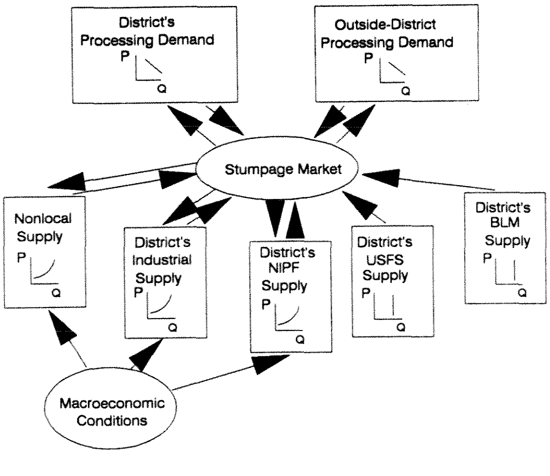


Figure 3.--Structure of the projection model.

economic conditions and demand-related price adjustments into the probabilistic portrayal of private supply. The model's solution algorithm was based on an iterative calculation of prices and quantities, and terminated when supply from all ownerships was equal to the quantity demanded.

Demand

Demand was "downward sloping," and quantified the relationship between the quantity demanded and the price mills would be willing to pay for sawtimber. Two demand relationships were developed: one was the relationship between the quantity demanded and price in the Eugene subregion only, and the second was the relationship between quantity demanded and price by mills throughout western Oregon.

The demand relationships allowed us to simulate two different equilibria between supply and demand. The first demand relationship was used to simulate supply and demand equilibrium under the assumption that price effects and supply adjustments would be confined to the Eugene subregion; the assumption was consistent with expected short-run response to changes in the Eugene District's ASQ, which would be felt first and most heavily in the Eugene area. The second demand relationship was used to simulate supply and demand equilibrium under the assumption that price effects and supply adjustments would eventually be felt throughout western Oregon. However, the results presented here for the Eugene subregion only demonstrate the effects of the first demand relationship.

The demand relationships were derived from estimates of sawtimber demand for western Oregon and western Washington calculated for year 1990 and 2000 with the Timber Assessment Market Model (TAMM) (Adams and Haynes 1982). The demand relations measured the change in stumpage price (constant 1967 dollars per thousand board feet) per million cubic feet of sawtimber demanded.

The horizontal disaggregation procedure for the two demand relationships was straightforward: a linear relationship was calculated using the TAMM price intercept and 1989 prices and quantities for western Oregon; the same approach was used for the Eugene subregion, except Eugene harvest quantities were used. The slopes of the demand relationships, which measured how much stumpage prices would change per million cubic feet of sawtimber, were key to the solution algorithm, because they allowed us to simulate the price effects of changing the BLM ASQ, and then calculate the resulting industrial and nonindustrial supply response.

Public Supply (ASQ)

Timber supply was assumed fixed at the planned ASQ levels for the BLM and National Forests, and assumed to be unresponsive to changes in stumpage price and changes in macroeconomic conditions. The projected National Forest harvest level of 81.2 million cubic feet per year over the 1991-2000 period was taken from Sessions (1990) as updated in Greber and others (1990). This represented the National Forest ASQ (preferred alternative - post Environmental Impact Statement analysis, *circa* March 1990) for the Siuslaw and Willamette National Forests, and did not include effects of implementing the proposed Interagency Scientific Committee Conservation Strategy for the northern spotted owl (Thomas and others 1990). The other public harvest level of 1.9 million cubic feet was taken from Sessions (1990) and reflected this ownership's 1983-87 historical average. The BLM Eugene District ASQ was 31.7 million cubic feet under No Action, and 48.8 million cubic feet per year under Alternative A. For purposes of this example, all reported ASQs by administrative unit were prorated to the Eugene subregion based on the proportion of forest land area (excluding wilderness) located within the subregion[8].

Private Timber Supply

Private timber supply was assumed to be a probabilistic process depending on stand conditions, and responsive to changes in stumpage prices and to changes in macroeconomic conditions.

We used the forest data collected by the

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[7] Oregon/Washington State Office, USDI Bureau of Land Management, Portland, OR. Personal communication.

[8] Lettman, Gary. Economic analyst. Oregon Department of Forestry, Salem, OR. Personal communication. These are the same proportions used in Sessions (1990) and Greber and others (1990).

Forest Inventory and Analysis (FIA) Work Unit from the Pacific Northwest Research Station for the 111 plots in the industrial and nonindustrial ownerships in Lane County, the county-level acreage expansion factor for each FIA plot, and the harvest probability relationships in Connaughton and Campbell (1991) as the building blocks of private timber supply.

We calculated private timber supply as:

$$Q_t = \beta \sum_i \sum_j Pr_{mij} V_{ijt} A_{ijt} \qquad (1),$$

where Q_t is the quantity supplied by private owners in the t-th decade; β is the ratio between total volume removed and volume removed from clearcut, salvage or overstory removal; Pr_{mij} is the probability of harvest (clearcut, salvage or overstory removal) for the j-th plot from the i-th ownership under the m-th macroeconomic scenario; V_{ijt} is the projected volume per acre of the growing stock on the j-th plot for the for the i-th ownership at the midpoint of the t-th decade; and A_{ijt} are the number of unharvested acres remaining in the t-th decade from the county-level acreage expansion factor for the j-th plot of the i-th ownership. In this application, t=1 (1991-2000). The ratio of total volume removed to volume removed by clearcut, salvage or overstory removal was calculated from FIA harvest records and public records on harvest levels in Lane County.

Connaughton and Campbell (1991) estimated the probability of harvest in western Oregon as:

$$\ln \frac{(Pr_j)}{(1-Pr_j)} = -2.401 - 11.24\ (Growth\ Rate)_j + .000264\ (Volume\ per\ acre)_j \qquad (2),$$

where Pr_j is the probability that the j-th plot will be harvested; $(Growth\ Rate)_j$ is the projected compound annual growth rate in growing stock for the stand on the j-th plot for the coming decade; and $(Volume\ per\ acre)_j$ is the per acre growing stock volume for the j-th plot at the beginning of the decade. Connaughton and Campbell conclude that there is no difference in the probability of harvest by ownership. Therefore, the distinction between industrial and nonindustrial sources is not reported (i.e., sub-script i suppressed).

Equation (2) is a logit model, which is based on the cumulative logistic function. The model form was chosen because observations for the dependent variable, Pr_j, take on values of either zero or one (1 = harvest, 0 = no harvest). Fitted values, therefore, were bounded by zero and one and represented the proportion of area represented by the plot that is harvested during the period. Connaughton and Campbell (1991) choose growth rate and volume per acre as explanatory variables because they are proxies for nonobservable variables that are the keys to the economically optimal harvesting decision.

Several adjustments in the FIA data were necessary to simulate private forestland conditions in 1990. Because Lane County was inventoried in 1985, the per-acre plot volumes were updated for growth. The county-level expansion factors were updated to account for acres harvested between the year of inventory and 1989. The adjustment procedure was to reduce the number of acres available for harvest by applying the probability function to the expansion factor for the 1985 inventory. A per-year adjustment was then calculated and applied to the three-year interval from 1986 to 1989 to simulate the number of unharvested acres as of 1990.

We calibrated the intercept term in equation (2) to simulate changes in private harvesting probabilities accompanying changes in macroeconomic conditions. Private harvest in western Oregon varied substantially from the mid-1970's to the mid-1980's. The peak year, 1979, occurred in conjunction with high macroeconomic activity and high demand for new housing. The low year, 1981, occurred in conjunction with the early-1980's recession.

The procedure was to calibrate the intercept in equation (2) such that when the calibrated equations were applied to simulated, plot-level volumes for the period 1976 to 1984, the predicted average annual volumes harvested equaled the observed harvest volumes for western Oregon private ownerships in 1979 (high macroeconomic conditions) and 1981 (low macroeconomic conditions). The observed harvest volumes, which were converted to cubic feet, were adjusted to account for acreage changes, and growing stock removals so that they would be comparable to the FIA plot-level volume data. Figure 4 shows how the calibration affected the cumulative probability function for a hypothetical, medium site, fully-stocked Douglas-fir. For any combination of growth rate and volume per acre, the probability of harvest was greater under high macroeconomic conditions than under low macroeconomic conditions.

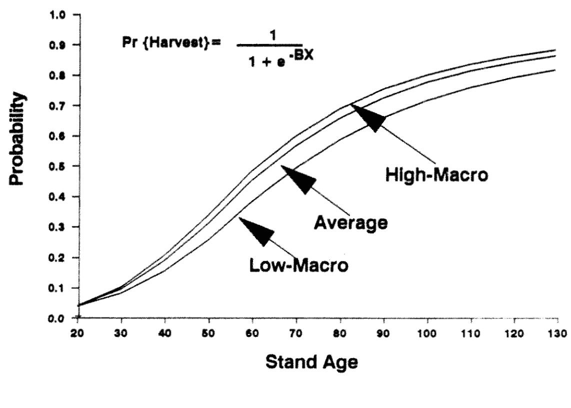

Figure 4.--The probability of harvest as a function of macroeconomic conditions.

The effect of stumpage price changes on the probability of harvest was derived from the relationship between the intercept term in equation (2) and stumpage prices in 1979, 1981 and over the interval 1976-1984. Stumpage prices in western Oregon were approximately $65 per thousand board feet in 1979 (in constant 1967 dollars) and about $26 per thousand board feet in 1981; for the period from 1976 to 1984, stumpage prices averaged about $45 per thousand board feet. We estimated a simple linear regression between stumpage price and the intercept term (fig. 5). The inverse of the regression slope measured the change in the intercept term (equation 1) as a function of a change in stumpage price.

Log Flows

Harvest from the subregion's forests differed from log consumption by the subregion's mills because of log flows between subregions. We used mill surveys (Howard 1984, and Howard and Ward [In Press]) to quantify the proportion of logs flowing out of a subregion. The flow information allowed us to model the quantity of timber flowing into the Eugene subregion, or nonlocal supply, as well as the quantity of timber flowing out of the subregion to fulfill nonlocal demand.

The log flow data varied by macroeconomic condition. We used the log flow data for 1982 (Howard 1982) to represent flow patterns for accompanying weak or low macroeconomic conditions. We used the log flow data for 1988 (Howard and Ward [In Press]) to represent the flow patterns for strong or high macroeconomic conditions. For the Eugene subregion (Lane County), eighty-five percent of the logs remained within the subregion during 1982, while in 1988 seventy-eight percent remained within the subregion.

Solution Algorithm: An Example

The algorithm for calculating the private supply response to a change in BLM ASQ is best described using the example of increasing BLM ASQ by 17.1 million cubic feet per year (the change from No Action to Alternative A). The

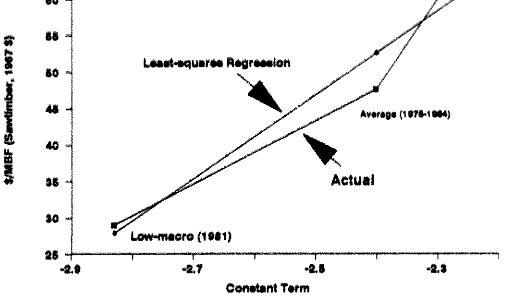

Figure 5.--The relation between stumpage price and the intercept term in the probability equation.

assumptions and initial conditions were: high macroeconomic conditions (78% of harvest processed locally), price effects confined to the subregion, slope of the demand relationship equal to -$1.28/mbf/mmcf, and a beginning private harvest of 85 mmcf/year.

The solution algorithm began by calculating the change in the BLM harvest that would be consumed within the Eugene subregion, and that would, therefore, affect stumpage prices in the Eugene subregion. Under the assumption of high macroeconomic conditions, 13.3 of the 17.1 mmcf/year increase (78 percent) was assumed to be processed within the Eugene subregion, with the remaining 3.8 mmcf/year exported to other western Oregon subregions. The change in stumpage price implied by the 13.3 mmcf/year increase was then calculated using the slope of the Eugene subregion demand relationship. The result was a decrease in stumpage price of 17.15 (1967 $/mbf).

The algorithm then adjusted the probability of harvesting a privately-owned stand by multiplying the price change (-$17.15/mbf) by the inverse of the slope of the regression (0.173) relating stumpage price to the intercept term in equation (2). The result was a change in the intercept that implied a lower of probability of harvest for all stands.

To project the private harvest at this new price, the algorithm applied the updated probabilities to equation (1). The result was a private harvest of 74.4 mmcf/year; a decrease of 10.6 mmcf. This represented an actual decrease in Eugene subregion processing of 8.3 mmcf/year because only 78 percent of the private harvest was processed within the subregion. The algorithm then checked for equilibrium between supply and demand by checking whether or not the new private harvest level was equal to the previous private harvest level. In this case it was not, so a second iteration began.

The second (and all ensuing) iteration began by calculating the change in price that would be expected to accompany the change in private supply. The reduction in private harvest remaining in the Eugene subregion (-8.3 mmcf) implied that prices would increase by 10.70 dollars per thousand board feet. The simulated price increase was then used to adjust the probability equation, which was then used to recalculate equation (1). The solution algorithm continued until no further changes in private supply were forthcoming. For demonstration purposes, we terminated the solution algorithm with this second iteration, one in which there was a 6.0 mmcf/year decrease in private harvest remaining in the Eugene subregion.

RESULTS

Table 1 displays the reporting variables of interest to the BLM if alternative A were implemented during a period of low versus high macroeconomic conditions. The private harvest response to the 17 mmcf/year increase in BLM ASQ was a modest drop from 58 to 55 million cubic feet per year under low macroeconomic conditions, and a drop from 85 to 79 million cubic feet per year under the high macroeconomic conditions scenario. Total harvest in the Eugene subregion, therefore, increased 14 million cubic feet (eight percent) under the low macroeconomic scenario, and 11 million cubic feet (six percent) under the high macroeconomic scenario.

DISCUSSION

Increasing the BLM ASQ by 17 mmcf/year translates into a potential increase in log consumption within the Eugene subregion by 14 mmcf/year under low macroeconomic conditions (85% of the ASQ increase processed locally), and by 13 mmcf/year under high macroeconomic conditions (78% of the ASQ increase processed locally). Our results show that after the private harvest adjusts to the new BLM ASQ, the net increase in log consumption will be slightly less at 12 mmcf/year and 8 mmcf/year under low and high macroeconomic conditions respectively. Therefore, the equilibrium adjustment to the ASQ increase leads to a lower level of log consumption than initially made available due to the offsetting private harvest reduction, regardless of macroeconomic conditions. However, the net contribution to local processing is proportionally greater under low macroeconomic conditions since the processing is more dependent on local timber supply, and the private harvest reduction is less pronounced.

Conditions outside BLM's control will continue to shape the subregion regardless of the adopted ASQ. The net harvest gain from implementing Alternative A is concentrated exclusively within the context of timber supply and can be dominated by macroeconomic conditions over which the BLM has no control. Table 1 indicates that the BLM can expect the private harvest to fluctuate between 55 and 79 mmcf/year if Alternative A is implemented. If high macroeconomic conditions prevail, the net gain in harvest is 11 mmcf/year (tab. 1). However, if macroeconomic conditions worsen, the ASQ induced gain would be more than offset by a 24 mmcf/year private harvest decline to low macroeconomic levels. That changes in macroeconomic conditions can lead to fluctuations in the private harvest makes it difficult for the BLM to stabilize local communities.

The perspective of BLM planners and decision makers is how will each alternative affect the nature of the timber industry in the Eugene subregion. In order to accommodate this perspective, we must couch our results in terms of where the subregion has been over the last 10 years as well as where it is headed over the next 10 years, and whether the impacts of changing the BLM ASQ are large or small compared to changes occurring beyond BLM's control. With respect to the latter, we have already seen that the net effect of increasing the BLM ASQ (what the BLM can control) is roughly 50 percent of macroeconomic driven fluctuations in the private harvest (what the BLM cannot control).

The complete picture for the Eugene subregion is as follows. The timber availability outlook for the subregion (215 mmcf/year; Greber and others 1990) can be thought of as representing the sustainable harvest projection under conditions of average demand. Since the timber availability projections hold the BLM ASQ at levels equivalent to No Action, a comparable average for our projections would be a weighted average of our No Action projections under high and low macroeconomic conditions (191 mmcf/year). Therefore, we cannot confirm that the private ownership has the willingness or ability to continue to harvest at the recent levels reported in Sessions (1990) and Greber and others (1990). This discrepancy is most likely due to differences in the beginning inventory and growth rates, with the timber availability projections using higher values than those used here.

By comparing our projected average (191 mmcf/year) to the historical average over the

Table 1.--Harvest and log consumption by BLM alternative for the Eugene subregion, 1991-2000.

MACROECONOMIC CONDITIONS	BLM: NO ACTION Annual Harvest by Ownership (millions cubic feet per year)				LOG CONSUMPTION (mmcf/year)	BLM: ALTERNATIVE A Annual Harvest by Ownership (millions cubic feet per year)				LOG CONSUMPTION (mmcf/year)	CHANGE IN HARVEST NO ACTION TO ALTERNATIVE A (millions cubic feet per year)				CHANGE IN LOG CONSUMPTION (mmcf/year)
	BLM	PRIVATE	NATIONAL FOREST*	TOTAL		BLM	PRIVATE	NATIONAL FOREST*	TOTAL		BLM	PRIVATE	NATIONAL FOREST*	TOTAL	
LOW	32	58	83	173	147	49	55	83	187	159	+17	-3	NC	+14	+12
HIGH	32	85	83	200	156	49	79	83	211	165	+17	-6	NC	+11	+ 9

* Includes other public (2 mmcf/year).

1980-89 period (215 mmcf/year; ODF [1981-90]), our anticipated decline in timber availability is nearly 25 mmcf/year. The implication is that industry has been adjusting to a declining timber availability; either by reducing capacity, or by going outside the subregion to secure raw material needs. Furthermore, this adjustment has been occurring under No Action ASQ levels for the BLM. If the BLM were to implement Alternative A, our projected average (across high and low macroeconomic conditions) for the subregion would be 203 mmcf/year indicating that 12 mmcf/year of the timber availability decline could be offset by the BLM. The converse is that any decrease in the BLM ASQ would exacerbate the timber availability decline.

Further Research

The results presented here are preliminary in that we have only analyzed the effects of increasing the BLM ASQ within the borders of the Eugene subregion. The next step will be to investigate whether changes in the BLM ASQ within the Eugene subregion have any effects rippling beyond the subregion. Furthermore, we have yet to address the more likely case where the BLM considers an ASQ decrease relative to No Action (Alternatives B-E), nor have we assessed BLM effects in other western Oregon subregions. By completing these tasks, we can provide decision makers with the necessary information to weigh the effects of different BLM Alternatives on subregional timber supplies in western Oregon.

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MODELING THE INTERACTION BETWEEN PUBLIC AND PRIVATE TIMBER SUPPLIES IN A LOCAL FOREST ECONOMY: A MATHEMATICAL PROGRAMMING APPROACH

Jay Sullivan and Michael Hite[1/]

Abstract.--A conceptual model for assessing public/private timber supply interactions in small regions is presented. A hypothetical mixed-ownership situation was developed to demonstrate the conceptual model. Simulation results illustrate the need to consider the condition of adjacent private forests when assessing the consequences of national forest ASQ levels.

Keywords: economic impacts, timber sales, forest planning, stumpage markets

INTRODUCTION

National forest timber harvests often have a profound influence on the economic well-being of adjacent communities: jobs are created in the harvesting and processing industries; the Forest Service spends money in the local economy to administer the timber sales; and in-lieu payments are made to local governments for schools, roads, and other services. These impacts are well documented (e.g., Bell 1977, Darr and Fight 1974, Dean et al. 1973, Flick et al. 1980, Grobey et al. 1987, and Schallau et al. 1969). However, a troublesome issue when assessing the effects of alternative levels of the allowable timber sale quantity on national forests is the influence that changes in public harvest levels will have upon private sources of timber supply in the local market area. Much less is understood about these "cumulative" impacts. Studies that have addressed the relationship between public and private sources of timber supply (e.g., Adams 1974, Adams and Haynes 1980, 1989, and Berck 1979) have focussed on the stumpage price effects of national forest harvests at an aggregate regional level, and from the projected price changes, inferred the behavior of private timber suppliers. However, the geographic resolution of these studies precludes analyses of public/private supply interactions in small regions, where the issue of stability in the local economies is particularly acute. The variety of local situations causes generalizations derived from the aggregate studies about the effects of public allowable sale levels on private forest ownerships to be of limited value for any individual community concerned about its economic well-being. This paper presents a local timber supply model that gives explicit consideration to the interactive relationship between public and private timber supplies. A conceptual model of a mixed public and private stumpage market is presented first, followed by an application of the approach to a hypothetical forest.

[1/]Authors are assistant professors, School of Forestry and Wildlife Resources, Virginia Polytechnic Institute and State University, Blacksburg.

CONCEPTUAL MODEL

The description of the model begins at the level of the wood processing industry, because it is from the demand for processed wood products that timber derives its commercial value. The model depicts the stumpage market of a small region that is adjacent to public forest land. Public and private stumpage are treated as perfectly substitutable factor inputs in the production process of the local wood processing industry. For illustrative purposes, we assume that dimensioned lumber is the only product being produced by a competitive wood products industry and that a downward-sloping demand function for lumber produced locally is known for each period into the future.

For the output of a competitive industry, the price and quantity are found at the intersection of the supply and demand curves faced by the local manufacturers. The demand curve for lumber is assumed to be given exogenously for each period, derived from housing construction or other wood-using activities at the national and regional scale, while the supply curve describes the combined profit maximizing behavior of the local firms in the wood processing industry. For a multiperiod model, this intersection point is found for all periods simultaneously by maximizing the difference between the area under the demand and supply curves as follows:

$$\underset{\{x_{nt}, x_{pt}\}}{Max} \sum_{t=0}^{\infty} \delta^{t} \left[\int_{0}^{q_t} p_{dt}(z)\,dz - \int_{0}^{q_t} p_{st}(z)\,dz \right]$$

subject to:

$$q_t = f(x_{nt} + x_{pt}, x_{ot})$$

where:

q_t = lumber produced in period t

x_{nt} = national forest stumpage purchased in period t

x_{pt} = private stumpage purchased in period t

x_{ot} = other production inputs

p_{dt} = demand function for lumber produced locally in period t

p_{st} = supply function for lumber produced locally in period t

δ^t = discount factor for period t

f() = production function for lumber

It should be noted that this objective function represents an analytical technique for finding the equilibrium solution. No meaning is ascribed to the objective function value, and the correspondence to any welfare criterion is coincidental.

Because the supply curve for the industry represents the marginal cost curve above average variable costs, the integral of supply represents total costs. The problem can be written more conveniently as follows:

$$\underset{\{x_{nt}, x_{pt}\}}{Max} \sum_{t=0}^{\infty} \delta^{t} \left[\int_{0}^{q_t} p_{dt}(z)\,dz - \sum_{j=1}^{n} w_j(x_{jt}) \cdot x_{jt} \right]$$

subject to:

$$q_t = f(x_{nt} + x_{pt}, x_{ot})$$

where:

w_j = quantity dependent price of input j

The quantities of factor inputs may be price responsive in this formulation, allowing the interactions between the public and private sources of timber to be considered. In this model, public stumpage prices determine the quantity of public timber obtained, influencing how the industry utilizes timber from private land. How the industry uses private timber in turn influences the amount it can afford to pay for public sawlogs. Prices and quantities of both public and private timber are also linked over time, because changes in timber inventory occurring through harvests in one period will determine the availability of stumpage from a given ownership in subsequent periods.

The price-responsive stumpage input quantities therefore represent timber supply models for public or private lands. For private timber supply, it is anticipated that a model delineating supply by accessibility, ownership objective, species and site class would be used. A dynamic age class timber supply model (e.g., Berck 1976, Lyons and Sedjo 1983) could suffice for describing private timber supply.

From the perspective of the wood products industry, the allowable timber sale quantities from national forest lands are determined exogenously. However, firms can decide on which of the offered sales to bid and how much to bid. For a competitive wood products industry, in which no firms have any geographic advantage when bidding for public stumpage, a firm would be expected to set a mill bid price that represents the maximum that they could pay for sawlogs delivered to their gate, and then calculate site specific bids for stumpage by reducing the mill price by the logging and hauling costs. The mill bid price, the Forest Service base rate for timber, and the logging and transportation costs determine the maximum distance that will be travelled to obtain timber. However, given that the mills are likely to be dispersed geographically in reality, bidding behavior may vary by sale location on the forest, depending upon the extent of overlap in mill timbersheds. This process could be represented in the model using a geographic information system (GIS) in which current inventories, geographic features, road networks, and mill locations are maintained and updated between time periods, much like that described by Berry and Sailor (1981).

Solving the model involves finding vectors of prices and quantities of public and private stumpage that satisfy the timber supply models over all time periods and maximize the objective function. An iterative search procedure could be used to find these vectors. This may ultimately prove cumbersome for a model that contains considerable detail. Though solving of all time periods simultaneously allows short and long run behavior of the wood products industry and the landowners to be consistent, it does imply that all actors behave as though they have perfect foresight when anticipating the demand for lumber from the local area and the supply of timber from other local sources in future periods.

No even-flow constraint is imposed on material passing through the local mills. However, the downward-sloping demand functions for the manufactured product in each period create an incentive to spread the available fiber input usage over time, even when considerable volumes of mature timber are present. This smoothing of harvests over time is also characteristic of harvest schedules generated with the ECHO approach (Walker 1975) and other nonlinear optimization approaches with a downward-sloping demand function in each period.

SIMULATIONS

A hypothetical mixed-ownership timbershed was developed to demonstrate the conceptual model described above. A public forest comprised of 1.5 million acres was created, of which 20% was designated for commercial timber production of a single species on a single site class (Douglas-fir, site index 140). Timber sales were distributed evenly across the total forest acreage in any period and the costs of delivering wood from the public forest were assumed to be a function of volume and distance only (i.e., only a single terrain class was incorporated). All mills were assumed to be agglomerated at a single location.

A 600,000 acre private forest was divided into two access classes of equal size, representing the relative extremes of the range of mill transport costs. All private land was assumed to be owned by forest industry in this example, most closely resembling the situation on the Pacific coast. As with the public forests, only the single species and site class were identified.

To highlight the interactive relationship between public and private timber supplies, four scenarios were developed from combinations of private forest structure (age class distribution) and public allowable sale quantities (ASQ). Two different forms of private forest age class structure were considered: (1) a forest with an equal area in each age class, and (2) an imbalanced distribution of age classes with acres divided between an "old growth" class (100,000 acres of age 80 or older) and two second growth classes (100,000 acres each in age classes 10 and 20). Two ASQ time paths on the public forest were represented: (1) an annual ASQ of 190 MMBF per year, and (2) a 40% reduction of the ASQ to 114 MMBF per year in all periods.

For all scenarios, a linear downward-sloping demand function for lumber in each of ten 10-year periods was specified. A linear downward-sloping demand function for export logs was also specified, though a larger price-intercept term was used, so for a given quantity of logs, the export value would be higher than the value of logs used in local manufacturing. Only logs from the industry lands were allowed to be exported.

A maximizing model of this type that is constructed for a finite time horizon is likely to call for all measurable timber (on industry lands in this case) to be harvested in the final period. To mitigate this problem, the model could be constructed for a time horizon long enough that the end-point problem has very little influence on model behavior in the initial periods. Alternatively, a set of ending inventory constraints could be included to require a particular forest structure at the end of the time horizon. The former approach was used in this example, using a 100-year time horizon.

The simulation results are not particularly startling, though we do believe they suggest that analyses of national forest ASQ levels should take into consideration the condition of adjacent private forestlands. The simulations show that for any given ASQ, bid prices for delivered national forest stumpage (Fig. 1) and public and private harvest levels (Figs. 2 and 3) may be volatile when an unbalanced age class structure exists on neighboring private lands, while a more balanced private forest may lead to smoother time paths. These findings support the contention that a steady ASQ on national forest lands cannot ensure stability in local wood products industries, or consequently in the economies of local communities.

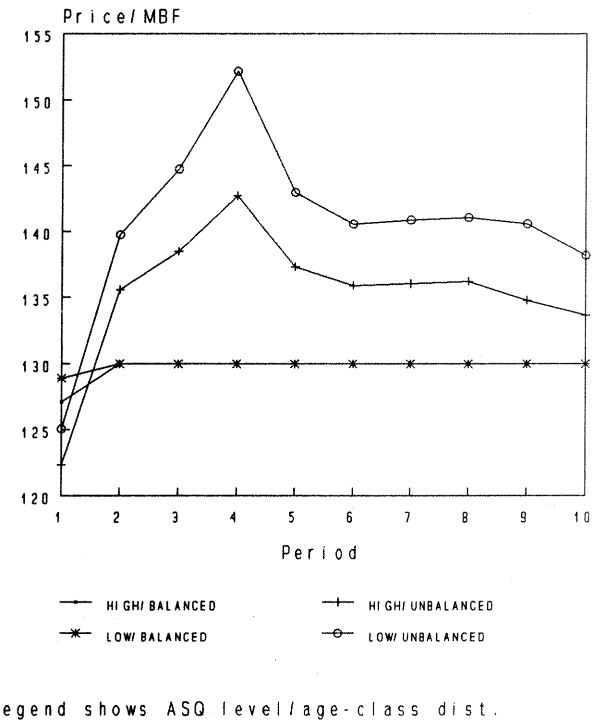

Figure 1--Public Stumpage Bid Prices

The simulations can also be used to assess the consequences of a reduction in the ASQ, by considering the vertical difference (or lack thereof) between the high and low ASQ scenarios for a given private forest structure. Our simulations indicate that the impacts of an ASQ reduction on the local wood products industry may be pronounced when private lands have an unbalanced distribution of age classes, showing relatively large changes in the bid prices for national forest stumpage (Fig. 1), in the volume of timber used in local manufacturing (Fig. 4), and in log exports (Fig. 5). As illustrated in Figure 3, private forestlands with unbalanced age classes may not be able to respond to a reduction in the national forest ASQ with higher levels of production as well as those with balanced age class structures.

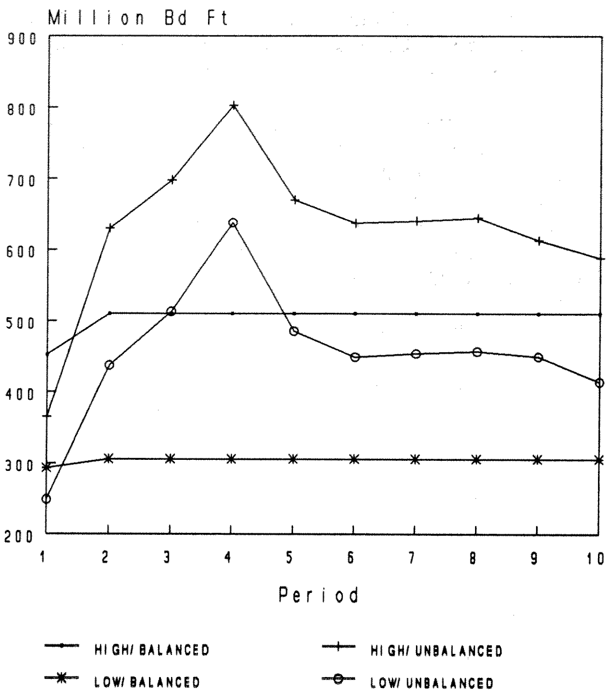

Figure 2--Public Timber Sales

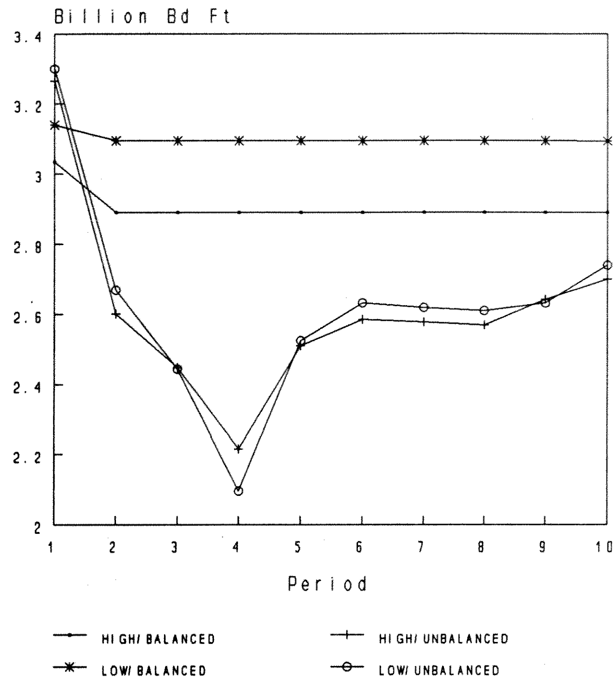

Figure 3--Private Timber Harvests

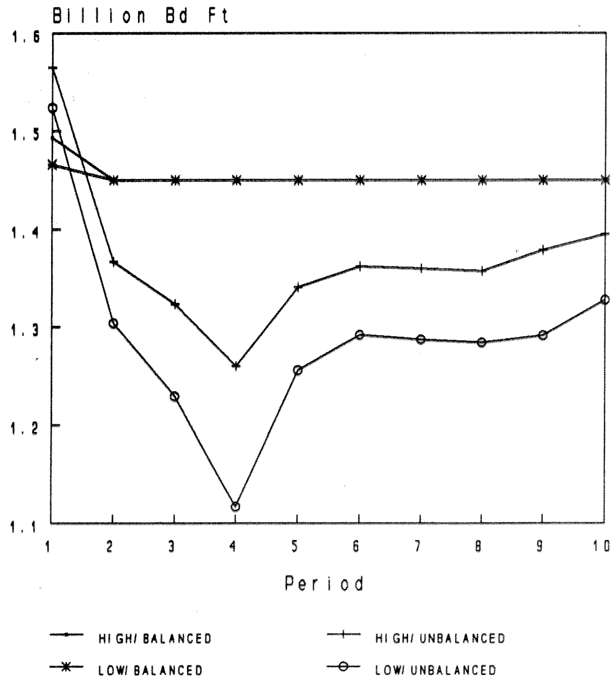

Figure 4--Local Processing

CONCLUDING SUMMARY

We have presented a general approach for assessing public/private timber supply interactions. A simple hypothetical mixed ownership situation was developed to demonstrate the approach. Though the data were hypothetical, we believe that the simulation results were reasonable and do illustrate importance of considering the condition of private lands surrounding a national forest when assessing the impacts of the ASQ level on the local economy.

Assessing public/private stumpage market interactions is a complex problem with many facets: timber and mills are dispersed geographically with some firms having a competitive advantage in certain locations while competitive conditions exist elsewhere, timber is under the control of managers with a variety of objectives, firms must speculate as they purchase timber from public lands that may not be harvested for up to five years into the future, and regulations restrict where logs from particular ownerships can be sold, to name a few. We believe that the general approach outlined here does show promise for incorporating many of these important details into timber supply analyses, though significant challenges remain.

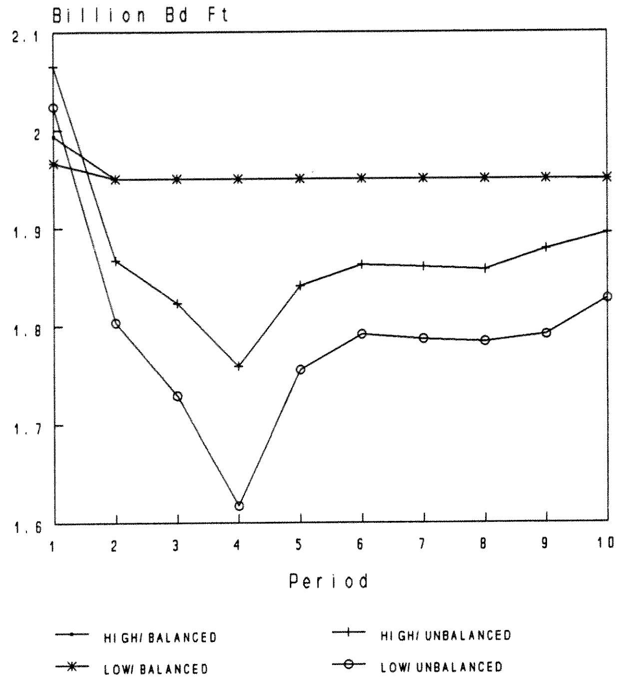

Figure 5--Log Exports

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SIMULATION OF HARDWOOD SAWMILLING OPERATIONS[1]

Roger J. Meimban
Paul C. Kersavage
Terry P. Harrison
Guillermo A. Mendoza[2]

Abstract. This paper examines modeling issues in the simulation of hardwood lumber manufacturing operations. Using the SIMAN simulation language, we developed a hardwood sawmill simulation model with the objective of addressing these issues. The paper focuses on the structure of the model and its operational characteristics. Results of test on the model's ability to simulate actual system are presented.

Keywords: discrete-event simulation, grade yield, machine breakdown, material flow, log breakdown.

BACKGROUND

Previous work in sawmill simulation modeling has primarily focused on two areas. The first class of models deals with the algorithmic representation of log breakdown and secondary mill activities. These models are descriptive in nature and attempt to imitate the patterns a sawyer would likely follow for given log characteristics. This group includes the pioneering work of Riikonen and Ryhanen (1965), McAdoo (1969), Tsokalides (1969), Cummins and Culbertson (1972), Reynolds (1970), Pnevmaticos, et al. (1974), Richards (1979),Savsar (1982), and Occena and Tanchoco (1988). A limited number of log breakdown models have the optimizing capability of searching for the best sawing pattern to maximize recovery as exemplified by the BOF algorithm of Hallock and Lewis (1971).

The second class of simulation models concentrate on the material flow in the sawmill and/or their combination with log breakdown logic. These models primarily use discrete event simulation. These include Martin (1970), Aune (1976), Adams (1984), and Wagner, et al. (1983). These material flow models tend to be holistic in approach. They further consider the time duration of sawmill activities and material and information interchange between the different sawmill subsystems.

Until the early 1980's, most of the models were designed to run on large, mainframe computers. The substantial amount of programming required to model the complexities of lumber manufacturing has also limited the scope of these simulation models. In many cases, models have to be constructed in a modular fashion, with each module addressing a different processing facility. One can use the models independently or fashion them together to form an integrated simulation system. This approach is well illustrated in the work of Van Wyk and Eng (1987) and Martin, et al. (1988) when they applied various simulation models in the step-wise analysis of sawmilling activities.

The development of simulation software has considerably reduced programming effort and has provided major advances in sawmill simulation. Wagner, et al. (1988) used SLAM in modeling southern pine mills while Kline (1989) evaluated hardwood processing facilities using SIMAN and CINEMA. Depending on how a model is structured, the use of specialized languages may still have certain limitations especially when the model would require further program manipulation to suit a particular operation. This limitation led to the proposal of Randhawa, et al. (1989) for a "desk-top" type simulation system for softwood sawmill managers. It was conceptualized as a stand-alone system and features the integration of log breakdown, material flow and sawmill databases.

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[1]Paper presented at the Systems Analysis in Forest Resources Symposium, Charleston, SC, March 3-7, 1991.
[2]Ph.D candidate and Assistant Professor respectively, School of Forest Resources, Penn State University; Associate Professor, Dept. of Management Science, Penn State University; Associate Professor, Dept. of Forestry, University of Illinois.

The previous work has demonstrated the utility of simulation in analyzing log breakdown procedures. Documented applications have likewise related how the technique is used in developing material flow systems and in designing sawmill facilities. Substantial improvement however remains to be exploited to gain greater advantage of the benefits offered by simulation and the availability of new modeling tools.

In modeling log breakdown operation, the inclusion of grade or quality of the material has received minimal effort. It is particularly important for a sawmill manager to gain an estimate of the grade recoveries from log inventories and from sawing policies. Similarly, minimal effort has been made in examining the effect of machine breakdown and other processing delays for the entire mill operation. Traditional methods of treating delays in mill operations, such as linear programming, have failed to capture the impact of this variable over time. Finally, there is the wider issue of how a simulation model should be designed in order to assist a sawmill manager in his day-to-day decision making. A model appropriate for this intent should be flexible enough for easy manipulation and use. Furthermore, it should be capable of providing the needed information in the shortest possible duration.

This paper discusses the development and performance of a hardwood sawmill simulation system with the objective of addressing some of the modeling issues presented such as the integration of material grade in log breakdown and the inclusion of delays in processing. It is developed within the framework of an existing simulation language - SIMAN. The model integrates various facets of lumber manufacturing with the flexibility of simulating several sawmill operating conditions. The paper describes the model's structure and some of the sawmill modeling concepts upon which it was developed.

MODEL ORIENTATION

The simulation model was developed using the combined block diagram/discrete event approach of SIMAN (Pegden, 1986).

The model was structured to minimize further program manipulation of potential users. It is equipped with front-end, data entry menus where the static and dynamic components of a sawmill can be specified. The program's organization and how it works under the SIMAN modeling framework is illustrated in Figure 1. The block diagram component models the flow of materials within the mill while the discrete event component models the log breakdown and other wood processing logic.

MATERIAL FLOW AND WORK STATIONS

The activities in a lumber manufacturing mill can be portrayed as a network of events. Each event has its own processing logic that dictates

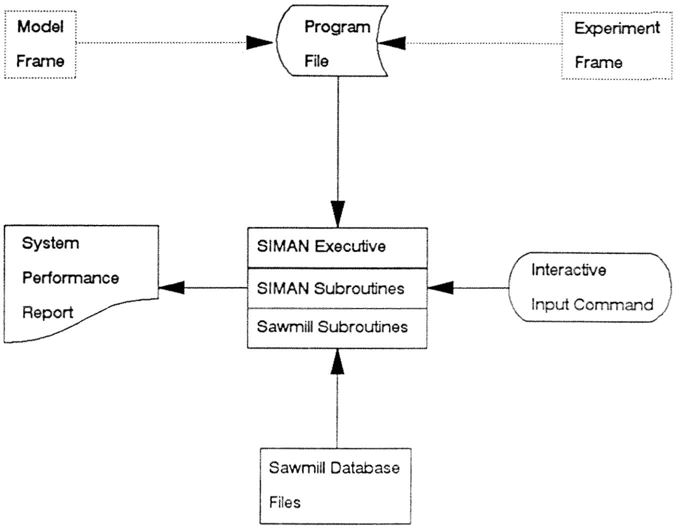

Figure 1. Overview of the interface between SIMAN and the hardwood sawmill simulator.

what changes will occur in the state of the system. When such changes occur, the dynamic characteristic of the sawmill is executed. The structure shown in Figure 1 is based on this discrete event modeling concept with the processing logic imbedded within the model as event subroutines. The network of processing centers that contain standard sawmill facilities are coded in the model frame. Physically, these processing centers are linked by conveyors and transporters and a series of buffer decks with design-dependent capacities. These centers also define the log deck station, headsaw area, edging and trimming stations and the lumber sorting area.

The model treats materials as entities and machines as resources. Entity routing in the mill is governed by the block diagram model and the event subroutines. Initially, a log (or mother entity) is scheduled to enter the system following a user-specified arrival distribution. In the process, the basic attributes or entity characteristics such as species, log grades and dimensions are assigned. Two methods of generating log attributes are used in the system. If the distribution of a log parameter is known, the model utilizes a sampling scheme to generate the necessary attribute from this distribution and assigns it to the entity. The second method assigns the real log parameters as attributes of an entity. This is accomplished by a routine that reads sequentially the log attributes from a data file. This file may contain a set of logs from a sawing schedule or it can represent the log inventory record of the mill.

As the log progresses through the headsaw, a duplicate entity (board or offspring entity) is created. The log engages the headsaw several times until it is completely sawn. The boards assume the basic attributes of the log and as

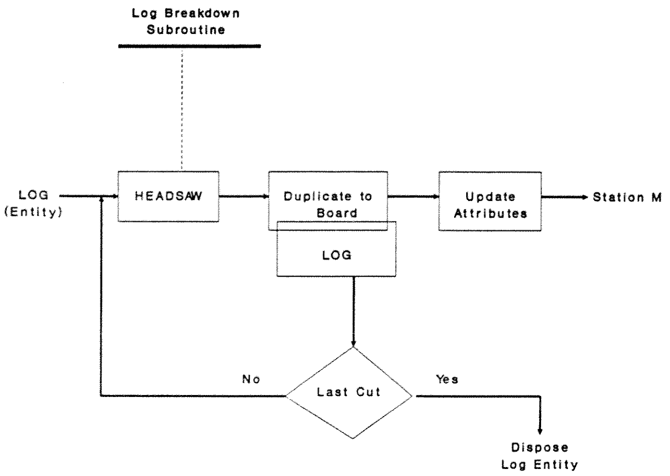

Figure 2. Schematic diagram of the model's log breakdown process.

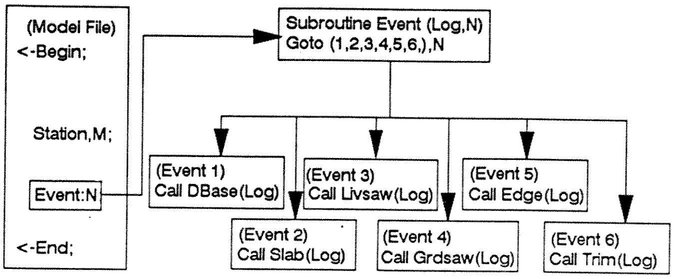

Figure 3. Overview of the interface between the sawmill material flow model and the log processing event subroutines.

they flow through the other processing centers, event subroutines are utilized to calculate and assign other atributes. These atributes include the board's original location in the log, board dimensions, board grade, and next routing station. This process is schematically depicted in Figure 2.

Some of the processing stations are coded as macro-submodels. That is, the stations are similar in structure but with minor differences such as the type of machine and processing subroutines involved, queue capacity, etc. For example, in the headsaw macro-station, one submodel may contain a circular headrig and the other may contain a bandsaw. Each of these substations may also call different log breakdown procedures. These macro-submodels provide a means of selecting the types of facilities that may be present in the mill that is being simulated.

LOG AND LUMBER PROCESSING SUBROUTINES

In the block diagram representation of the system, an entity entering a station may encounter an EVENT block. This block provides the means of accessing the appropriate subroutines for the current operation. These subprograms are FORTRAN-coded log and lumber machining rules. Figure 3 illustrates this interface and further identifies the major subprograms that comprise the simulation model.

The log breakdown subroutines (LIVSAW and GRDSAW) are descriptive simulation routines that mimic the decisions of a sawyer in handling logs of given attributes. The live sawing model is built upon the mathematical formulation developed by Savsar (1982) for hardwood logs. This method focuses on the volume calculations of sawmill by-products and provide the means of analyzing sawmill-fiber balances.

In grade sawing, decisions regarding face orientation and log turning are based on the expected grade that is generated for a cutting face. Initially, grades are assigned to the four faces of the log. The first two cuts are made on the highest graded face where cutting progresses until the board grade drops. The log is then oriented to the next candidate face and the same routine is executed. Another log breakdown procedure- cant sawing, is treated in the model as a variant of grade sawing. This involves an all-around sawing of the log, leaving the largest square cant at the center.

In the edging and trimming subroutines, a modified and extended version of the formulation developed by Kersavage, et al. (1990) was employed. Board sides to be edged are ripped half of the board length. Depending on its original location inside the log, a board may be edged on one side only, on both sides, or it may not undergo edging at all. Trimming allowances are dependent on the values entered by the user.

GENERATION OF GRADES

In real-life grade sawing, grades largely influence the sawyer's selection of cutting patterns. The heterogenous characteristic of wood makes it difficult to precisely simulate the sawyer's actual decision in terms of the number of cuts made on each side of the log, or when to rotate the log from the current cutting face. The dearth of information regarding the internal distributions of log defects further contributes to this difficulty. As a means of providing default values for lumber grade assignment, the simulation model utilizes the grade yield expectation values provided in FPL No. 63 (Vaughan, et al.,1966) These values were transformed into discrete distributions and stored in the system's experiment file. Once an entity is generated and its basic attributes defined, a table look-up function included in the program is used to scan the lumber grade recovery expectation tables. Grade assignment is based on species, diameter, log grade and the board's width.

We note that the averages provided in FPL No. 63 are based on a large number of mills and do not represent any specific hardwood sawmill. The potential descripancies that may arise in simulating the output of grade recoveries is shown in Table 1. The first column contains the empirical results of grade sawing 50 yellow poplar logs that were reported by Peter (1966). Two simulation runs were conducted using two different experimental conditions. In the first simulation run, the empirical distributions established in Peter's study were used. The simulated recoveries from these distributions are shown in column 2 of the table. The other experiment based its grade generation on the industrial averages contained in FPL No. 63 and the simulated results are shown in the third column. Note from the table that simulating from representative distributions results in accurate prediction of grade yield and volume recoveries. On the other hand , a significant difference results if a mill bases its grade generation on industry averages. Thus, we conclude that in real-life application of the grade sawing model, the users should provide their own history of grade recoveries to realistically simulate the quality of their products.

Table 1. Actual and simulated grade recoveries of 50 yellow poplar logs.

	Actual Recoveries	Simulated from Empirical Data[a]	Simulated from FPL Data[b]
Lumber output	6036 bf	6014 bf	5862 bf
FAS	12.84 %	15.3 %	0.70 %
SAPS	30.84	24.2	4.94
SELECTS	8.96	10.3	0.70
No. 1C	28.72	31.8	32.90
No. 2A	5.99	15.5	19.50
No. 2B			7.10
No. 3A	12.63	2.9	3.40
No. 3B			24.50
SELECTS & Better	52.64	49.8	6.34
No. 1C & Better	81.36	81.6	39.24

[a]Empirical grade yield distributions specific for the 50 logs were used in grade generation.
[b]The industrial averages published in the grade yield tables were used in grade generation.

TIME DELAYS AND MACHINE BREAKDOWNS

The time spent by an entity in the system is a major determinant of a sawmill's throughput rate. As material progresses through the mill, time delays are encountered. These delays could be due to the unavoidable time requirement of processing, waiting time in queues, or it could also be incurred by machine breakdowns. In the headsawing operation for instance, the processing time for one log would include the log loading time on the carriage, cutting time, log turning to another cutting face, and the unloading of the last board or shim.

Traditional evaluation of the effect of machine downtime on mill operation involves averaging the total production downtime into a production shift. If used in a simulation model, this approach however cannot capture the operational behavior of the system over time. In the simulation model, machine downtime is incorporated in two ways. First, if the distribution between the occurance of machine breakdown is known, a delay scheduler entity is generated which seizes the machine and delays it for the duration of repair time. However, it is often difficult to establish the distribution of machine breakdown. The second method employed by the model uses logical branching which gives an arriving entity a chance that it will cause a machine breakdown. In practice, this probality is approximated by recording the number of times the machine went down and the number of entities it processed during that period.

SYSTEM INPUT AND OUTPUT

The components of the simulation model presented in the previous discussion can be accessed by the user through a menu-driven, front-end interface which is also the module for entering other information. The input parameters needed to run the model and the program flow of the interface is shown in Figure 4. The input module is coded in SIMAN's subroutine PRIME which is automatically activated at every program execution. Data files such as log inventory files and sawmill layout information can be created, saved and accessed by the model.

Included in the model is a routine which writes the results to an output file. The output report includes the following information: 1) total volume and number of logs processed, 2) lumber volume by grade and species, 3) simulated sawmill operating time, 4) average sawing time of logs, 5) utilization of machines, 6) queue/buffer decks statistics, and 7) number and total length of downtime, if any.

Depending on what aspect of sawmill operation the user wishes to examine, he can interpret the results from several vantage points. For example, if he uses the log counter limit as his simulation run termination criterion, the model will estimate the required time necessary to process the specified log schedule. Likewise, he can record the queue length statistics of several mill layouts or compare the recovery of materials and utilization of resources that results from different log sawing policies.

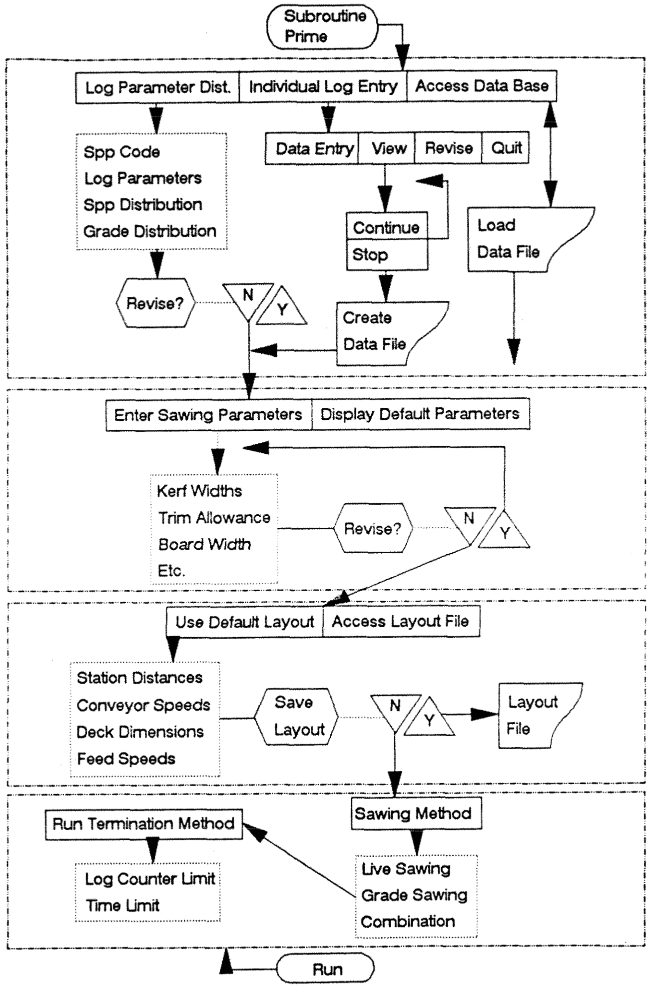

Figure 4. Program flow of the data-entry interface.

TESTING THE SIMULATION MODEL

The ultimate test of a simulation model is its ability to represent the physical system. This section presents the results of simulation runs that were conducted to determine how accurately the model can simulate the operation of an existing hardwood sawmill.

The original information used in testing DESIM (Adams, 1984) was used in this validation. The test mill produced approximately 32 MBF of lumber per 10 hour shift. Among its primary facilities are two circular headrigs, a debarker, an edger and a trimmer. A more detailed description of the test mill and its actual operating performance is provided by Adams (1988).

Among the sawmilling variables that were compared are: 1) the number of logs processed, 2) gross log scale volume, 3) net product yield volume 4) percent product overrun, 5) the total number of times each headrig went down and the total down times, and 6) the average processing time per log. Due to the absence of grade recovery data for that particular sawmill, no attempt was made to validate the grade yield recoveries. The results of 30 replication runs and the actual sawmill performance are summarized in Table 2.

During the 30 simulated 10 hour shifts, an average of 341 logs were processed compared to the 342 logs that were processed on the day the data were gathered. The average sawing time per log for both the simulated and actual operation is 3.23 minutes. For these variables and for the volume of lumber output, actual values fall within one standard deviation of the corresponding means of the simulated variables. A look at the other variables would however reveal the difficulty of closely simulating operation downtimes. The actual values of variables fall within two standard deviation of the simulated means. However, the actual durations of the delays fall within one standard deviation for both headsawing stations.

The simulated log sawing time reported in the table represent the mean of the 30 averages and the standard deviation figure might be misleading. To clarify this matter and for purposes of determining the accuracy of simulating the minute details of log breakdown, the results of a representative simulation run was examined. Figure 5 presents the real and simulated elemental time components of the operation. The slight differences in the time elements would suggest that the model can simulate even the lowest level of detail in log breakdown operation. Figure 6 would further show that the simulated total time from this single simulation run is not significantly different from the actual time.

Table 2. Actual versus simulated values for the test mill.

FACTORS	Actual Values	SIMULATED RESULTS Mean	SD	Percent Difference
Logs processed	342	341	7	-.3 %
Log scale vol.,bf	36680[a]	37928	1082	3.4
Product tally volume,bf	32465	32788	1016	1.0
% overrun	-11.49	-13.55	1.7	-17.9
Delays: Headsaw 1				
Number	31	37	4	19.4
Minutes	33.59	39.5	11.8	17.6
Delays: Headsaw 2				
Number	18	14	3	-22.2
Minutes	27.07	28.9	16.1	6.7
Aver. Sawing time per log, min	3.23[b]	3.23	.02	0.0

[a]International 1/4 inch rule.
[b]Weighted average sawing time for the 2 headrigs.

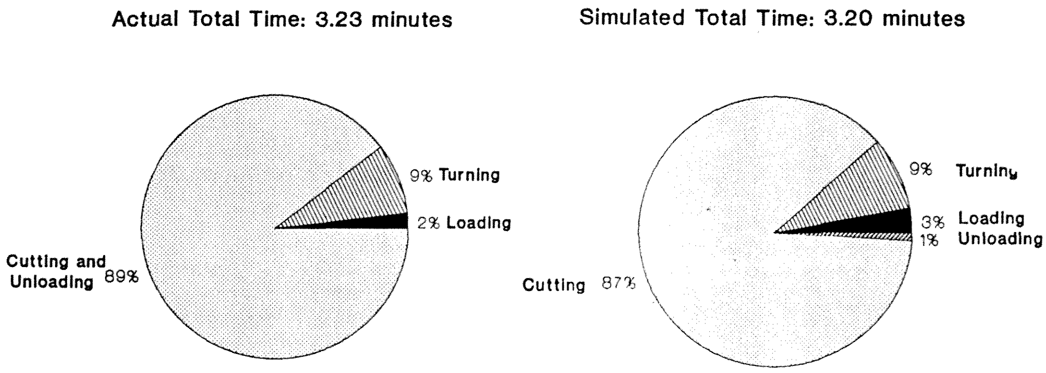

Figure 5. The time elements that comprise the log breakdown operation (grade sawing).

INTERVALS: LOG BREAKDOWN OPER.

IDENTIFIER	AVERAGE	STANDARD DEVIATION	.950 C.I. HALF-WIDTH	MINIMUM VALUE	MAXIMUM VALUE	NUMBER OF OBS.
MEAN TIME	3.20	.587	6.250E-02	1.85	6.32	341

```
                     INTERVALS : LOG BREAKDOWN OPER.

                      1.85          3.20                              6.32
MEAN TIME             <-------------X)--------------------------------->
                                 3.13   3.26

------------------------------------------------------------------------------
| < = MINIMUM   ( = LOWER 95% CL   X = AVERAGE   ) = UPPER 95% CL   > = MAXIMUM |
------------------------------------------------------------------------------
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Figure 6. Confidence interval of the log breakdown processing time.

From these results, it can be satisfactorily concluded that the model can simulate the operation of the existing mill. Under the operating conditions that were specified during the validation, the model can serve as the computer version of the mill where potential improvements could be explored.

SUMMARY AND CONCLUSION

The simulation model presented addresses several areas of hardwood sawmilling. It can be used in many ways such as the analysis of log breakdown operation and sawing policies, as a tool for creating look-ahead scenarios for different production schedules, and in the design and analysis of alternative production systems.

The model works satisfactorily within the boundaries of the sawing parameters specified by a user. For example, the accuracy of simulating grade yield is dependent upon individual milling situations. The present model can handle any thickness of lumber but it is not capable of sawing mixtures of thicknesses from one log. While it is possible to model mixtures of lumber products, the size of the global variable array in the language version we used has limited the capability of the model. Finally, the model still possess some degree of rigidity. Manipulation of the block diagram model might still be needed in simulating very complex sawmill designs that feature a large mixture of processing facilities.

In spite of these limitations, the current model version can represent many types of hardwood sawmills with standard processing procedures. The most recent version of the language we used likewise hopes to overcome the limitations presented. The modeling structure will still be the same but the availability of more user-definable global arrays will allow the representation of other generic processing stations and products. The model is also adaptive in many situations. In the recent work of Mendoza, et al. (1991) for example, the ability of the system to link with other components of an integrated hardwood sawmill decision support system was successfully tested.

The current model version was designed to run on personal computers using the SIMAN simulation language. Previous runs indicate satisfactory computing time, depending on the complexity of the system being simulated. For the study mill presented in the previous section, the model simulated a 10 hour production shift at around 15 minutes on a 286 IBM PC. This fact plus the ease of entry of information on the front-end interface further makes the model a promising tool for real-time control of hardwood sawmill operations.

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CEASAW: A USER-FRIENDLY COMPUTER ENVIRONMENT ANALYSIS

FOR THE SAWMILL OWNER[1]

Guillermo Mendoza, William Sprouse,
Philip A. Araman and William G. Luppold[2]

Abstract.--Improved spreadsheet software capabilities have brought optimization to users with little or no background in mathematical programming. Better interface capabilities of spreadsheet models now make it possible to combine optimization models with a spreadsheet system. Sawmill production and inventory systems possess many features that make them suitable application environments for spreadsheet optimization. This paper describes a spreadsheet model that optimizes log allocation and lumber production.

Keywords: spreadsheet, optimization, bid analysis, log inventory, sawing.

INTRODUCTION

In today's world of advanced technology, many industries have adopted computers to improve efficiency and enhance their business. Some sawmill owners have become interested in the use of computers, not only as an information processing tool, but as a means to help improve their operation and make more efficient use of their resources. However, in spite of the wide acceptance and popularity of computers among many production and manufacturing industries, some sawmill owners remain skeptical and have refrained from adopting any computer-based system.

In an effort to reduce the computer mystique and apparent barrier on the adoption of computers in the sawmill industry, this paper describes a user-friendly computer program purposely designed for hardwood sawmills. **CEASAW** was developed to assist sawmill owners primarily in two areas: Bid Analysis and Log Inventory.

[1]Paper presented at the 1991 Symposium on Systems Analysis in Forest Resources, Charleston, SC, March 3-7, 1991.

[2]Associate Professor, Department of Forestry, University of Illinois, Urbana, Illinois; Resource Analyst, U.S Army Construction Engineering Research Laboratory (USA CERL), Champaign, IL; Project Leader, Southeastern Forest Experiment Station, Blacksburg, VA; Project Leader, Northeastern Forest Experiment Station, Princeton, WV.

Before presenting CEASAW, a brief description of earlier work by the authors dealing with computer-assisted production planning in the hardwood industry is provided in the next section. This previous work lead to the development of **CEASAW** which is discussed in more detail.

EARLIER WORK

Spreadsheet-based models have been recognized as a powerful tool in forest production planning (Leefers, L. 1990; Manness, T. 1990; Davis, L.S., F. Schurr, R. Church, and others, 1990). Recognizing the potential of spreadsheet models in hardwood manufacturing, the authors (Mendoza, G., W. Sprouse, W. Luppold, and others, 1990) developed a spreadsheet-based model called **SEASAW** (Spreadsheet Environment Analysis for the SAWmill owners). The system was developed with two separate modules: **SEASAW** and **SEAIN**. Both modules were developed within the Lotus (1985) environment and are menu-driven. Due to some limitations in programming Lotus's Macros, and restrictions for future expansion and improvements of the two modules within the Lotus spreadsheet environment, another software was developed, namely **CEASAW**. Both systems (i.e. **SEASAW** and **CEASAW**) are similar in that they can both perform tree (or stumpage) sale analysis and log inventory. The major difference in these two systems is the software requirements. **SEASAW** requires that the user has the Lotus spreadsheet program while **CEASAW** is a stand alone, Pascal coded program, requiring no other software to run. Both systems have their advantages and disadvantages.

Since SEASAW operates under Lotus environment, there are many built in advantages to this system. **SEASAW** can take advantage of these inherent capabilities and desirable features of Lotus spreadsheet, such as: 1) relative ease of operation, 2) use of traditional scheme for entering information in a row-and-column format, and 3) highly convenient user-oriented environment, relying on menus, built-in mathematical and statistical functions, including graphics. **CEASAW**, on the other hand, is an executable stand alone program which does not require Lotus, or any other software. At the present time, **CEASAW** has no graphic capabilities and statistics are limited to maximum, minimum, and average values. Future enhancements of **CEASAW** will include export capabilities for outputing ASCII files for further processing.

CEASAW

Computer Environment Analysis for the Sawmill owner or **CEASAW** was developed as a management tool to assist sawmill owners or managers in making better decisions and production plans. The program is a part of a larger system currently being developed involving a computer-assisted decision support system for the primary processing of hardwood trees. In running **CEASAW**, the user is lead through the program by a series of menus and prompts providing for a very convenient, easy and friendly user environment. A schematic diagram of **CEASAW** is shown in Figure 1.

Currently, **CEASAW** has four main modules: (1) Bid Analysis, (2) Inventory Set-up, (3) Log Inventory, and (4) Help Modules. The following sections describe the first three main modules briefly.

Bid Analysis

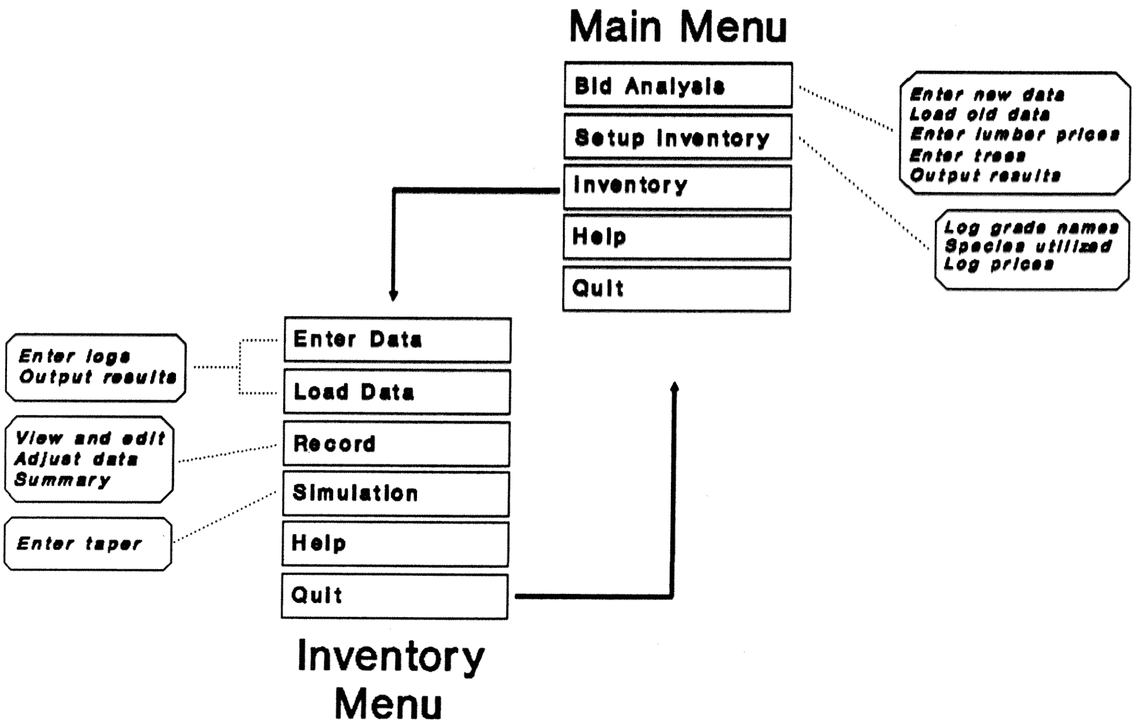
The Bid Analysis Module estimates the amount of lumber conversion by grade and species from each of 17 hardwood timber species. This module is based on the conversion rates reported by Hanks (1976). The rates are estimated for each lumber grade using a regression model:

$$VOL = a + b_1*DBH^2 + b_2*HT + b_3*(DBH^2*HT)$$

where a, b_1, b_2, and b_3 are regression coefficients; DBH is the diameter (in inches), and HT is the height (in feet). Using the estimated volume and given the estimates of lumber prices, the value of a tree or a woodland may be estimated.

After choosing the Bid Analysis module, the user is prompted with the option to either "Enter Data" (thru the keyboard) or "Load Data" (previously created data on file). The user can view, edit, and save the data as needed. Before entering the data (consisting of coded species and grade, DBH, and height), the user has the option to enter or edit lumber prices by species and grade.

Figure 1: Computer Environment Analysis for the Sawmill (CEAsaw)



A complete summary report is shown on the screen while a copy is sent to a file named by the user. Also, there is an option to send a copy to the printer. Table 1 shows an example of the first summary table. This table shows tally information by species and tree grade. Table 2 is also an example of the volume report for each species present during the analysis. Lumber volumes are in board feet while lumber cost or value are estimated assuming lumber price of one dollar per board feet. These prices figures are hypothetical and were used primarily for developmental and illustrative purposes.

<u>CEASAW Inventory Setup</u>

The Inventory Setup Module is used to initialize the Inventory Module. The user enters the log grades used by his/her mill and the prices for each species. **CEASAW** allows for 15 log grades. The program refers to these log grades during calculation as numbers 1 to 15. However, for reports and input entry, the log grades are referred to by the names entered in the Setup Module. Also, the user could set up the program using his own grading system. Next, the user is asked to pick the species used by the mill from the list of 17 possible species.

Table 1: Bid Analysis Summary Table

CEAsaw Summary Statistics

Species Code	Species Name	Total Number	Grade 1	Grade 2	Grade 3
1.	Black Cherry	3	1	1	1
2.	N. Red Oak	1	0	1	0
3.	Black Oak	2	0	1	1
4.	White Oak	2	1	0	1
5.	Yellow Poplar	2	1	1	0
6.	Red Maple	2	0	1	1
7.	Basswood	2	1	0	1
8.	Sugar Maple	2	1	1	0
9.	Yellow Birch	1	0	0	1
10.	Paper Birch	1	1	0	0
11.	Chestnut Oak	1	0	1	0
12.	Black Walnut	1	0	0	1
13.	Ash	1	1	0	0
14.	Hickory	1	0	1	0
15.	Elm	1	0	0	1
16.	Sclarlet Oak	1	1	0	0
17.	Beech	1	0	1	0
Total Number of Trees =		25	8	9	8

Table 2: Bid Analysis Summary Table

CEAsaw Volume Summary
BLACK CHERRY

	--------- tree grade ---------				
	Grade 1	Grade 2	Grade 3	Lumber (Bd ft)	Lumber Value (@ $1/bd ft.)
FAS	62.26	0.00	5.26	67.51	67.51
FAS1F	0.00	0.00	0.00	0.00	0.00
Selects	0.00	6.58	10.65	17.23	17.23
Saps	0.00	0.00	0.00	0.00	0.00
No. 1C	0.00	26.37	15.57	41.93	41.93
No. 2A	0.00	0.00	0.00	0.00	0.00
No. 2B	0.00	0.00	0.00	0.00	0.00
No. 2C	0.00	19.43	16.69	36.12	36.12
SW	0.00	0.00	0.00	0.00	0.00
No. 3A	0.00	3.73	4.27	8.00	8.00
No. 3B	30.87	0.00	1.99	32.86	32.86
No. 3C	0.00	0.00	0.00	0.00	0.00
TOTALS	93.13	56.10	54.43	203.66	203.66

This helps limit the input of prices to only those species utilized. The program will alert the user if he enters a species in the inventory module that has not been marked as being utilized. This avoids invalid or missing prices. After the initial setup, the user does not need to enter the Setup Module again until information, such as prices, are changed.

CEASAW Inventory--Enter Data

When the inventory module is picked from the main menu another menu is displayed. Within the Inventory Module there are three options, Enter data, Load data, and Record.

Enter data allows the user to enter inventory data at the keyboard, within **CEASAW**, one log at a time. When using this option, the user is prompted for some identification information so that each log can be referenced appropriately. The user has the option to use these optional information or leave them blank. These information are used later in the summary section under the Record option. An output file is named which will contain tree number, DBH, length, volume, and cost.

Figure 2 shows an example of the first input screen displayed when Enter Data is chosen. The current log number and the last log number are shown. This is done automatically by the program. A file is created containing the last log number entered during the last session. Each time the Enter Data option is picked, the file is read and the log numbers are changed automatically. This option is provided for the sawmill owner who wishes to perform conversion studies of the logs in the inventory (i.e using Bid Analysis option), or simply to keep an accurate record of log inventories. If the logs are not tagged as they come into the yard the log number can be ignored.

Once the data for one log has been entered the user has the option to quit, edit the current entry, or continue. Once all of the logs have been entered a summary of the session is displayed on the screen. Figure 3 gives a summary of the log size as well as a tally of the species. A similar table is displayed which gives a tally by log grade. These tables may be sent directly to a printer.

Figure 2: ENTER INVENTORY DATA SCREEN

```
output file = test.out

                                 Last Input
  130                  4             1           18          24
   Log number        Species       Grade        DBH        Length
  ----------------------------------------------------------------

  131

                        PLEASE USE THESE SPECIES CODES
1 = BLACK CHERRY           8 = SUGAR MAPLE          15 = ELM
2 = NORTHERN RED OAK       9 = YELLOW BIRCH         16 = SCARLET OAK
3 = BLACK OAK             10 = PAPER BIRCH          17 = BEECH
4 = WHITE OAK             11 = CHESTNUT OAK
5 = YELLOW POPLAR         12 = BLACK WALNUT
6 = RED MAPLE             13 = ASH
7 = BASSWOOD              14 = HICKORY
```

Figure 3: Summary Table

```
                        CEAsaw Mill Inventory Summary

Mon., Aug. 27, 1990                               OPERATOR : BILL
FILE : test.out              LOAD # : A           ID # : B

TOTAL NUMBER OF LOGS...    4
TOTAL VOLUME (DOYLE)...  192.00
TOTAL COST.............    0.00

MAX DBH................   12.00              MAX LENGTH...........    12.00
MIN DBH................   12.00              MIN LENGTH...........    12.00
AVERAGE DBH............   12.00              AVERAGE LENGTH.......    12.00

**************************** SPECIES COUNT SUMMARY *************************

     BLACK CHERRY....4
```

CEASAW Inventory--Load Data

The Load Data option is very similar to the Enter Data option. Load Data will import an ASCII file for the inventory data. The only difference is that the log number is read from the input file and is not entered by the program. It is suggested that the Enter Data Option be used in order to track logs more accurately.

CEASAW Inventory--Record

The Record option allows the user to perform a number of summaries of the data already entered into the program files. This option also allows the user to look at an individual record entered and to adjust data from logs to lumber. Adjusting logs to lumber keeps accurate inventory of logs remaining in the yard and those logs which have been milled.

Summaries can be done by a particular day, week, month, year, load number, identification code, or all of the data in the file. The summaries are then displayed once the data has been read and the summary statistics calculated.

A PROTOTYPE SPREADSHEET OPTIMIZATION MODEL

End user optimization is becoming more widespread. Current software that links optimization with spreadsheet systems now make it possible for a user with limited or no quantitative analysis background to develop useful management decision tools utilizing optimization or mathematical programming. One example of this commercially available spreadsheets with optimization capability is QUATRO-PRO (1990).

The use of mathematical models in various aspects of forest products manufacturing is well described in the literature. Various types of optimization models have been developed for log bucking (Pnevmaticos and Mann, 1972; Eng, G., H.G. Dallenbach, and A.G.D. Whyte, 1986), log allocation (Mendoza, G. A and B.B. Bare, 1986); and lumber manufacturing (B. Faaland and D. Briggs, 1984).

One of the major stumbling blocks in adopting these mathematical models as decision aids for the forest products industry stems from the amount of mathematical rigor required by the models. To install and make effective use of these models would require a staff of technically trained personnel, which is often beyond what most forest product firms can afford. To help alleviate this problem, a spreadsheet-based optimization model for hardwood sawmills was developed as described in the next section. The model is still in developmental stage but initial results appear very encouraging.

The prototype spreadsheet optimization model was developed using QUATPO-PRO. It should be noted that the spreadsheet optimization model is just one of a number of components or modules within an integrated decision support system currently under development which covers a wide range of manufacturing aspects such as: bid Analysis, log Inventory, sawmill design, simulation and optimization.

In developing the model, it was necessary to make all programming transparent to the user in order to relieve him of the intricacies of data manipulation and model building. While it is desirable to make the model totally menu-driven, it was not possible to develop a "generic" as well as a flexible model that could be used by different end-users. This is especially true in an optimization environment where the parameters and the scope of the problem to be optimized must be well-defined. Sawmills have different lay-outs, including other physical attributes and operational environments. To make the model more relevant, and at the same generic and flexible enough to accommodate various manufacturing conditions, it was necessary to develop "modular" optimization models, where each module addresses a more specific manufacturing scenario. One of the modules already developed is the Log Allocation Module described below:

Log Allocation Module

This module was developed to address a log allocation problem typically found in many sawmills. One of the concerns in lumber manufacturing is what log mix should be processed to meet a lumber demand on a daily or weekly basis. It is also common among sawmills to merchandise their logs instead of processing them into lumber. Hence, sawmill managers are often faced with the problem of deciding what type of logs (by species, grade and size) should be allocated to the log market for merchandising, and what mix of log input (by grade, species and size) should be processed to meet actual and projected demands for various lumber products.

This log allocation problem for a given species, can be simply described as a mathematical programming problem as follows:

$$\text{Maximize } R = \Sigma P_k Y_k - \Sigma c_{ij} X_{ij} + \Sigma m_{ij} Q_{ij}$$

$$\begin{aligned} \text{s.t.} \quad Q_{ij} + X_{ij} &\le L_{ij} && \text{for all } i,j \\ Y_k &\le D_k && \text{for all } k \\ \Sigma \Sigma r_{ijk} X_{ij} - Y_k &= 0 && \text{for all } k \end{aligned}$$

where: R = economic return
P_k = price of lumber grade k
C_{ij} = cost of processing (sawing) log grade i, of size j
M_{ik} = price of log grade i, size j sold in the market
Y_k = amount of lumber grade k produced
Q_{ij} = amount of log grade i, size j sold in the market
X_{ij} = amount of log grade i, of size j sawn
L_{ij} = amount of log grade i, of size j *stored in the inventory*
D_k = estimated demand for lumber grade k
r_{ijk} = lumber recovery rate in percent, of processing log grad i, size j, into lumber product k

Interfacing CEASAW with Spreadsheet Optimizer

The interface capabilities of QUATRO-PRO provides a very convenient way of combining **CEASAW** with the log allocation optimization module described above. The structure of this interface is described in Figure 4.

The subprogram CEAOpt basically constitutes the vehicle that interfaces **CEASAW** and QUATRO-PRO. CEAOpt takes the information from **CEASAW**, specifically through the Log Inventory and Lumber Conversion, then systematically derive the conversion rates and log availability for each species and grade. These information will provide values for L_{ij} and r_{ijk} in the log allocation module. CEAOpt automatically creates an input file for subsequent optimization. A separate input file can be created for each species. These input files are designed and created so that they are compatible with the format required by QUATRO-PRO Optimizer. CEAOpt requires from the user information on prices of log and lumber products, processing and procurement costs, and expected demand for log and lumber products. Other than these pieces of information which are entered interactively by the user, the program is automated through menu-driven user-specified options eliminating any programming or data manipulation requirement from the user.

At this time, the output processor is still under development. Efforts are underway to design the output so that only relevant and useful information are displayed and summarized.

CONCLUSIONS AND FUTURE DEVELOPMENT

CEASAW offers an easy to use program that the sawmill manager can use to estimate lumber conversion as well as keep track of the log inventory. The program is completely operational although further testing is still being conducted. At the same time, refinements and further developments on the program are in progress. As previously stated, **CEASAW** is a part of a larger system designed as an integrated decision support system for hardwood sawmills. Besides **CEASAW**, a sawmill simulator has also been developed as an integral part of the decision support system. **CEASAW** can now be interfaced or linked to the simulator. Besides interfacing **CEASAW** with the simulator, it can also be linked to an optimization program using QUATRO-PRO. This optimization program is designed to provide the user with the capability to allocate and process available raw materials into final products in the most efficient manner.

ACKNOWLEDGEMENTS

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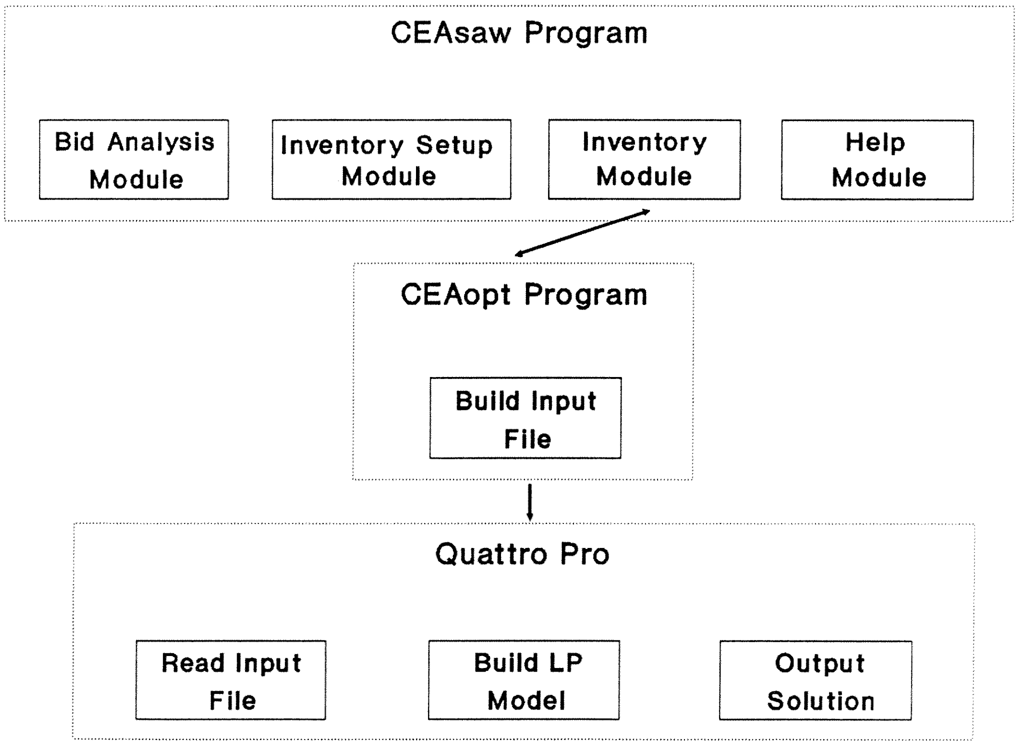
Figure 4: Link between CEAsaw, CEAopt, and Quattro Pro



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ASSESSMENT OF COMPUTER INTEGRATED MANUFACTURING ISSUES RELATED TO THE HARDWOOD LOG SAWMILL[1]

Luis G. Occeña[2]

Abstract.--This paper assesses the issues and presents alternatives on how to integrate the various technologies now available to hardwood log sawmills, so that these technologies will cooperate in helping the sawmill achieve better lumber yield. Computer integration issues and the current sawmill setup are reviewed. Models of a computer-integrated hardwood sawmill are then described. Issues concerning the integration of both hardware and software are also discussed.

Keywords: Computer integrated manufacturing, hardwood log sawmill, issues, assessment.

INTRODUCTION

The hardwood log sawmill, traditionally operated by small private owners using long-time manufacturing methods, has undergone a gradual yet major change in the last ten years. A modern hardwood sawmill today is equipped with numerically controlled headrigs that allow for precise positioning of the log relative to the band saw, as well as low power laser emitters that provide fine beams used as alignment reference lines in cutting. The sawmill may also have microcomputers that assist the sawyer in estimating the eventual yield of a log given its gross dimensions, and perhaps a program to compute for an adapted best opening face.

These new equipment, however, exist as islands of automation. Powerful in their own right, but only co-existing, not cooperating. The ultimate determinant in the breakdown of the hardwood log and consequently in its yield, is the human sawyer who must decide with the aid of these separate equipment how to break the log into useable sections. There are more new equipment on the way. Studies in several universities, private and governmental institutions are looking into the feasibility of applying non-invasive log scanning equipment that will provide views of the internal condition of the log (Chang, Olson, & Wang, 1989; Donald, Anderson, & McMillin, 1990). Eventually, the presence of these technological developments if allowed to merely co-exist will result in information overload for the human sawyer that will cause the sawyer to either use the information incorrectly, or simpy to ignore the information.

This paper will assess the issues and present alternatives on how to integrate the various technologies now available to hardwood log sawmills, so that they will cooperate in helping the sawyer and the sawmill achieve better lumber yield. Computer integration and the current sawmill setup will be reviewed. Models of a computer-integrated hardwood sawmill will then be described. Issues concerning integration of both hardware and software will also be discussed.

COMPUTER INTEGRATED MANUFACTURING

Computer integrated manufacturing (CIM) has been a buzz word in the manufacturing industry within the last decade. What exactly is CIM? Is it a new technology? Is it a set of techniques for gaining manufacturing productivity?

CIM is not a type of technology. Neither is it a set of techniques. Rather it is a way of thinking, an approach to structuring information necessary to run a system of people, machines, and materials. Central to CIM is of

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[2]Assistant Professor of Industrial Engineering, University of Missouri-Columbia, Columbia, MO.

course the computer, without which such an approach would be difficult to achieve. The basic premise in CIM is that decisions are interrelated, and thus should not be made in isolation. This premise holds true, regardless of the application area.

Examples of CIM can be found in fabrication industries where the importance of the link between product design and product manufacturing have only of late finally been realized.

In 1981, John Deere Tractor Works in Waterloo, IA won the LEAD (Leadership and Excellence in Applications and Development) award from the Society of Manufacturing Engineers in recognition of their CIM application (Thompson, V. & Graefe, U., 1989). With objectives of producing top quality products, performing work in the most efficient way, and providing employees with a supervisory work environment, John Deere reorganized functional manufacturing activities in a cellular arrangement. Cellular arrangement groups together machines and operations involved in producing products with similar process and routeing operations, thereby providing a complete production cell that can perform the major operations from beginning to end. As a result, John Deere achieved a 25% reduction in number of machines required, a 70% reduction in the number of departments, a 56% reduction in job change and material handling, an 8-to-1 reduction in required lead times and corresponding reduction of inventory, and a clearer delineation of responsibility among shop supervisors (Thompson, V. & Graefe, U., 1989).

Schlie and Goldhar (1989) reported on findings by the Boston Consulting Group that by using CIM and concurrent activities, Japanese companies could develop projection TV systems in one-third the time required by U.S. firms; develop plastic injection moulds in one-third the time required by U.S. firms at 30 percent lower cost; and develop new cars in half the time required by U.S. firms, with half as many people. Table 1 in the appendix illustrates an example of completion times for different stages in the development of marine gears, as reported by the Boston Consulting Group (Schlie & Goldhar, 1989).

Schlie and Goldhar (1989) also described the case of Allen-Bradley, a division of Rockwell International that makes programmable controllers and other electronic components, which built a CIM facility to make motor contactors and control relays. The facility could produce 600 different versions of these products in lot sizes as small as one, with zero defects, and with lead times as short as 24 hours or less. The interesting thing was that the facility was built, not for cost-payback reasons, but for strategic purposes of competing in world markets where different design standards prevailed, and countering foreign imports.

CIM, however, does not depend on technology itself. Thomson and Graeffe (1989) reported that a Canadian mission to Japan quickly realized that automation in a variety of forms, e.g., numerical controlled machines, robots, etc., was not the key to streamlined production because each only improved an area of specialization. Neither is CIM to be attributed to the interconnection of these automated machineries because interconnection only achieved "interfacing of islands of automation", not true integration. Neither CIM advantage to be found in increasing the efficiency in each step of production from sales order to packing slip, because direct production costs today account for only a small fraction of total product cost.

The key to CIM can be found in improving the coordination and control between steps in the process, especially for support systems, such as in-process inventories, excessive management structures, and equipment, which now account for the largest share of total product cost. This perspective is consistent with the basic premise in CIM of unified decision-making stated at the beginning of this section. CIM will require a team approach, an opening of communication between the various hierarchical levels and departmental structures in the manufacturing system, even perhaps the re-definition of these levels and structures if necessary. Foremost in the realization of CIM is the concept of information integration. All else, i.e., the application of group technology and the flexible manufacturing cell concept, just-in-time and inventory reduction practices, quality assurance, etc., proceed from information integration. Figure 1 in the appendix reflects this position.

CIM has been viewed in a number of ways. Thomson and Graefe (1989) viewed CIM as a paradigm that promotes the integration of organization, planning and control as a solution to improved productivity by the maintenance of a single, information record. Others hold the more conventional view that CIM is a machine-driven development rought about by the advent of computer-aided systems such as computer-aided design (CAD), computer-aided process planning (CAPP), computer-aided manufacturing (CAM) employing numerical control and robotics, and the need to integrate these technologies together. Symon (1990) and Havn (1990) reported a contrary view of CIM as a human-centered endeavour, arising from their work with the European ESPRIT project.

A common thread in all these views is still the central theme of information integration. The machine-driven CIM perception relies on the availability of mathematical models, i.e., algorithms and heuristics, which provide a "predictive" capability of system behaviour. Human-centered CIM emphasizes the presence of a "non-predictive" capability which only humans can fulfill. Support systems, such as computer simulation tools provide a middle-ground between predictive and non-predictive capabilities through the use of statistical analyses.

THE HARDWOOD LOG SAWMILL

Hardwood log processing can be viewed in three stages. Stage 1 involves the harvesting of the log from the forest, where a tree is felled, delimbed, bucked and topped into a log, scaled, graded, and finally hauled to the sawmill. Stage 2 involves the sawing of the log into flitches, followed by edging and trimming of the flitches into green lumber, grading, and drying. Veneer production is a variation in that the log is quartered into sections for veneer slicing. Stage 3 involves the cross-cutting or ripping of dried lumber in to blanks for final use, as in furniture-making. The focus of this paper is the second stage, which takes place in the hardwood sawmill. The first and third stages, however, will be alluded to later in the paper.

Hardwood sawmill processing consists of at least seven basic operations: debarking, loading on dock, positioning on carriage, sawing, edging, trimming, and grading. Debarking of the log, or bark-removal, is a pre-processing done to help maintain the saw blade, and to upgrade the quality of bark chips that can be salvaged for other uses. When sawing is about to be performed, the debarked logs are loaded onto a log deck, a sloped platform with a log-stop at the end, where logs await processing. Figure 2 in the appendix illustrates a typical sawmill layout.

When the log-stop is lowered, the log rolls down and is caught by a loader mechanism which loads the log on to the carriage. The log is held on the carriage by two claw-like fixtures known as dogs. The carriage is a heavy-duty trolley that runs on tracks, and feeds the log into the saw in a number of passes. The log is turned over in the log-carriage so the sawyer can decide the best-face to saw. Turning is done using a log-turner mechanism which thrusts up at the log as it rolls outward from the carriage when released by the dogs, flipping the log along its longitudinal axis.

Log sawing is accomplished by passing the log, held by the dogs and the carriage knee, past a belt-driven saw. The carriage is indexed towards the saw by the thickness of the flitches to be removed. The saw, which can be a band or circular blade, is housed in a frame known as the headrig. As the carriage passes by the headrig, a slab or flitch is sawn from the log. The slab or flitch drops onto a powered conveyor which takes the slab or flitch to the next operation. The carriage then retracts to the feed position. After a log face is chosen, the carriage indexes outward for the next pass.

The sawyer operates the carriage control, and judges how the log is to be sawn. The sawyer sits in a control box with an end-view of the log and the saw. The sawyer is aided by numerical control, a video monitor hooked up to perimeter video-cameras, and a low-energy laser-generated beam for sight alignment of log and saw.

With hardwoods, the log is usually sawn on the same face, until a defect, i.e., knot, split, etc., is detected on the face. The log is then turned 90 degrees for an orthogonal cut, intended to prevent distribution of the detected defect in the subsequent flitches. The log is turned again whenever defects are detected on the current sawing face. This log breakdown pattern, known as sawing-for-grade or around-sawing, attempts to box in the center of the log from which most defects emanate. A number of other log breakdown patterns exist.

Edging immediately follows sawing. The task is performed by an edgerman who retrieves the flitch from the conveyor and positions twin saws at the flitch edges, i.e., parallel to the longitudinal axis of the flitch. Edging is done to remove wane and other edge defects, and to produce a parallel-edged lumber piece. Whereas before, light-generated "shadow lines" were used as guides in positioning the twin saws, today, the job can be done with the help of low-energy laser beams.

The board then goes to the trimmer saws, where wane and other defects are removed from the ends and the lumber piece can be cross-cut to desired length. This task is done by a trimmerman, who like the edgerman, judges the amount of wane and wood to remove. The end result is known as green lumber. After being sorted by size and species, the lumber is then evaluated by a professional grader. The grade is based on the estimated proportion of clear cuttings that can be extracted from the poorer of the two lumber faces. Rules for grading have been defined by the National Hardwood Lumber Association.

Recent developments report the application of non-invasive imaging technologies, such as computed axial tomography (CAT) (Donald & Anderson, 1990; Bryant & Funt, 1987) and nuclear magnetic resonance (NMR) (Chang, Olson, & Wang, 1989), to the detection of internal log defects. This capability will enable proactive, rather than reactive, sawing decisions on the part of the sawyer. There is also increasing use of programmable controllers, which can activate devices and switches as outputs in response to the conditions of input sensors. There have also been studies in the automated utilization of non-invasive scanning information in directing log breakdown decisions (Occeña & Tanchoco, 1989; Occeña & Tanchoco, 1991).

These developments, while providing specialized control of certain aspects of log processing, also provide additional information that has to be digested by the sawyer. As early as 1970, Hallock (1970) reported studies (Wilke, 1966) which showed that human operators can evaluate information and make correct decisions at a maximum rate of five bits per second. More recent studies by ergonomists have shown, not only that the rate at which human workers can process sensory inputs and generate information outputs is biologically limited, but that the human error-rate, i.e., the fraction of information outputs that is garbage, tends to rise sharply as the worker approaches maximum output (Ayres, 1989).

Thus, unless the information made available by technological advances is integrated, the sawyer under duress of information overload may choose to simply ignore the information, or interpret it incorrectly. There can be no more compelling reason for consideration of CIM than the improper use of costly capital investments. There is also untapped potential for productivity improvements from streamlining control of existing equipment that merely co-exist as islands of automation.

CIM AND THE HARDWOOD LOG SAWMILL

So where does one begin in relating CIM and the hardwood log sawmill? Begin by looking at the types of technological applications, activities, and information active in the sawmill system. Table 2 in the appendix gives an outline of the pertinent types. For example, the internal imaging operation involves non-destructive imaging technology and provides information on log and defect profiles. The sawing operation involves numerical control, laser, programmable control, and data acquisition technologies, from which provide information on log positioning, control parameters, and sawing results.

The information provided by the different operations can then be examined for interrelationships which signify candidate information for integration. It is possible to visualize, for instance, the interrelationship between sawing, edging, and trimming. While they are separate operations performed by three different people, it is not unreasonable to think that when the sawyer examines a log face and decides to saw a flitch, the sawyer estimates a possible lumber grade with a particular edging and trimming pattern in mind. Without communication, or without the integration of information, the edgerman and trimmerman downstream will have no way of knowing the intended edging and trimming, resulting in different cuts. Message passing between remote workstations is now possible through local area computer networks that can convey multi-media information in broadband mode.

With this line of thinking, it becomes apparent that while intermediate activities exist which provide boundaries, such as log grading and lumber grading, there are relationships across the three stages of hardwood processing. As Figure 3 in the appendix illustrates, the result of bucking and topping in stage 1 constrains the lumber that can be sawn from the log in stage 2, whereas the sawing operation in stage 2 constrains the blanks that may be extracted during roughmilling in stage 3. Perhaps there should be a feedback loop between stages, as denoted by the dashed lines in Figure 3, to integrate information about end-use in later stages in the earlier stages. It is interesting to note with the prevailing emphasis today in just-in-time and pull systems, that the early sawmills operated in a "pull" system environment, i.e., lumber was cut based on customer orders.

From the types of information passed, a computer integrated sawmill system may be organized with two major activity phases: process planning and process control. The sawmill process planning phase, as depicted by Figure 4 in the appendix, involves a planning activity which can take place off-line, prior to sawing. It will have internal scanning information, roughmilling requirements, and grading requirements as inputs, and sawing, edging, and trimming decisions as outputs. The input information has to considered concurrently, thus in an integrated fashion. Information processing tools might include mathematical algorithms and heuristics (predictive), computer simulations and statistical analyses (quasi-predictive), and the dimension of human analysis and expertise (non-predictive).

The sawmill process control phase, depicted by Figure 5 in the appendix, represents the execution phase where the actual sawmill operations are carried out. It will therefore involve on-line monitoring, and adaptive measures. For example, position monitors on the log carriage will supply feedback information on log position, while the sawing operation is ongoing so the log can be properly positioned. Sawing information, including intentions for grade yield, will be passed on as instructions to the edging and trimming operations. Lumber grading can also feed back grade information to sawing, edging, and trimming operations as a baseline for performance evaluation.

Implied in the above description is the processing of information, for automatic planning and control if possible, and for integrated presentation to the human operators where automation is not possible. It is not inconceivable that in a human-centered computer integrated sawmill, the sawyer can interact with a computer to plan for the best breakdown pattern that will be specific for a given log, prior to actual sawing.

CONCLUSIONS

This paper presented an assessment of computer integrated manufacturing issues related to the hardwood log sawmill. It covered a review of computer integrated manufacturing issues, a review of the status quo of hardwood log sawmills, and a description of an approach to the application of CIM concepts to the hardwood log sawmill. A human-centered CIM model is a viable option for the hardwood log sawmill, with associated integration of the information content found in the sawmill and the other two hardwood processing stages.

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Table 1. Comparison of Marine Gear Development Stages (Schlie & Goldhar, 1989).

Development Stage	Western Company (approx. months)	Japanese Company (approx. months)
Conceptualize Design	3	1.5
Complete Design	3	1.5
Review Design	0.5	1.3
Detail Design	4.5	1.3
Build Prototype	7	2.3
Do Pilot Test	3	1.5
Do Field Test	10	4.6
Manufacture First Product	7	4.5
TOTAL	38	18.5

Table 2. Outline of Operations, Technologies, and Information in the Sawmill.

OPERATIONS	TECHNOLOGIES/ ACTIVITIES	INFORMATION
Log Scanning	non-destructive imaging	log and defect profiles
Setworks	numerical control; programmable control; laser sight; data acquisition	positioning; operational control parameters
Sawing	video-monitoring; feedback control; computer	sawing decisions; yield estimates
Edging	laser alignment, numerical saw	positioning; edging decisions
Trimming	numerical saw	trimming decisions
Grading	computer	grading decisions

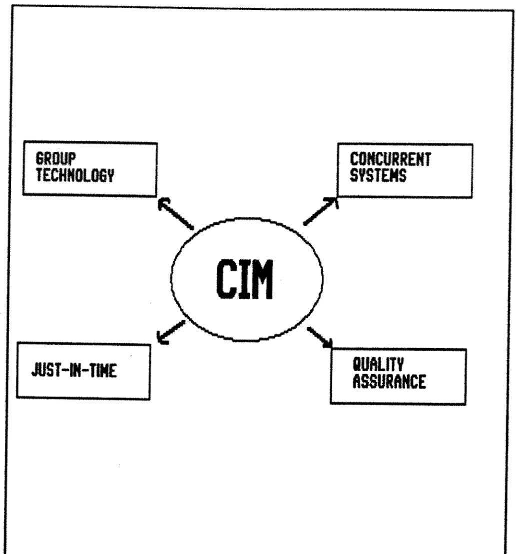

Figure 1. Central role of CIM

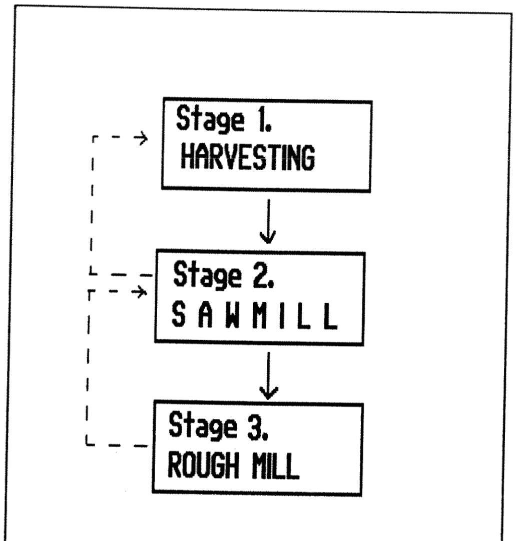

Figure 3. Cross-stage dependencies

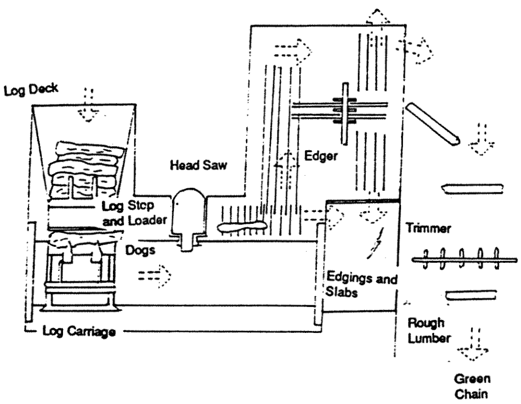

Figure 2. A Typical Sawmill Layout.

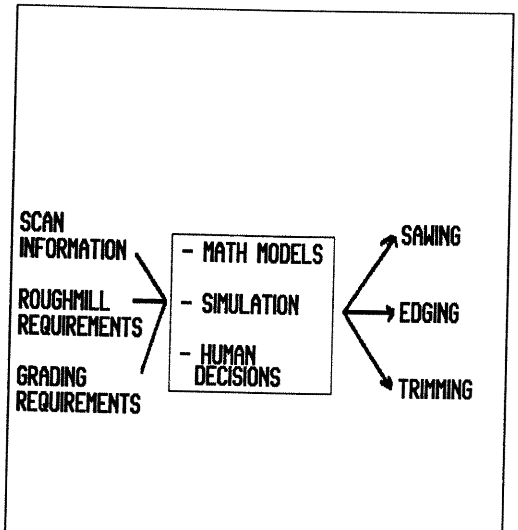

Figure 4. Sawmill process planning

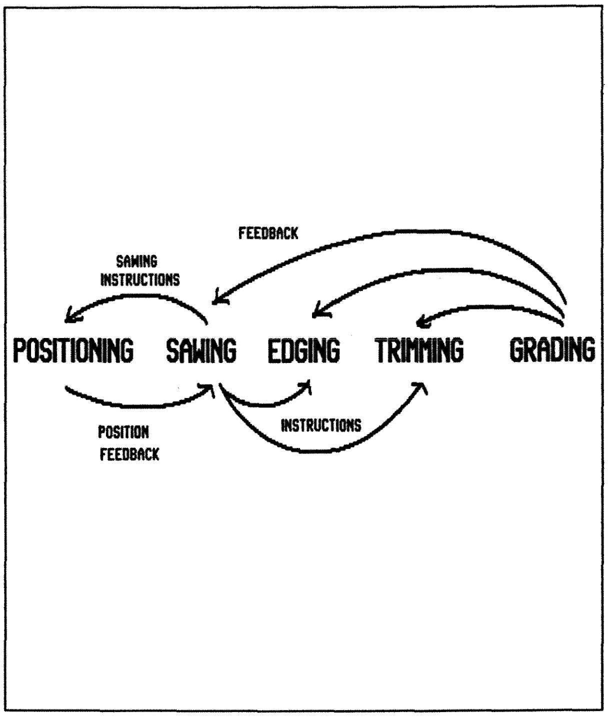

Figure 5. Sawmill Process Control

THE EVOLUTION OF ANALYTIC APPROACHES TO SPATIAL HARVEST SCHEDULING[1]

J. Douglas Brodie and John Sessions[2]

Abstract.--After nearly three decades of attention to strata-based allocation and scheduling problems, recent research and practical attention has focused toward plans that provide actual implementable plans on a harvest unit basis. In addition to traditional stability and sustainability concerns, issues of transportation, habitat maintenance, corridors and landscape adjacency are addressed.

Keywords: integer programming, Lagrangian relaxation, random pattern search, heuristics

INTRODUCTION

Early computer based approaches to the harvest scheduling problem evolved to maturity during the 1960's and 1970's. Linear programming was the primary tool, and due to its limitations, the problem was necessarily conceived as an allocation of large-area resource strata over time, in a manner that could optimize production while meeting stability sustainability and limited concerns dependent on strata distinctions.

During the 1980's, larger and more sophisticated versions of these approaches evolved (Johnson and Stuart 1987) in tandem with increasing computational power and an exponential increase of technicians conversant with the approach. As the solution to the strata-based scheduling problem was approaching maturity, policy concerns were redefining the problem from one of strata concern to one of spatial concern. These spatial concerns were not in essence the macro-spatial concerns of the classical economic spatial equilibrium model (Takayama and Judge, 1964). These concerns are micro-spatial and wicked in that they superimposed individual harvest unit concerns of access over time, adjacency over time, habitat dispersion and fragmentation and habitat and riparian corridors on the existing concerns of production, stability and efficiency over time.

Before moving to discussion of these concerns specifically, it is interesting to look at several approaches initiated in the 1970's that provided impetus to the current spatial focus.

In the late 1970's, Navon (1990) enhanced his existing Timber Resource Allocation Model (RAM) to Roading Timber RAM. This package utilized mixed integer programming methods to optimally select road projects and harvesting methods.

Johnson and Scheurman (1977) produced a seminal monograph that summarized and formalized previous efforts in mathematical programming approaches to harvest scheduling. Contemporaneously they were working on the TREES model (Tedder et al 1980). This approach combined classical approaches of area and volume control and innovative binary search approaches in an integrated software package of fairly simple algorithms (Chappelle and Sassaman 1968, Sassaman et al 1972). These approaches refined and extended, through simple computer algorithms, the standard area-volume check approach. Inadvertently, this approach would provide linkage to the optimal control literature via inclusion of the PNW or ECHO (Walker 1976) option.

Binary search approaches use fairly large strata and provide continuous solutions. They are no more spatially oriented than linear programming, however, they do overcome the binding limitations on number of strata inherent in mathematical programming formulations.

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[2]Authors are Professor, Forest Resources and Professor, Forest Engineering, College of Forestry, Oregon State University, Corvallis, Oregon 97331. Research supported by the Coastal Oregon Productivity Enhancement (COPE) Program and the Oregon State University Forest Research Laboratory.

Aggregation is undertaken with these techniques for purposes of simplification, not as a "shoehorn" to fit a technique. The solution and approach sacrifice general optimality conditions, which are of importance to analysts at least, and a theoretical flexibility of simultaneous constraint formulation. These approaches tended to wean the profession of what might be called "optimality innocence" and paved the way for heuristics.

The pioneering linkage between strata-based scheduling and spatial concerns was undertaken in the late 1970's and utilized the classical mathematical approaches of mixed integer programming. Kirby et al (1980) undertook this spatial analysis almost a decade before general interest in the problem had developed within the profession. In the process, they set the pattern for later studies and approaches and defined the limitations of classical integer programming approaches.

The first limitation of integer programming is analogous to linear programming. It is the dimensionality or sheer size of problem specification. It is overcome in two ways. First, by applying the technique to small areas or sub-basins. Secondarily, as more harvest units are added in the integer programming problem, there is a tendency to underspecify the existing formulation or re-specify the problem with fewer types of constraints or very short time horizons. The second limitation, once a specification within the limits of existing software is reached, is a computational burden to find and prove optimality.

To summarize, many interesting problems cannot be specified for existing software, and many specified problems take impractical lengths of time to solve. Kirby et al (1980) also defined and explored techniques for transportation and harvest method optimization either within the integer programming formulation, which compounds the problems mentioned above, or as a secondary optimization problem. These early studies explored the bounds of mathematical programming techniques in the context of spatial harvest scheduling, and when limitations were encountered, practical rationalizations were proposed that are suggestive of later purely heuristic approaches.

SPATIAL SCHEDULING APPROACHES

We will deal with three broad categories of approaches to spatial scheduling. These in order of complexity are: random search approaches, programming derived approaches (Lagrangian Relaxation), and combinations of heuristics. These distinctions are essentially adopted for orderly presentation rather than classification, since all of them are essentially heuristic and of course can be combined for particular problem specifications.

Random Search Approaches

Random search approaches key off the observation that while optimal solutions to integer problems are difficult to find and prove, there are often a large number of feasible integer solutions to many problem specifications. These solutions, while non-optimal, can often be generated rapidly and often made to conform to outside information about the problem. An example would be avoidance of very low-valued solutions by allowing the random search process to save only solutions with objective function values no more than 5 percent below a corresponding continuous formulation or in volume formulation, related to some theoretically determined sustained yield. Selection of activities that would be known to contribute to high valued solutions can be "pre-biased" by weighting the random generation process (O'Hara et al 1989). We have generally found pre-biasing unnecessary, however, constraints such as minimum harvest ages can simplify the array of choices.

Random search methods have most frequently been applied to adjacency or harvest dispersion problems or lagged adjacency problems. More recently, they have been shown to be applicable to meeting habitat connection corridor constraints to meet riparian or wildlife travel concerns (Sessions and Sessions, 1990). Given a random start, algorithms are available to provide connective corridors at minimum cost or maximum benefit (Sessions 1991). Such corridors can be described as "optimal" subject to the random number seed. Another example of secondary optimization within a random search process is provided by Sessions and Sessions (1990). For each adjacency feasible solution provided by random search, a harvest system plus road construction minimization is performed using network analysis. Extraction costs are minimized given a feasible but not necessarily optimal spatial harvest pattern. Recent examples of random search approaches to spatial harvest scheduling, in addition to those cited above, have been provided by Nelson et al (1991) and Clements et al (1990).

There are several shortcomings of the random search approach. First, it is usually applied to short time horizon problems, meeting adjacency constraints for 2-3 or rarely 4 periods. Short time horizons simplify the problem of course, but there is also a problem of feasibility for extended periods. Building a harvest pattern from a single initial-period random seed in a sequential manner will eventually preclude future period feasibility. The solution is to develop a process that preserves a larger number of harvest orderings. Such a method will be discussed later.

A second shortcoming is that the harvest level in each period must be exogenously supplied. Nelson et al (1991) accomplished this by solving a corresponding longterm sustained yield continuous problem and supplying this harvest level to a shorter term area-based problem.

Alternately, various harvest levels can be explored iteratively. This is also a serious analytic criticism, because the harvest level has no link with the constraint set other than feasibility or infeasibility. It is, therefore, almost impossible to derive the interaction of constraint intensities and combinations and objective function value by these methods. Other more complex methods discussed below can overcome this criticism.

A final criticism of the technique is that feasible solutions have no known properties of optimality. This criticism can be applied to any heuristic, however, the random search approach involves no convergence process. Statements concerning the quality of the solution must be related to sampling properties of the solution process. For small problems, a random search process may be compared with a laboriously derived integer programming solution (Nelson and Brodie 1990).

Lagrangian Relaxation

The original Lagrangian Relaxation paper in the forestry literature was provided by Hoganson and Rose (1984). It was an original isolate in that Hoganson and Rose discovered the process independently without reference to the existing literature. Their problem was limited in scope--maximization of the nondeclining flow of benefits from integer harvest of a large number of stands over time. The discussion in the paper emphasizes the capability to vastly increase the dimensionality of standard mathematical programming problems. Several researchers experimented with the technique, but until recently, incorporated no constraints other than harvest flow and the integer land accounting by stand.

The inherent integer nature of the solution provides a link to spatial concerns, which was capitalized on by Torres et al (1991a) and Torres et al (1991b).

In addition to the basic harvest flow constraints, concerns of adjacency and deer-elk habitat proportional maintenance were added to the problem through the addition of composite surrogate constraints. Empirical results are dependent on the sub-basin map condition in the initial period and the particular constraint set. Harvest flow and adjacency or harvest flow and habitat maintenance could be achieved at little reduction in objective value compared to harvest flow alone. Combinations of flow and non-adjacency and habitat maintenance reduced harvest by 25 to 35 percent in small watershed problems. It is the flow maintenance over long periods of time from a sub-basin unit that is driving this process, and higher total harvests would be available on an interruptible basis.

Integer programming and programming like approaches have produced a number of heuristic methods for formulating adjacency constraints. The number of constraints have lead to methods of parsimonious formulation (Gross and Dykstra 1988; Meneghin et al 1988; Torres and Brodie 1990). A test provided by Yoshimoto and Brodie (1991) showed that parsimonious formulations may provide the reduction in dimensionality necessary to solve larger problems within existing software limitations. However, the least parsimonious (pair-wise) formulation is computationally most efficient in solution.

The strengths of the Lagrangian approach is that it gives a feasible or near feasible solution of high objective value. In the case of a feasible solution, there is no guarantee of optimality. The solution can be compared with the corresponding relaxed linear program which is usually only slightly higher and, of course, infeasible in an integer context. The technique can develop harvest levels for substantial periods of time while simultaneously meeting all or almost all of the integer spatial constraints. Some problem specifications are inherently infeasible if the required condition, such as habitat proportions, does not exist in the initial periods. In these instances, the solution is near feasible, and minimally infeasible.

The advantage of simultaneous development of harvest while meeting constraints is that trade-offs can be examined. Since the technique involves dual and primal problem specification, there are dimensional limitations when environmental spatial constraints are added to the original sparse flow-constraint set. The computational burden is less than integer programming but still substantial. In comparison with techniques discussed below, it can be less efficient.

Methods of Combined Heuristics

Methods to deal with spatial planning problems in forestry are still at an early stage of proliferation, and major progress can be made by creatively combining techniques currently applied to smaller problems. An example of this would be use of network analysis to minimize transportation cost for a randomly generated spatial harvest pattern (Sessions and Sessions 1990). Existing techniques will be imported from the operations research literature. An example would be annealing algorithms currently previewed.

Yoshimoto et al (1991) have produced a combination of heuristics and compared this approach to branch and bound integer programming and composite relaxation (Torres and others 1991a). The integer programming comparison was conducted to a fixed number of iterations (100,000) since heuristics don't guarantee optimality, and guaranteeing optimality is the primary computation burden. Integer programming comparisons could only be conducted for short time horizon problems, and the proposed algorithm was tested up to 10 time periods. Relaxation was less efficient and reached a dimensional limitation with the largest problem. Yoshimoto and Brodie (1991) used the new algorithm to evaluate alternative riparian harvest and protection plans.

Yoshimoto named his configuration of approaches SSMART (Scheduling System of Management Alternatives for Timber-Harvest). It combines elements of the PATH algorithm (Paredes and Brodie, 1987, Yoshimoto et al 1988) with binary search to determine harvest level and minimize flow fluctuation. An additional technique named ROHO (Random Ordering Heuristic Optimization) was proposed and utilized to overcome the problem of initial selection of harvest units limiting long-term feasibility for meeting adjacency constraints. Briefly, stands are assigned a random sequence number. The highest is selected and adjusted for adjacency and then the next highest that was not ruled out for adjacency. The sequence is then reordered with the second highest number first and the highest last and the process repeated throughout the sequence. A large number of feasible sequences are thus retained. The PATH algorithm solves sequentially for each period with feasibility of flow guaranteed only for the subsequent period. Binary search finds the highest feasible level and minimizes harvest fluctuation between periods. The approach combines in a new application, known techniques along with ROHO to preserve a wider range of harvest alternatives.

CONCLUSIONS

Environmental concerns have created demands for spatial requirements in scheduling solutions. These requirements soon taxed the capability of existing integer techniques to provide solutions. A remarkable number of alternative approaches have evolved in a relatively short period of time.

Existing techniques can be modified for application and new techniques imported from the operations research literature. Meanwhile, ecologists and planners continue to subjectively specify additional corridor problems and pattern requirements for dispersion or alternately for minimum fragmentation. The next few years should be productive for analysts who can specify these concerns analytically and import, generate, and modify techniques for solution.

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A HEURISTIC PROCESS FOR SOLVING LARGE-SCALE, MIXED-INTEGER MATHEMATICAL PROGRAMMING MODELS FOR SITE-SPECIFIC TIMBER HARVEST AND TRANSPORTATION PLANNING[1/]

J. G. Jones, M. L. Meacham, A. Weintraub, A. Magendzo[2/]

Abstract.--A heuristic procedure is described for solving a mixed-integer, linear programming formulation for site-specific planning of land management and transportation projects. Feasible solutions with objective values within 10 percent of optimum can usually be found with substantially less computer time than required by mixed-integer, branch-and-bound algorithms.

Keywords: Heuristic integer programming, heuristic decision rules, mixed-integer programming, land-management planning.

INTRODUCTION

Implementing long-range strategic plans presents a host of timber harvest and transportation decisions and considerations. Harvest unit arrangement and timing, silvicultural method, logging method, access route and timing all affect the profitability of sales, environmental impacts, and the extent to which various multiple-use objectives are met. Tactical planning must be concerned with these integrated, site-specific questions.

The mathematical programming formulation developed by the Integrated Resource Planning Model (IRPM) (Kirby and others 1980) is useful in identifying the spatial arrangement and timing of harvest activities and road construction and reconstruction projects that efficiently implement management objectives. In addition to IRPM, this formulation can also be developed using the Integrated Resource Analysis System (IRAS) (Jones and others 1990), and the project option within FORPLAN (Johnson and others 1986).

One distinguishing feature of the IRPM-type formulation is the mixed-integer mathematical programming base; that is, both continuous and 0,1 integer variables are present. Unfortunately, mixed-integer problems are often difficult to solve, and the IRPM-type formulation is no exception. Although this formulation can be solved using a branch-and-bound algorithm, experience has shown that this approach is feasible for only relatively small models. It proved to be too expensive in applications that contain 200 or more integer variables.

This paper describes a heuristic procedure for solving the IRPM-type formulation. This procedure has been coded in FORTRAN and is part of a set of software routines that reside at the National Computer Center at Fort Collins, CO (NCC-FC). Full-scale models containing up to 4,000 rows, an equal number of columns, and 300 or more integer variables can be solved. Approximately 20 minutes of central processing unit (CPU) time is needed, and costs range from $50 to $200 given July 1990 rates at NCC-FC. IRPM-type formulations developed with IRPM, IRAS, and FORPLAN can be solved using this procedure.

The paper begins with a presentation of the IRPM-type formulation. Next, the heuristic process is discussed. Finally, results are presented that compare the heuristic process with a branch-and-bound algorithm and other methods used in conducting tactical planning.

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2/ Research Forester, Intermountain Research Station, Forest Service, U.S. Department of Agriculture, Missoula, MT; Statistician, Intermountain Research Station, Forest Service, U.S. Department of Agriculture, Missoula, MT; Professor of Industrial Engineering, University of Chile, Santiago, Chile; and Research Associate, Department of Industrial Engineering, University of Chile.

THE IRPM-TYPE FORMULATION

The IRPM-type formulation combines a land allocation and scheduling model with a cost-minimizing transportation network model. Land is delineated into contiguous tracks (for example potential harvest units or stands), hereafter called polygons. "Resource projects," varying by the type and timing of management treatments, are formulated for these polygons. A proposed road network, comprised of the viable access options, is developed for the transportation component. This network is divided into "links," bounded on the ends by "nodes." "Road projects," varying by construction standard and timing, are specified for links representing proposed new roads, and for existing roads having an improvement option. Network traffic is assumed to originate with the resource projects, and is channeled through the network to one or more "final demand" nodes, representing, for example, a sawmill.

The basic structure of the IRPM-type formulation is presented below. In actual applications, extensions or modifications may be made to this basic structure.

Decision Variables

1. Resource projects:

   X_{lit} = the fraction of the resource project comprised of management alternative l to be implemented on polygon i in period t. ($0 \leq X_{lit} \leq 1$)

2. Road projects:

   $Z^k_{ab,t}$ = 1 construct (or reconstruct) the link connecting nodes a and b to standard k in period t,

   = 0 otherwise.

3. Traffic flow variables:

   $T^k_{ab,t}$ = amount of traffic on road standard k traveling from node a to node b in period t. (A return trip in the opposite direction is implied.)

   $D_{bf,t}$ = amount of traffic traveling from node b to final demand node f in period t.

Constraints

1. Only one road project may be selected per link:

$$\sum_k \sum_t Z^k_{ab,t} \leq 1 \qquad \text{(for all } ab) \qquad (1)$$

2. Traffic flow equations:

$$\sum_l \sum_i V^b_{lit} (X_{lit}) + \sum_{a \varepsilon A} \sum_k T^k_{ab,t} = \sum_{c \varepsilon C} \sum_k T^k_{bc,t} + \sum_{f \varepsilon F} D_{bf,t} \qquad \text{(for all } b,t) \qquad (2)$$

where, V^b_{lit} is the amount of traffic loaded by resource project X_{lit} onto node b in period t; A is the set of adjacent nodes that may send traffic to node b; C is the set of adjacent nodes that may accept traffic from node b; F is the set of adjacent final demand nodes that may accept traffic from node b. These constraints equate the traffic entering a node to the traffic leaving that node, thereby channeling all traffic to a final demand node.

3. Capacity equations:

$$(T^k_{ab,t}) + (T^k_{ba,t}) \leq \sum_{g=1}^{t} [C^k_{ab,g} (Z^k_{ab,g})] \qquad \text{(for all } k,ab,t) \qquad (3)$$

   where $C^k_{ab,g}$ is the capacity of standard k on link ab in time g. These constraints (1) ensure that a road project for link ab is selected before or during period t, if the link is to carry traffic in period t, and (2) limit the quantity of traffic on link ab in period g to $C^k_{ab,g}$.

4. Only one (or the equivalent of one) resource project may be selected for each polygon, i.

$$\sum_l \sum_t X_{lit} \leq 1 \qquad \text{(for all } i) \qquad (4)$$

5. Side constraints (optional):

   Side constraints are user-defined management constraints, including constraints placed on costs (such as road construction costs, or hauling costs), on physical outputs (such as timber yields, or water production), and on net revenues. They may contain any of the three types of decision variables and may be formulated for an entire study area, or for specific geographic portions of a study area.

Objective Function

Various objectives may be maximized or minimized. Examples include maximizing present net value, minimizing total discounted cost, maximizing timber harvest over the planning horizon, or minimizing environmental impacts.

THE HEURISTIC INTEGER PROGRAMMING (HIP) PROCEDURE

The HIP procedure is an iterative process. In each iteration a continuous linear programming (LP) solution is solved, this solution is processed by the heuristic rules, and the resulting decisions and modifications are incorporated into the LP matrix in preparation for the next continuous LP solution. The process is completed when all the road projects have been assigned a value of either 0 or 1, and no modifications can be found that would improve the objective function value without violating any constraints. This generally requires from 7 to 12 iterations.

The initial formulation modifications and heuristic decision rules applied in the iterations are described below. We include only the detail needed for a basic understanding of the process. See Jones and others[3] for a more thorough presentation of the HIP process.

Formulation Modifications

Several modifications are made to the IRPM-type formulation in preparation for the HIP solution procedure. First, the road projects are defined as continuous decision variables (to solve the model as a continuous LP problem). Second, a pair of "deviation variables" are added to each side constraint to avoid infeasible LP solutions caused by side constraint violations. (Infeasible LP solutions are not useful for making heuristic decisions.) When a side constraint is violated, the extent of the violation is absorbed by these deviation variables, thereby maintaining a status of feasible in the continuous LP solution. The penalty for violating a side constraint is imposed in a step-wise manner. The amount of constraint violation that can be tolerated due to the inaccuracies and random nature of constraint coefficients establishes the upper bound for the first step. Any constraint violation greater than this amount is forced into the second step. When this occurs, the solution is considered infeasible.

Iteration 1

The first LP solution is checked for an infeasible, unbounded, or null status. Processing stops if any of these conditions are found. If the LP solution is infeasible, then the more restrictive mixed-integer problem is also infeasible. If it is unbounded, the mixed-integer solution will also be unbounded because all the decision variables are bounded by constraints in the continuous LP (Equations 1 and 4 place an upper limit of 1 on road and resource projects, and Equation 3 limits the traffic variables). If the continuous LP solution is null (no variables were selected) the optimal mixed-integer solution is no action.

Following these checks, the first iteration adjusts the road capacity coefficients ($C^k_{ab,g}$) in the capacity equations (Equation 3). Typically, the capacity coefficients are much larger than the actual traffic flows, causing the road projects to assume values substantially smaller than 1 in the first continuous LP solution. These small values are undesirable because only a small fraction of the impacts from road construction are included in the LP solution. The capacity coefficients are reduced to approximate the largest quantity of traffic observed on any link. The objective is to obtain larger fractions for road projects in subsequent iterations. The original capacity coefficients are restored when the road projects are rounded to 0 or 1 in later iterations.

Two additional LP matrix modifications are made. First, the Equation 1 constraints (the sum of the road projects for a link cannot exceed 1) are modified to nonconstraining rows. This allows road construction projects to assume values greater than 1 in subsequent iterations--a change made necessary by the capacity adjustment discussed above.

Second, the objective function coefficients for the traffic variables are divided by 100 to give hauling costs a smaller weight relative to road construction costs in the next continuous LP solution. This is another modification designed to counteract the under-accounting of road building costs that result from fractional road projects. The original traffic variable coefficients are restored in the next iteration.

Iteration 2

Iteration 2 conducts a second capacity coefficient ($C^k_{ab,q}$) adjustment, in which the capacity for link *ab* is modified to the larger of (1) the average observed traffic flow on the network, or (2) the observed traffic flow on link *ab*. This adjustment encourages traffic in subsequent LP solutions to travel over the links that carried relatively high volumes of traffic in the current LP solution (when the effects of road construction costs were magnified relative to haul costs).

The original objective function coefficients for the traffic decision variables are reinstated in the LP matrix at the end of this iteration.

Iteration 3

Iteration 3 marks the start of rounding fractional road projects to 1 or 0. The first step in this and subsequent iterations is to develop a list of "candidate road projects" for rounding, one from each link having flow in the current LP solution. The project selected has (1) the lowest road standard that will handle the volume of traffic in each period on that link, and (2) an implementation period corresponding to the earliest period having a significant amount of traffic flow over the link.

Next, an index is calculated for each "candidate road project," and projects are ranked in ascending order. (Projects with smaller index values are preferable.) This index is a unitless number comprised of the following:

(1) The contribution of the road project to the side constraints relative to the slack (unused space) in the side constraints, weighted by 1 minus the activity level (solution value) for the

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[3] Jones, J.G.; Weintraub, A.; Meacham, M.L.; Magendzo, A. 1991. A heuristic process for solving site-specific land management and transportation planning models developed with IRPM and FORPLAN. Unpublished manuscript. U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 85 pp.

road project in the current LP solution. The larger this component, the larger (less desirable) the index.

(2) The amount of flow on link *ab* relative to the average flow on the network in the current LP solution, multiplied by -1. The greater this component, the more desirable the index. This component uses quantity of traffic as a measure of importance for the links.

(3) The relative cost of the road project, weighted by 1 minus the activity level for the road project in the current LP solution. The greater this component, the less desirable the index.

The next step determines which "candidate road projects" connect to the "developed portion of the road network." The "developed portion of the road network" consists of existing roads, plus road project variables that were rounded to 1 in the current and previous iterations. Only road projects connecting to the "developed portion of the road network" may be rounded to 1, to ensure a continuous developed network that connects to the demand nodes.

Next, from the list of "connecting" road projects, round to 1 the project with the best (lowest) index, providing it is feasible with each of the side constraints. If rounding this project is not feasible, select the "connecting" project with the next best (lowest) index, providing it is feasible. At most, no more than 50 percent plus 1 of the original candidate projects can be rounded to 1 in iteration 3 or 4. This is increased to 75 percent plus 1 beginning with iteration 5. These cutoff points avoid making too many decisions in any one iteration. Experience has shown this can result in poor mixed-integer solutions.

Rounding a candidate road project is considered feasible if the impact of that road project plus the cumulative impact from projects previously rounded in the current iteration does not exceed the total "allotted space" in any side constraint. The "allotted space" is the total impact from rounding variables permitted in the current iteration.

Calculation of "allotted space" begins with "actual space." "Actual space" is an estimate of the space available for absorbing the impacts of rounding road projects in side constraint i at the beginning of an iteration. Arithmetically, it equals the right-hand-side value of constraint i minus the total impact from the previously rounded road projects, the traffic variables, and the resource projects.

"Allotted space" is then computed by adjusting "actual space" by two factors. The first factor applies an adjustment that is proportional to the importance of road construction projects within side constraint i. The second factor reduces the impact of the first factor as the number of iterations increase. This ensures that the total available space in the side constraints eventually is available for rounding projects.

Two additional changes are made to the LP matrix. First, the original capacity coefficients are reinstated for those links having a road construction project rounded to 1 this iteration. Second, the mutually exclusive constraints (Equation 1) associated with the links having a project rounded to 1 are reinstated as less than constraints. (They were changed to nonconstraining rows in the first iteration.)

Iteration 4+

The first step assesses the need for an additional capacity adjustment. If the average traffic flow on the remaining links having fractional road projects is less than 10 percent of capacity, another capacity coefficient adjustment is made. As the rounding iterations proceed, the road projects closest to the final demand nodes are rounded first. The remaining fractional links tend to be closer to production points and carry smaller flows. Their fractional values can be increased by applying the capacity adjustment procedure described for Iteration 2. If capacities are adjusted, the iteration ends.

If capacity adjustment is not needed, the rounding decisions made in previous iterations are modified according to the following rules, providing side constraint feasibility is preserved.

1. Road Standard: The road standard selected for link *ab* is decreased if a lower standard has sufficient capacity to handle the traffic flow in the current LP solution. The standard is increased if the traffic flow on link *ab* equals the capacity of the previously selected road standard.

2. Timing for Construction: Road construction for link *ab* is postponed if the traffic flow in the period of construction is less than 5 percent of the average flow on the network in that period. The period selected is the earliest period that flow on link *ab* exceeds this 5-percent threshold.

3. Closing Links: A link is closed (all road construction variables applying to that link are set to 0) if its traffic in each period is less than 5 percent of the average flow on the network.

After all the modifications to previous rounding decisions have been made, a test is conducted to determine if these modifications moved the impact on any side constraint within 10 percent of its bounds. If not, the rounding procedure described in Iteration 3 is conducted. If so, the iteration concludes without rounding any fractional road projects.

The heuristic process stops when all road projects have integer values and no feasible changes can be identified that improve the solution (modifying road standards, etc.). This generally occurs within 7 to 12 iterations. The solution reported is the mixed-integer solution with the best objective function value, which also satisfies the side constraints. In nearly all cases, this is the last LP solution obtained in the heuristic process. If the procedure is unable to find a feasible mixed-integer solution, it reports its best mixed-integer solution. In these cases the activity values of the deviation variables measure the amount of side constraint violation.

TEST RESULTS

Comparison With Optimal Mixed-Integer Solutions

Six formulations of Small Twin Rocks, a land management and transportation planning problem adapted from a portion of the Twin Rocks area (Jones and others 1986), were solved using both the HIP process and a branch-and-bound algorithm. These formulations represent a combination of constraints and objectives typical of an actual planning problem. The size statistics for this model are summarized in Table 1. The costs associated with the branch-and-bound process prohibited making similar comparisons with full-scale models.

Table 1.--Size statistics for the five models included in this report

Category	Small Twin Rocks	Copeland Creek	Moose Creek	Lowman Area	TUJO-RECOYLE Area
Polygons	28	282	301	324	569
Road Links:					
Proposed	22	84	194	126	167
Existing	2	64	79	104	67
Total	24	148	273	231	234
Demand Nodes	2	2	4	4	1
Periods	3	3	2	3	3
Matrix Data:					
Rows	365	2,281	2,150	3,326	3,033
Columns	260	1,651	1,923	3,515	4,046
Integers	67	318	546	693	702
Density[a]	3.1%	0.8%	0.4%	0.4%	0.4%

[a] The percent of matrix coefficients that are nonzero.

The results are summarized in Table 2. The objective values of the HIP solutions were within 10 percent of the optimal mixed-integer solution in all but one case--formulation 3. Although the HIP process did not find optimal mixed-integer solutions, it did develop solutions having objective function values closely approximating the values for the optimal mixed-integer solutions.

Comparison With a Conventional Planning Method

A common tactical planning method in the Northern Rockies is to use professional judgment to make the harvesting selections and a road network cost-minimization model, such as NETWORK[4], to make the roading selections. Plans developed via the HIP algorithm were compared against this method on two planning areas in the Northern Rockies: Copeland Creek (Kootenai National Forest in Montana), and Moose Creek (Helena National Forest in Montana). Identical data and management objectives were used in both the conventional and HIP approach. For the Copeland Creek area, the HIP solution process was used to develop a management alternative to compare against an alternative previously developed via the conventional approach in an earlier study (Jones and others 1986). The Moose Creek area comparison was conducted by National Forest System personnel[5]. The size statistics for both models are presented in Table 1.

The resulting present net values (PNV), the objective maximized by each approach, were:

	Copeland Creek Area	Moose Creek Area
	--- ($M) ---	
(1) First cont. LP solution	4,491	1,665
(2) HIP	4,296	1,332
(3) Conventional method	3,014	978
(4) Percentage increase [Row (2) minus (3) as a percentage of (3)]	43%	35%

In both cases the HIP process developed plans with substantially higher objective function values while meeting the management constraints.

Comparison With The First Continuous LP Solution

A third basis for comparison is the objective function value of the first continuous LP solution made in the HIP procedure, which is a bound on the optimal mixed-integer solution. Because it is unknown how tight that bound is for any one problem (unless, of course, the optimal mixed-integer solution is known), useful information is obtained by this comparison only when the difference between the HIP solution and the first LP solution is small. A large difference does not necessarily indicate a poor HIP solution because it could be reflecting a large difference between

[4] Sessions, John. [n.d.] Network analysis using micro-computers for logging planning. Department of Forest Engineering, College of Forestry, Oregon State University, Corvallis, OR.

[5] Personal communication on May 14, 1990, with Fred Bower, Regional Transportation Analyst, Northern Region, USDA Forest Service, Missoula, MT.

Table 2.--Comparing HIP solutions with the optimal mixed-integer solutions for six formulations of the Small Twin Rocks model

Category	Formulation					
	1	2	3	4	5	6
Objective	Max. PNV[a]	Max. PNV	Max. PNV	Max. PNV	Min. SED1[b]	Min. DTCOST[c]
Objective Function Values:						
(1) 1st Cont. LP	175.2	175.2	175.2	175.2	131.3	231.0
(2) HIP	80.8	69.1	61.2	77.6	313.0	335.7
(3) Optimal mixed-integer solution	85.1	71.5	71.5	79.6	289.5	319.7
Difference between (3) and (2) as a percentage of (3)	5.0%	3.4%	14.4%	2.5%	8.1%	5.0%

[a] Present net value measured in thousands of dollars.

[b] Additional sediment production in period 1 measured in tons.

[c] Discounted total cost measured in thousands of dollars.

the optimal MIP solution and the first LP solution. For example, in the Small Twin Rocks model (Table 2) the difference between the HIP and first LP solutions was quite large, while the difference between the HIP and optimal MIP solutions was small.

Table 3 compares the difference in objective function values between 15 HIP solutions and their respective first continuous LP solutions. These solutions represent variations in the constraints, the right-hand-side value of constraints, and the objective functions for three full-scale models: the Moose Creek model (described earlier); the Lowman Area model[6] (Boise National Forest in Idaho); and the TUJO-RECOYLE[7] (Lolo National Forest in Montana). See Table 1 for the size statistics.

Table 3.--Comparing the difference in objective function values between 15 HIP solutions and their respective first continuous LP solutions

Model	Number of solutions	Percent difference		
		Aver.	Min.	Max.
Lowman Area	6	3.3	1.5	9.3
Moose Creek	4	26.6	24.1	29.3
TUJO-RECOYLE	5	10.8	4.1	21.5

The HIP objective function values for the Lowman model were within 5 percent of the value of the first LP solution in all but one case, and within 10 percent in all cases. For these cases, the objective function values of the HIP solution closely approximated the mixed-integer optimums. For the Moose Creek and TUJO-RECOYLE models, the differences were generally larger. But, as discussed, the larger deviations do not necessarily indicate poor solutions.

Computer Requirements

The central processing unit (CPU) times, input/output (I/O) times, and total costs associated with the 15 full-scale model solutions presented in Table 3 were:

	Average	Smallest	Largest
CPU time (min)	21.9	13.5	37.0
I/O time (min)	47.9	22.5	74.1
Total cost ($)	120.1	57.4	198.7

These solutions were run on a UNISYS Model 1193 computer at NCC-FC, and the costs are based on the July 1990 t-priority rates. While not small,

[6] Personal communication on May 14, 1990, with Fred Bower, Regional Transportation Analyst, Northern Region, USDA Forest Service, Missoula, MT.

[7] Personal communication on August 7, 1990, with Fred Bower, Regional Transportation Analyst, Northern Region, USDA Forest Service, Missoula, MT.

these requirements are modest compared to the mixed-integer branch-and-bound algorithm available in the Functional Mathematical Programming System available at NCC-FC. Attempts at solving models of a similar size using this branch-and-bound algorithm would typically cost in excess of $500 and yet not find the optimal mixed-integer solution.

DISCUSSION

Several trends suggest there is an increasing potential for the IRPM-type formulation in the future. First, the evolution of analysis in forestry is clearly toward more geographic site-specificity, one of the strengths of the IRPM-type formulation.

Second, the proliferation of geographic information systems is expected to enhance the ability to construct IRPM-type models in the future. One of the major barriers in this type of modeling has been collecting and entering data. Often geographic data were missing or incomplete and in a form requiring manual data entry. Geographic information systems have the potential of automating much of the data entry process.

Third, advances in microcomputer hardware and software continue and show little sign of abating. It is now feasible to obtain LP solutions for full-scale IRPM-type models on this class of computer, and an effort is underway to develop a personal computer version of the HIP algorithm. Microcomputers provide a number of advantages that enhance the ability to build and solve models: the potential for lower computing costs, fewer communication problems and costs, quicker turnaround times for batch processes, and most important, the potential for embedding the modeling process in a user-friendly system.

There are several potential improvements that could be made in the heuristic process. In the current configuration, the LP solver and the heuristic program are separate programs, linked together in a control language loop. Each time these processes are accessed (typically 7 to 12 times for a HIP solution), the internal arrays and variables must be reinitialized from data stored in files. Substantial savings in I/O time are possible by integrating the decision rule program and an LP solver into one program.

Another possible improvement is to extend the heuristic process to provide the option of rounding resource projects to values of 0,1. Some land management activities are better modeled by resource projects that are strictly integer variables. For example, some types of logging systems require that polygons be chosen for harvesting in their entirety or not at all. Exploratory work aimed at extending the heuristic rules to include resource projects has been undertaken and preliminary results in small- and medium-sized test problems have been promising (Magendzo and others 1990).

The IRPM-type formulation is not new, and to this point has received only somewhat modest use. But trends toward site-specific analysis and advances in microcomputer technology suggest this approach may well be coming into its own. We believe the HIP process has very good potential for providing solutions which arrange and schedule land management activities and road construction projects in ways that efficiently meet specified management objectives. This efficiency should be valuable in helping land managers meet the increasing demands being placed on our forest lands.

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THE EFFECTS OF CLEARCUT SIZE AND EXCLUSION PERIODS ON HARVEST LEVELS AND ROAD NETWORK DEVELOPMENT[1/]

J.D. Nelson and S.T. Finn[2/]

Abstract.-- To assess potential clearcutting regulations, a computer model was used to simulate harvests on a coastal watershed. Harvest levels and road construction and maintenance schedules are reported for combinations of cut block size and exclusion period lengths. Decreasing block size and increasing exclusion periods consistently reduced harvest levels from the aspatial solution. A combination of 20 ha. openings and a 30-year exclusion period reduced harvests by 43 percent, and caused a high percentage of the road network to be constructed in the early decades. In this tightly constrained formulation, 30 percent of the forest became inaccessible, causing a reduction in the total length of road constructed and maintained over the 100-year planning horizon.

Keywords: random search algorithm, spatial constraints, integer program

INTRODUCTION

Large clearcuts and relatively short exclusion periods (the time before adjacent stands can be harvested) has been common practice in British Columbia. However, the trend is towards smaller openings and longer exclusion periods because of concerns about environmental stability and visual impact. Wildlife habitat is particularly important since an appropriate spatial distribution of age classes is needed for forage, hiding, and winter range. The impact that revised clearcutting regulations may have on harvest schedules and the development of road networks is not well understood. Such regulations may have important economic implications for both industry and government in the form of timber supplies, harvesting costs, and stumpage revenues.

To address some of these concerns, a computer model was used to simulate harvesting in an undeveloped watershed when more rigid clearcutting regulations are applied. The objective was to determine what impact cut block sizes and exclusion periods have on the annual allowable cut (AAC), the rate of road construction, and the amount of road maintenance. First, a brief description of the spatial planning problem and the planning techniques currently used is presented. Next, the methodology used to model the area-based plans is presented, followed by the results of a sample problem. Finally, we discuss the implications of these results and possible extensions of this work.

SPATIALLY CONSTRAINED HARVEST SCHEDULING

In spatially constrained harvest planning (also referred to as area-based planning), the objective is to schedule blocks for harvest so that maximum opening sizes and minimum exclusion periods are satisfied. The plan must also schedule the construction of road network links in order to access these harvest units. In the case of a progressive clearcut, where a maximum

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2/ The authors are respectively, Assistant Professor of Harvesting, Faculty of Forestry, University of B.C., Vancouver, B.C. V6T 1Z4 and Assistant Instructor of Forest Resources, British Columbia Institute of Technology, Burnaby, B.C.

opening size and a minimum exclusion period are lacking, one simply advances into the "wall" of timber until the AAC is satisfied. This gives a uniform road construction schedule until the entire road network is in place.

When scheduling cut blocks that are subject to a maximum opening size and a minimum exclusion period, the problem becomes more complex. To meet these spatial constraints in any time period, cut blocks must be harvested in their entirety, or not at all, and road links must be completely constructed or left unbuilt. These restrictions lead to integer variables in the problem formulation. Mixed integer programs to schedule both cut blocks and road networks can be formulated (Kirby et. al., 1980), but only relatively small problems can be solved within reasonable time limits because of the integer restrictions.
Random search algorithms are an alternative method for generating complex, spatially feasible harvest plans. Previous applications have been made for relatively short planning horizons (Nelson and Brodie 1990, Sessions 1987), and others have not addressed the road access problem (O'Hara et. al. 1989, Clements et. al. 1990). While random search techniques cannot guarantee optimality, they offer an operationally viable method for generating feasible solutions to the large integer programs encountered in long-term, area-based planning.

METHODOLOGY

The problem was formulated with an objective function that maximized total volume produced over the planning horizon, subject to constraints that: 1) specified a minimum harvest level in all periods, 2) specified a minimum harvest age for cut blocks, 3) harvested the most accessible blocks first, 4) specified maximum opening size and minimum exclusion periods, 5) constructed all the necessary road links to access the harvested blocks, and 6) prevented road links from being constructed more than once.

The first step was to design formations of cut blocks for the entire forest, using 80, 40, and 20 ha. openings. Associated with each formation was a road network that contained the necessary main road links needed to access the cut blocks. Secondary roads were defined as those roads that were needed to harvest only the block that contained them. In other words, the secondary roads were not required as starting points for subsequently developing adjacent blocks. Blocks were designed so that the same logging system, and therefore, the same main roads could be used in all cases. Secondary roads changed as the block size changed, however, the total length of the road network remained constant. Shorter and more numerous main road links were needed as the block size decreased.

Since our planning problems had approximately 2000 - 5000 integer variables, optimization techniques were impractical. As an alternative, a random search technique was used. The basic steps used by this technique are described below:

1. Identify all cut blocks that are available for harvest in this period. These blocks will be at least as old as the minimum harvest age, and not be adjacent to recently harvested blocks that are imposing an exclusion period constraint.

2. Queue the list of cut blocks identified in step 1 according decreasing accessibility. Those blocks closest to the start of the road network will be at the front, and those at the extremities of the road network will be at the end of the queue.

3. Randomly select a block near the front of the queue and add its volume to the periodic harvest. Immediately, update the queue of available blocks to reflect that this block's adjacent neighbors are now unavailable until the exclusion period has passed. Select the next available block in the queue, and repeat the process until the minimum harvest level has been met. If the minimum harvest cannot be satisfied from the available blocks, return to the start of step 3, and try a new random block selection. If repeated attempts fail, it is unlikely that a solution exists, and the minimum harvest constraint must be reduced.

4. The road links needed to provide access for the harvested blocks are identified and used to determine the total amount of road maintenance. These links are then checked to ensure that they have not been constructed in a previous period. Those that must now be constructed are summed to give the total construction length for this period.

5. Adjust block ages for harvests and growth, and increment the planning period by 1. If the planning period is greater than the planning horizon, stop, otherwise go to step 1.

This queuing method was very useful for preventing early harvests (decades 1-3) from occurring at the extremities of the road network.

RESULTS AND DISCUSSION

For comparison, the problem was solved as a progressive clearcut using the 80 ha. blocks. In this formulation the blocks were progressively harvested from the start of the road network without regard for adjacency rules. Figure 1 plots the road construction and maintenance schedule for the progressive clear cut solution. The volume harvested per decade for this alternative was 360,000 m^3.

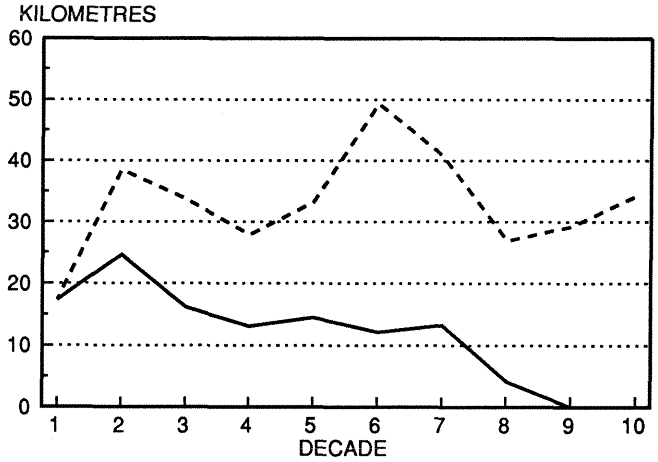

Figure 1.--Road construction and maintenance schedules for the progressive clearcut solution.

Figure 2 summarizes the percentage reduction in periodic harvests (from the progressive clearcut solution) for each combination of block size and exclusion period. Figures 3.a., 3.b., and 3.c. show the road construction schedules for each block size when the exclusion period was 1, 2 and 3 decades, respectively. The road maintenance schedules are similarly illustrated in figures 4.a., 4.b., and 4.c.

Figure 2 indicates that the exclusion period had a greater effect on harvest levels than did block size. Volume reductions associated with block size were due to irregular shaped units. When these blocks were split into smaller units, more adjacent blocks resulted. As the exclusion period increased, previous harvests on adjacent blocks began to limit the number of available units, thus reducing the volume cut. Increasing the exclusion period from 1 to 2 , and from 1 to 3 decades caused volumes to drop on average 15% and 33%, respectively. The combination of smaller blocks and longer exclusion periods resulted in large reductions in allowable cuts (up to 43%). In the case of the 20 ha. blocks with an exclusion period of 3 decades, the spatial constraints prevented any harvests on almost 30% of the cut blocks.

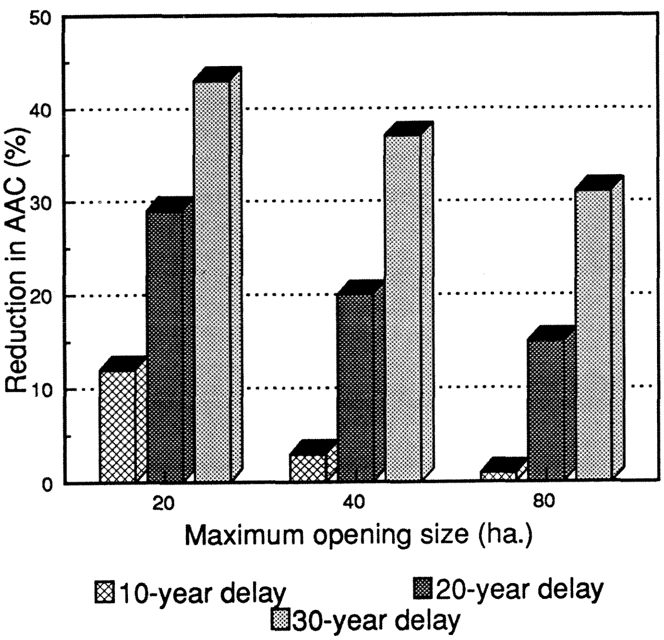

Figure 2.--Percentage reductions in AAC due to spatial constraints. The progressive clearcut solution is the datum.

Figure 1 illustrates that the road construction schedule for the progressive clearcut was relatively uniform in comparison to the examples in figure 3 where spatial restrictions were applied. In figure 1, by period 7, construction dropped since most of the network was built at the end of the first rotation. Road maintenance (defined to occur when the road was used, regardless of the volume hauled) reached its maximum in period 6 and then declined, which also corresponded to the end of the first rotation. The smaller peak in period 2 and subsequent decline in periods 3 and 4 was due to development and abandonment of branch roads.

In figure 3, it is apparent that smaller cut blocks required more road construction in decades 1 and 2 in order to develop a sufficient number of units to meet the allowable cut. Beyond the second decade, road construction for the smaller blocks tended to be marginally less than that observed for the larger blocks, since more of the network was already developed. Another important trend shown in figure 3 is the decline in the total amount of road built as the exclusion period increased. These declines are directly related to the cut blocks that could not be harvested due to spatial restrictions. For exclusion periods of 2 and 3 decades, approximately 4% and 8% of the road network was not constructed.

ROAD CONSTRUCTION SCHEDULES

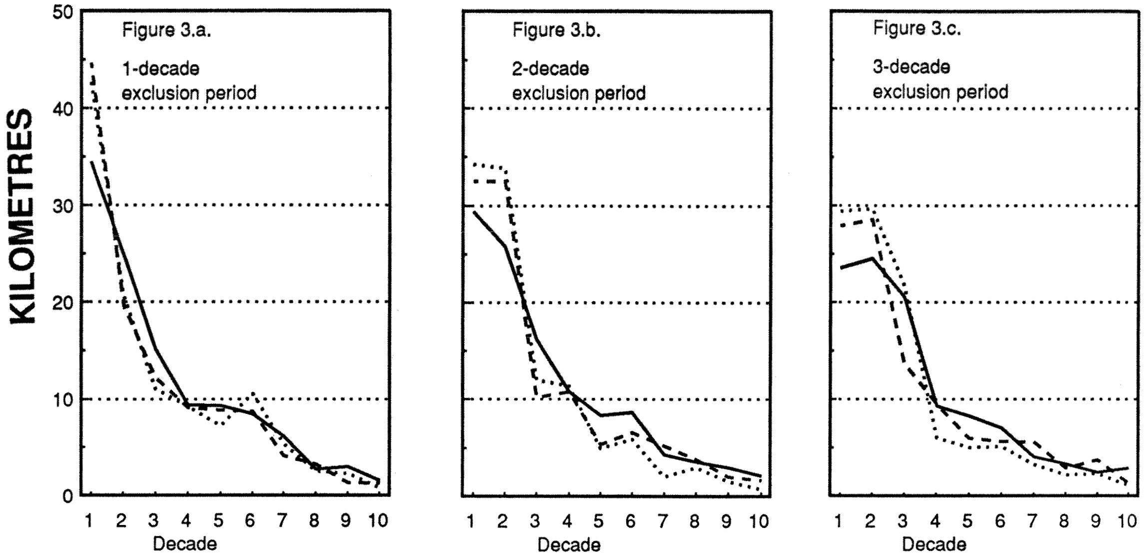

Figure 3.--Road construction schedules for combinations of block size and exclusion period.

ROAD MAINTENANCE SCHEDULES

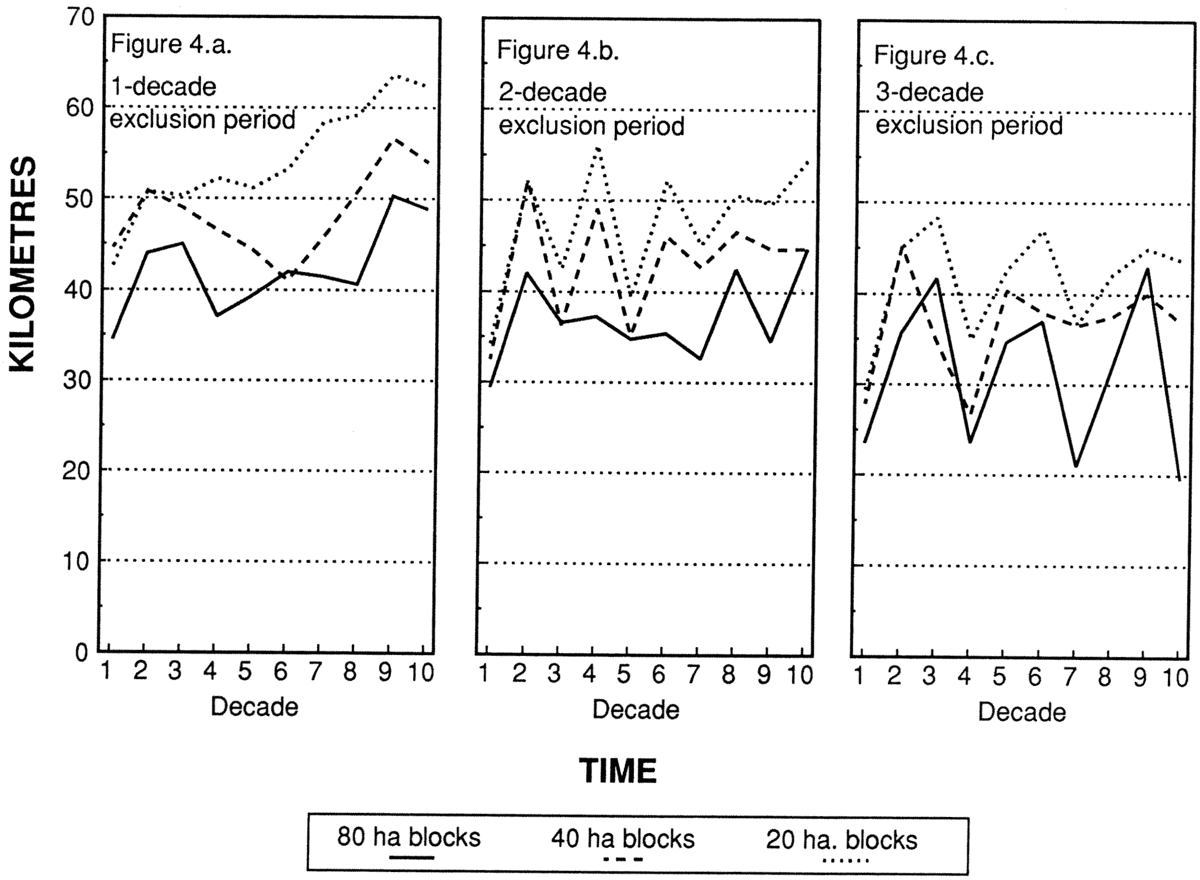

Figure 4.--Road maintenance schedules for combinations of block size and exclusion period.

The road maintenance schedules shown in figures 4.a. through 4.c. also show a trend towards smaller road networks as the exclusion period increased. When the exclusion period was held constant, small blocks required a greater amount of road maintenance than did larger blocks, even though less volume was being harvested. This was caused by the splitting of cut blocks and adjacency constraints that forced more dispersed harvests.

Our results indicate that current harvesting levels on a fixed land base cannot be maintained when smaller cut blocks and longer exclusion periods are used. If allowable cuts are to stay at their present levels, then additional forest land must be assigned to timber production. If forest land is scarce, cuts will drop, unless intensive forest management or some form of "best use" of land is implemented.

Under spatial constraints, the common practice of writing off road costs against the current harvest will be inappropriate because these roads are now accessing considerable portions of the forest for future harvests. Road costs need to be amortized over a longer period, otherwise it is possible that early stumpage values could be driven negative. Adding constraints that limit the amount of road construction (or constraining road budgets) would only further reduce the harvest in early periods. In forests that already have a major part of the road network in place, spatial constraints will have less impact on road construction, since the increased accessibility allows for a more dispersed harvest. Increased road maintenance, and additional operational moves from block-to-block resulting from adjacency restrictions will also reduce stumpage revenues. These economic parameters need to be investigated for managers (and the public) to make informed choices about resource allocations on public lands.

As the block size decreased, the forest became more fragmented. A highly fragmented forest might not provide sufficient habitat for various wildlife species, and the increase in total block perimeter may be detrimental because of potential wind damage. At some point, depending on local conditions, there is realistically a minimum block size. To address this problem, more complex adjacency rules could be defined to leave specified age class distributions within the forest, or more likely, within sub-zones. Under these rules, block size would vary within specified limits, rather than all units being of equal size. How these rules would affect harvests and road networks is a topic for further research.

The area-based planning methodology we employed to analyze block size and exclusion period lengths could be extended to examine other spatial problems associated with harvest scheduling and road networks. Examples include buffer widths associated with riparian zone management, partial cuttings, landscape management techniques, and long-term rotations aimed at retaining reserves of old-growth. All these examples need to be assessed over the long-term, and it is imperative that spatial resolution is included in the analysis.

CONCLUSIONS

The effects of block size and exclusion period length on harvest and road schedules were analyzed using a random search algorithm. These problems had thousands of integer variables that discouraged the use of optimization techniques. It was found that small openings in conjunction with long exclusion periods can cause significant reductions in the harvest levels, and necessitate the early construction of a high proportion of the eventual road network. Our findings suggest that if it is desired to maintain current harvest levels and operate under spatial restrictions, then additional forest land must be made available for timber production. If forest land is scarce, then spatial restrictions will force a reduction in current harvest levels. Intensive forest management may partially offset these declines.

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AUTOMATION OF HARDWOOD LOG BREAKDOWN DECISIONS

USING PATTERN DIRECTED INFERENCING[1]

Luis G. Occeña and Jose M. A. Tanchoco[2]

Abstract.--This paper presents a study conducted to answer some of the questions pertaining to the use of information obtained from non-invasive defect detection imaging in hardwood logs. A method was developed to take the information, process it using computer aided pattern recognition, and convert it into a form that can directly drive the saw equipment controllers to perform the log breakdown. The results of the study are presented, and methods developed will be described.

Keywords: Log breakdown, hardwood, decision automation, pattern directed inferencing, wood engineering.

INTRODUCTION

Faced with competition from synthetic wood substitutes and imported wood products, the United States forest products industry must seek alternate methods of wood utilization as well as productivity improvement in current methods of production operations. The research to be presented in this paper pertains specifically to the hardwood log breakdown in the sawmill. Owing to the nature of the end utilization, the log breakdown practice for hardwoods is different from softwoods. In softwoods, the objective is to maximize lumber volume recovery, resulting in patterns such as best opening face (BOF) which are founded on geometric considerations. In hardwoods, the objective is to minimize defects on the resulting lumber faces, resulting in highly judgmental breakdown decisions performed by the sawyer in patterns such as grade sawing or around-sawing.

Thus, whereas the softwood log breakdown problem is basically geometric, the hardwood log breakdown problem is both geometric and decision-oriented. Over the years, the human sawyer has been calling saw placement decisions based on the limited information provided by the external view of the log shape, visible external defects, and whatever internal defects are eventually revealed on the cut log faces by the sawing pattern. Planning of how the hardwood log can be sawn to improve recovery of high-value lumber is hampered by the inability of the sawyer to foresee or "see" the internal defect distribution and orientation inside the log.

Recent work on the application of computed axial tomography and other means of non-invasive internal scanning of solids have opened up new avenues in the log breakdown planning problem (Donald, Anderson, & McMillin, 1990; Wagner, Taylor, Ladd, McMillin, Roder, 1989; Chang, Olson, & Wang, 1989; Funt & Bryant, 1987; Taylor, Wagner, McMillin, Morgan, & Hopkins, 1984). With new information now available related to the distribution and orientation of internal defects that can degrade the lumber value, questions arise on how this new information can be appropriately put to best advantage. How do we recognize the individual defects? Do we need to identify each defect? How do we organize and process the internal defect information? How do we use it to determine sawing cuts? Will it really make a difference?

This paper presents a study conducted to answer some of the above questions, particularly on how such new information can be put to use. A method was developed to take the information, process it using computer-aided

[1]Presented at the 1991 Symposium on Systems Analysis in Forest Resources, Charleston, SC, March 3-7, 1991.

[2]Assistant Professor of Industrial Engineering, University of Missouri-Columbia, Columbia, MO; Professor of Industrial Engineering, Purdue University, West Lafayette, IN.

pattern characterization techniques, and convert it into a form that can directly drive the saw equipment controllers to perform the log breakdown. The results of the study will be presented and the methods developed will be described.

RESEARCH APPROACH

A sawmill is envisioned where a log is scanned by an internal defect detection device before the log is sent to the saw headrig. By the time the log reaches the headrig, a breakdown plan on how to saw the log will have been generated by the computer to assist the sawyer, and downloaded to the numerical controller for the saw. Figure 1 in the appendix illustrates the flow of both information and material. The solid lines denote material flow, while the dashed lines denote information flow. The scope of the research is indicated in the flowchart, with the preprocessed log and defect information from the scanning as the input, and sawing instructions for the numerical controller as the output.

The objective of the research was to use the internal defect information obtained from a non-invasive log scan to generate a specific breakdown plan for that log, and to implement this breakdown plan generation process automatically. A pattern directed inference model was developed to handle the automated breakdown planning, and along the way supporting analytical tools were also developed.

To gain familiarity with the log breakdown process and to obtain data for modelling, sawmill visits were made in which six yellow poplar logs were actually sawn for grade. Figure 2 in the appendix shows the type of data collected, which includes measurements of dimensions and external defect locations before sawing, photographs and videotapes of the breakdown process, and measurements of dimensions and internal defect locations after sawing. These data were used to reconstruct the same type of log and defect information that could be obtained from a tomographic imaging, and were stored in the computer.

Figure 3 in the appendix summarizes the research approach in schematic form. The research was conducted in two phases. Phase 1, depicted on the right hand side of Figure 3, was a sawing analysis activity. A graphic sawing simulator interfaced to a lumber grading program was developed (Occeña & Tanchoco, 1988), and used to repeatedly saw sample logs under various breakdown patterns. The sawing simulator enabled three-dimensional graphic representation of solid logs, and simulated their breakdown using regularized constructive solid geometry (CSG) Boolean operations. The yellow poplar sample logs were reconstructed using the simulator, and used in the sawing pattern analysis.

The knowledge gained from the sawing simulation experiments were then formalized in a knowledge base which formed the basis for Phase 2. Phase 2, shown on the left hand side of Figure 3, involved the development of a pattern directed inference model that could generate a set of breakdown instructions from the log and defect information, using the breakdown rules in the knowledge base and a logic-based inference mechanism (Occeña & Tanchoco, 1989). The C-Prolog declarative programming language used for modelling came with a built-in depth-first back-tracking mechanism, and a predicate logic representation format. The former was coupled with rule ordering to provide a more powerful best-first search strategy. The sawing simulator was used to verify the computer-generated breakdown plans.

Sawing Analysis via Graphic Simulation

A graphic sawing simulator named GSS (Graphic Sawing Simulator) was developed as a supporting analytical tool for studying the hardwood log breakdown process. The GSS was based on the solid modelling concept of boundary representation, which represents a solid in a hierarchical relationship composed of component faces, edges, and vertices in three-dimensional space. A polyhedral solid modeller (Mashburn, 1987) which simplifies solid representation through the use of polygonal patches was accessed in batch mode to handle the sawing effect via regularized constructive solid geometry Boolean operations. A flitch can be "sawed" off a log, for example, by an intersection Boolean operation between a log representation and a saw representation. The remaining log can be obtained as the result of a difference Boolean operation between the same set of solids. The resulting flitches were then edged and trimmed automatically, and graded by a computer grading program (Huang & Sparrow, 1987) to arrive at a value yield for the log.

The core of the GSS was a FORTRAN program that read in log and defect information from data files and rendered the log and defect images graphically using a device-independent graphics package (DI-3000, 1984). The program then makes program calls to the polyhedral solid modeller to perform interactive sawing simulation, and to the grading program to evaluate the resulting lumber. The interactive sawing was implemented on a Tektronix 4105 raster graphics terminal running under Berkeley Unix on a VAX 11/780.

Log and Defect Reconstructions and Decompositions

Following the polyhedral format of the solid modeller, the sample data had to be converted to boundary representation format. The representation was performed in three stages: first, the raw data was preprocessed to relate to its source; second, polygonal loops were formed to define each face of the flitch, slab, or defect. Where needed, multiple triangularizations were done; third, the polygons were arranged in polygon file standard. Figure 4 in appendix illustrates pictorially and schematically the three stages. The log and internal defects were built up from flitch data to enable reconstruction of the location and orientation of internal defects. This activity benefitted greatly from the Boolean union operation capability of the GSS.

Figure 5 in the appendix shows a sample saw reconstruction poised to "saw" a log representation. The procedure followed in the simulated sawing experiments is summarized by Figure 6 in the appendix. This procedure was used to test several generalized sawing patterns, as well as non-traditional sawing patterns. The tests resulted in a pattern directed sawing policy.

PATTERN DIRECTED SAWING

From the simulated sawing analysis, it was found that when internal defects were aggregated, they form specific configurations with distinctive axes. By bounding or splitting these configuration axes, the defects can be contained at the edges for easy removal in finishing operations. Another consideration in the analysis was the importance of obtaining wide lumber as a secondary goal. Four configuration types or patterns for classification were identified, namely: Clear Log, Single Dominant Axis, Multiple Dominant Axes, and No Dominant Axis.

The single Dominant Axis and the Clear Log configurations were the simplest cases, where the breakdown plan was to live-saw, parallel to the defect axis in the former case, and parallel to the widest side in the latter case. The resulting patterns were effective in containing the defects in the fewest flitches. For the Multiple Dominant Axes configuration, recursive decomposition of the log into log sections by sawing parallel to major axes eventually results in log sections that were of the simple cases. Thus the sawing policy can be considered as a decomposition procedure that recursively reduces a complex case to a set of well-defined simple cases. The No Dominant Axis configuration was treated as a special case that required around-sawing.

The aggregate results of the sawing experiments were summarized in Table 1 in the appendix, showing the pattern directed procedure in the last column performing well in the higher grades. This outcome is consistent with the objective of containing defects in the fewest flitches. Though no statistical analyses were done because of the small sample size, the pattern directed procedure shows up as a viable approach for automated hardwood log breakdown planning.

The Inference Model Development

The model, named PDIM (Pattern Directed Inference Model), was implemented as a knowledge based system because of the presence of multiple conditions, which when combined together produced a specific action. The knowledge based structure also provided ease of knowledge manipulation, as well as the modularity of a detached knowledge base. Facts and rules were asserted and retracted only as needed. C-Prolog was a suitable representation medium because of its declarative syntax and built-in features of backtracking, resolution-proving, and pattern-matching which enabled inferencing.

The information flow for the PDIM is shown in Figure 7 in the appendix. The solid boxes denote the PDIM modules, and the dashed boxes denote extraneous programs. The log and defect information from the log scan were first converted into Prolog fact clauses, then subjected to defect configuration extraction and characterization using rule clauses resident in the knowledge base. The two latter processes constituted the automated recognition capability which replaces the visual recognition step normally performed by the human sawyer. This capability was considered superior to a graphic imaging approach because of the elimination of the time-consuming image processing and rendering steps. This capability parallels efforts in the integration of computer aided design and manufacturing in metal processing (Henderson & Anderson, 1987; Choi, Barash, & Anderson, 1984). Once the defect configuration had been extracted and characterized, it was then processed automatically using the pattern directed sawing approach described earlier. Finally, a set of log positioning and sawing instructions were generated, which could be converted to numerical code to drive the saw controller.

Automated Defect Configuration Extraction

The defect configuration was extracted automatically in five steps: log boundary extraction, initial defect filtering, density measurement, density filtering, and defect hull extraction. In the first step, the log boundary was extracted to define the computational workspace. The same log boundary was used as a reference in the second step for the initial filtering of defects. The filtering was done to screen out defects near the log ends and log surface. The premise was that these defects were eventually removed by subsequent operations such as edging and trimming, and need not be carried over in the analysis.

The three-dimensional defect data was then mapped on to two-dimensional space in the third step by summing up the Δz's for each (x,y) pixel. This mapping was done to avail of well-defined characteristics of two-dimensional graphs. The resulting two-dimensional values were called density measures because they represented the intensity of the defects along the length of the log (z-axis). A high-density measure could be due to overlapping defects, as shown in Figure 8 in the appendix. Density measures less than 1-¼ inches were considered non-degrading according to standard grading procedures, and were therefore discarded in the fourth step.

The remaining density measures represented degrading defects. The defect configuration was extracted using a defect hull procedure which scanned the extreme y points along the x-axis and the extreme x points along the y-axis, and concatenated the resulting lists into an ordered list. The ordered list defined a defect hull. The hull was not convex, yet that was precisely desirable because it allowed the accumulation of defects to appear in the form of axes. As shown in Figure 9, the procedure held well for star-shaped hulls in general.

Automated Defect Hull Characterization

After the hull was extracted, it had to be characterized for the appropriate treatment to be identified. The characterization was done using the inflection point/axes relation procedure. The procedure called first for the identification of hull points that were inflection or transition points in the directed hull. An inflection point was considered a potential defect axis vertex if it satisfied two necessary conditions: (1) the inflection point was convex in a counterclockwise sweep of the hull, and (2) the inflection point was dominant relative to neighboring inflection points.

The convexity test was performed using the right-hand rule (Preparate & Shamos, 1985). The dominance test consisted of two phases. Phase 1 established the edge relations. **v** and **c** combinations denoted the position of an edge in the directed transition between bounding inflection points, where **v** stands for concave and **c** stands for convex. **vc**, for example, defined an edge bounded by a concave point and a convex point in the counterclockwise direction. Figure 10 in the appendix illustrates this concept. Phase 2 examined the characteristics of the **v** and **c** combinations to ensure that the height of the inflection point was greater than its base width. For example, **cc** → **vc** or **cv** → **vc** combinations denoted a potential axis, for which the bisector length and base width line ratio was checked. A ratio ➤ 1 indicated an axis vertex.

PDIM Ratings

Test runs of the PDIM made with the sample logs showed that both the manual and computer implementations of the pattern directed sawing policy performed well in the high to upper middle grades. Table 2 in the appendix shows the PDIM to be dominant for Saps across the board, and to outperform the LIVE and CANT sawing patterns in the FAS category. Thus, the PDIM is a viable approach to automated hardwood log breakdown planning. Figure 11 shows a sample program run.

CONCLUSIONS

This paper presented the results of a study to use non-invasive scan data to automatically determine a log breakdown pattern based on defect patterns detected inside the log. The methods used in the study were described, including the modelling of logs and defects using polyhedral boundary representation, a graphic sawing simulator, a pattern directed sawing policy predicated on making cuts parallel to a dominant defect axis, its implementation as a recursive decomposition procedure, a procedure for extracting and characterizing defect configurations as defect hulls, and the development of a pattern directed inference model.

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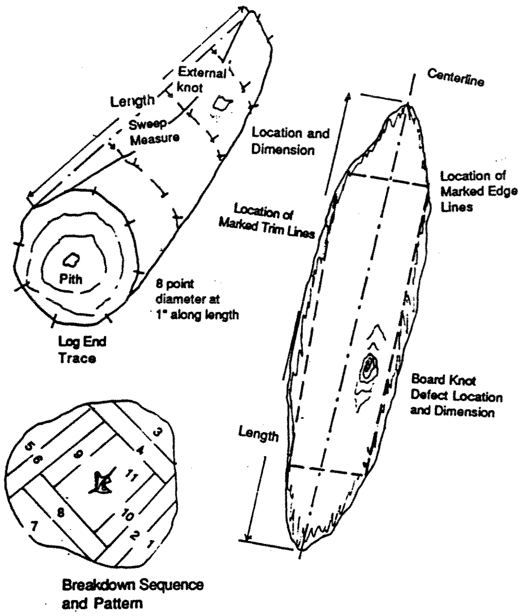


Figure 2. Sample data collected from sawmill site visits.

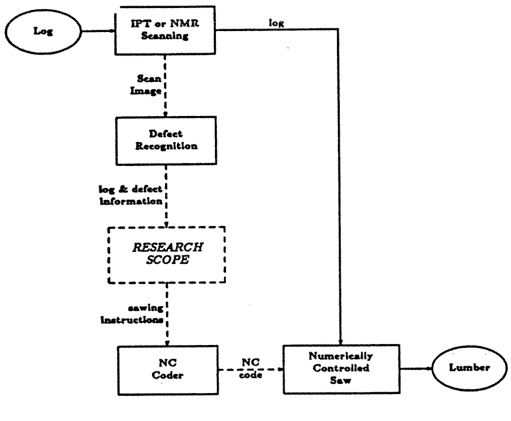


Figure 1. Information and material flow.

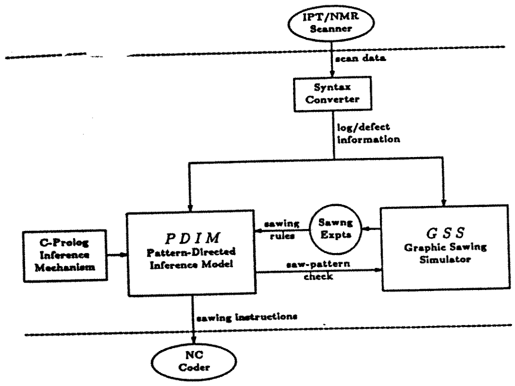


Figure 3. Research approach flowchart.

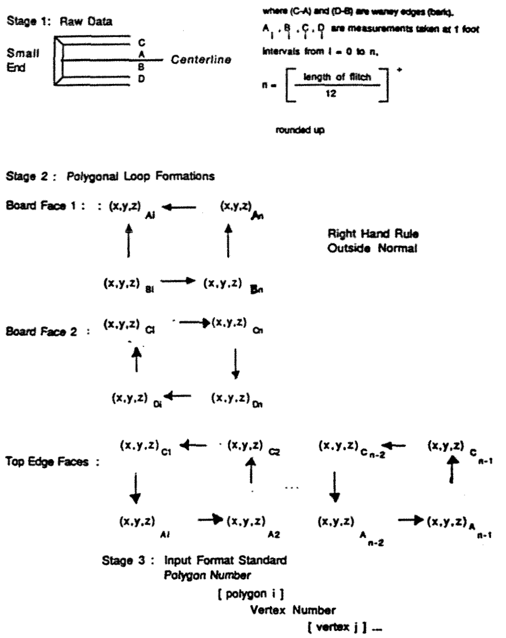


Figure 4. Data conversion to polyhedral format.

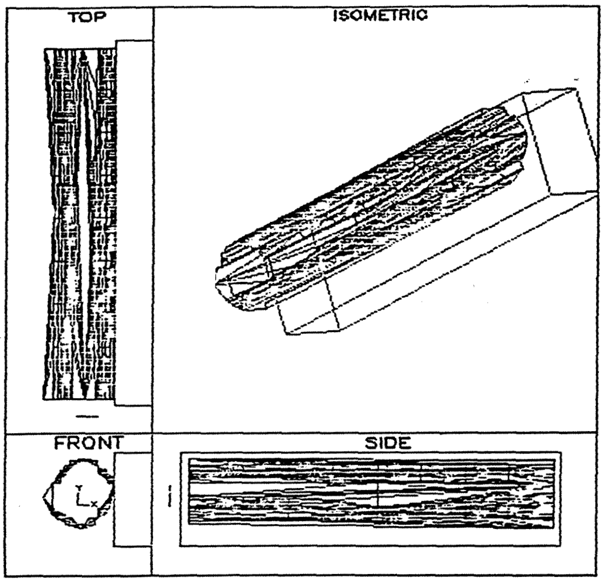


Figure 5. Log and saw representations.

INTERACTIVE SAWING PROCEDURE

1. Bring up log representation on screen.
2. Superimpose defect representations for guidance.
3. Visually detect defect configuration (major axes, orientation, etc.).
4. Position log representation relative to saw representation.
5. Perform simulated sawing.
6. Repeat 3 to 5 till log completely sawn.
7. Postprocess flitches.
   - 7.1 From each flitch, subtract corresponding defects.
   - 7.2 Extract flitch faces.
   - 7.3 Edge and trim according to predefined procedures.
   - 7.4 Extract grading requirements and perform computer grading.
   - 7.5 Consolidate log yield.

Figure 6. Interactive simulated sawing procedure.

Table 1. Summary of simulated sawing results.

Aggregate Results for Six Logs Surface Measure, (Number of Boards)					
Grade	Sawing Pattern				
	Origin.*	Live	Cant	Around*	Pattern
FAS	88 (12)	31 (4)	31 (4)	91 (12)	100 (13)
Saps	7 (1)	66 (9)	42 (6)	7 (1)	76 (13)
Sel	46 (6)	136 (15)	56 (8)	44 (6)	97 (14)
1C	214 (32)	250 (31)	242 (40)	241 (31)	167 (25)
2AC	149 (20)	199 (24)	207 (28)	139 (18)	217 (31)
2BC	71 (10)	22 (4)	77 (20)	75 (11)	34 (4)
3AC	2 (1)			4 (1)	
Total	577 (82)	704 (87)	.655 (106)	601 (80)	691 (100)

* cant not resawed.

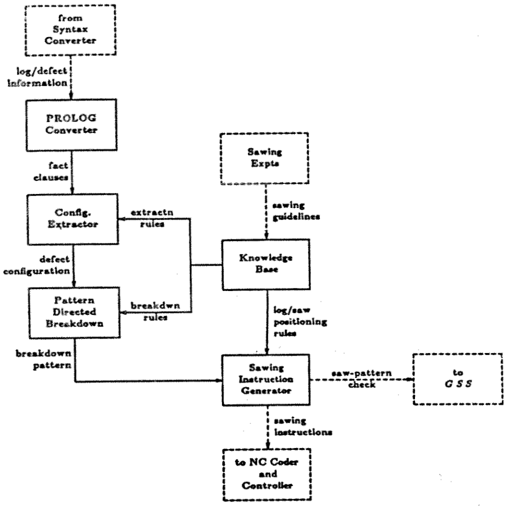


Figure 7. PDIM flowchart

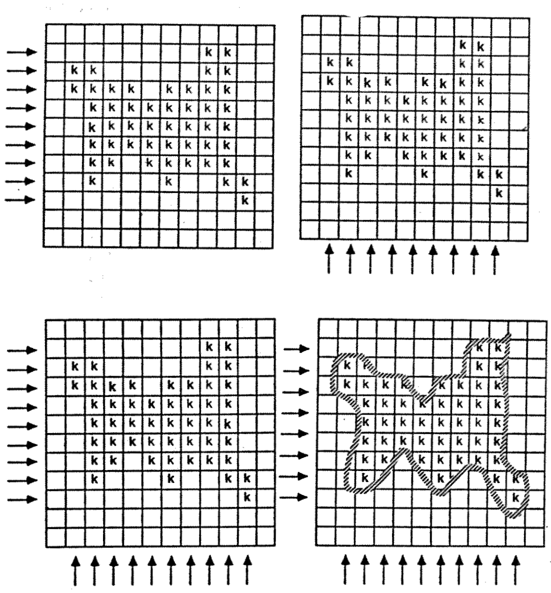


Figure 9. Defect hull formation

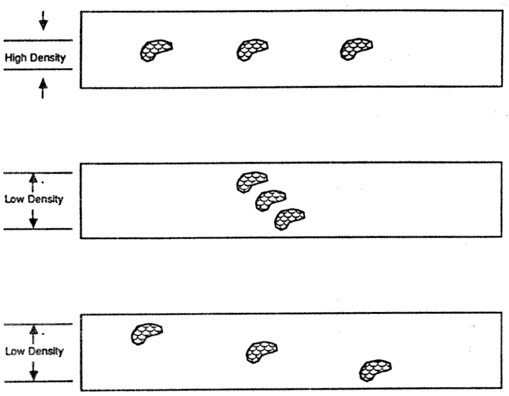


Figure 8. Defect location effect

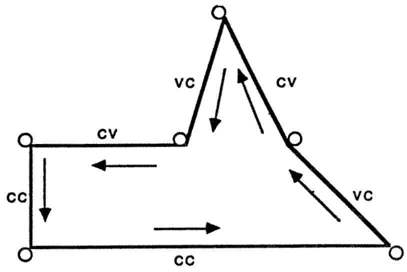
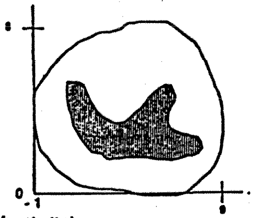


Figure 10. Edge relations

Table 2. Comparison of the PDIM to other sawing patterns.

Aggregate Results for Six Logs Surface Measure, (Number of Boards)					
Grade	Sawing Pattern				
	Origin.	Live	Cant	Around	PDIM
FAS	88 (12)	31 (4)	31 (4)	91 (12)	69 (9)
Saps	7 (1)	66 (9)	42 (6)	7 (1)	97 (18)
Sel	46 (6)	136 (15)	56 (8)	44 (6)	117 (16)
1C	214 (32)	250 (31)	242 (40)	241 (31)	167 (25)
2AC	149 (20)	199 (24)	207 (28)	139 (18)	156 (21)
2BC	71 (10)	22 (4)	77 (20)	75 (11)	35 (5)
3AC	2 (1)			4 (1)	
Total	577 (82)	704 (87)	655 (106)	601 (80)	641 (94)

6.4.3.3. Multiple Axes Example 2



| ?- [testhull2].

yes

yes

yes

yes

yes

yes

yes

yes
testhull2 consulted -2472 bytes 0.433339 sec.

yes
| ?- test_hull.

HULL FORMATION

x [(3,3),(1,3),(1,2),(1,1),(4,1),(3,2)]

Figure 11. A sample program run.

y [(4,1),(3,3),(2,2),(1,3),(1,1),(2,1),(3,1),(4,1)]

singlex [(3,3),(1,3),(1,2),(1,1),(4,1),(3,2)]

singley [(3,3),(2,2),(1,3),(1,1),(2,1),(3,1),(4,1)]

hull [(3,3),(2,2),(1,3),(1,2),(1,1),(2,1),(3,1),
(4,1),(3,2),(3,3),(2,2)]

HULL CHARACTERIZATION

inflection_pts [[(3,3),(2,2),(1,3)],[(2,2),(1,3),(1,2)],
[(1,2),(1,1),(2,1)],[(3,1),(4,1),(3,2)],
[(4,1),(3,2),(3,3)],[(3,2),(3,3),(2,2)]]

convex_pts [(1,3),(1,1),(4,1),(3,3)]

relatives [[(2,2),(1,3),(1,1)],[(1,3),(1,1),(4,1)],
[(1,1),(4,1),(3,2)],[(3,2),(3,3),(2,2)]]

1,3 2.34314 1
1,1 2.87999 6.5
4,1 3.15397 2.5
3,3 1.17158 0.5

axes [[(1,3),(1.58579,1.58579),2.34314],
[(4,1),(2.35924,1.67962),1.26159],
[(3,3),(2.58578,2),2.34316]]

number of axes = 3
major_axis2 above major_axis3 by 135 degrees
major_axis3 below major_axis2 by 135 degrees
major_axis2 above major_axis4 by 44.9999 degrees
major_axis4 below major_axis2 by 44.9999 degrees
major_axis4 above major_axis3 by 89.9999 degrees
major_axis3 below major_axis4 by 89.9999 degrees

direction(major_axis4,(3','3),(2.58578','2),2.34316).
direction(major_axis3,(4','1),(2.35924','1.67962),1.26159).
direction(major_axis2,(1','3),(1.58579','1.58579),2.34314).

logdef_status(log_boundary1,multiple_axes).

logbnds(log_boundary1,[-1,0,9,8]).

hullbounds(log_boundary1,[1,1,4,3]).

RUN TIME DIAGNOSTICS

axis major_axis4
list_of_axes [major_axis2]
rm_dupl [major_axis2]
numb_axes1 1
list_of_axes2 [major_axis3]
rm_dupl2 [major_axis3]
numb_axes2 1
axis_head 2.58578,2 axis_tail 3,3
edgelist [[(6,8),(2,8)],[(2,8),(-1,6)],[(-1,6),(0,2)],
[(0,2),(2,0)],[(2,0),(6,0)],[(6,0),(9,2)],
[(9,2),(8,6)],[(8,6),(6,8)]]
intersectlist [(1.82843,0.171574),(5.07107,8)]
sector1 []
sector2 [[2,0,9],[6,-1,8],[8,2,6]]
sector3 [[0,2,6]]

SAWING INSTRUCTIONS

rotate log_boundary1 22.4999 degrees counterclockwise
index log_boundary1 4.84356 inches forward
saw ... for resaw2
in this position log_boundary4 is 4.84356 inches wide
and 6.49435 inches high
index log_boundary4 towards saw 1.17178 inches
saw
rotate log_boundary4 180 degrees counterclockwise
index log_boundary4 towards saw 1.17178 inches
saw
index log_boundary4 towards saw 1.25 inches
saw
rotate log_boundary5 90 degrees counterclockwise
in this position log_boundary5 is 6.49435 inches wide
and 5.92596 inches high
index log_boundary5 towards saw 0.747175 inches
saw
index log_boundary5 towards saw 1.25 inches
saw
rotate log_boundary5 180 degrees counterclockwise
index log_boundary5 towards saw 0.747175 inches
saw
index log_boundary5 towards saw 1.25 inches
saw
index log_boundary5 towards saw 1.25 inches
saw

yes

HW-BUCK: A COMPUTERIZED HARDWOOD BUCKING DECISION SIMULATOR[1/]

James B. Pickens, Gary W. Lyon,

Andrew Lee, and W. Edward Frayer[2/]

Abstract.--Recent research indicates that current field bucking practices in the Upper Peninsula of Michigan underachieve the possible value of hardwood logs produced by 39 to 55 percent. This paper describes a computerized decision simulator for training buckers to improve value recovery when bucking hardwood stems. The program presents the trainee with a picture of the hardwood log to be bucked, allows the trainee to select the sequence of cuts to buck the tree, and then presents a side-by-side comparison of the trainee's bucking choices and the optimal bucking cuts.

Keywords: Dynamic programming, optimal bucking, hardwood log bucker training.

The gross value of logs produced from the bucking of northern hardwood trees strongly influences the profitability of logging and forest ownership enterprises. The extent to which the potential value of every felled tree is recovered depends, initially, on how the bucker (usually operating in the forest) cuts the tree into logs. Poor decision-making on the bucker's part leads to value losses which are, ultimately, the concern of landowners, primary processors, and loggers alike. The main causes of poor bucking decisions are: the complexity of industry specifications; unquantified or imprecise specifications; the large number of log grades; production pressure; lack of incentives; lack of training; and lack of decision aids (Twaddle and Goulding 1989). Furthermore, the number of feasible combinations of acceptable log lengths and cull sections that can be cut from most hardwood trees is very large. Evaluating even a small proportion of these options requires significant mental effort.

Several bucking optimization models, capable of maximizing the total value of logs produced from an individual tree, a stand, or over a planning period, have been developed. The models evaluate alternative bucking decisions and identify the optimal solution through the application of operations research techniques. The most common technique for selecting the optimal bucking pattern is dynamic programming. This application was first discussed by Pnevmaticos and Mann (1972). Bucking optimization models tend to be species specific, taking into account the defect and form characteristics of the species and the log grading rules that are applied to it.

Previous models have been designed for softwood species such as Douglas-fir, Caribbean pine, and radiata pine. Studies of softwood bucking practices in New Zealand and the Pacific Northwest of the United States have revealed gross value losses ranging from 5-26 percent (Geerts and Twaddle 1985; Sessions et al. 1989; Twaddle and Goulding 1989).

The optimal bucking problem for northern hardwoods was recently addressed by researchers at the School of Forestry and Wood Products of Michigan Technological University. One product of the study was an estimate of the value loss associated with current bucking practices. The value improvement of optimal bucking over current practice was

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[2/]The authors are Associate Professor, Assistant Professor, former Graduate Research Assistant, and Professor and Dean, respectively, School of Forestry and Wood Products, Michigan Technological University, Houghton, MI. Andrew Lee is currently with the American Language Center in Rabat. Morocco.

estimated using a sample of 166 trees from five different stands harvested by four logging crews. The value improvement estimates ranged from 39 to 55 percent using six different historical price relationships (Lee et al. in process). Thus, only 65 to 72 percent of the potential value was recovered. The increase in value resulted mainly from a 150 percent increase in veneer yield in the optimal bucking pattern. Slightly more scaled volume was also produced, due mainly to reduced scale deductions for sweep. This indicates that a tremendous opportunity to improve profitability is available if the quality of bucking decisions can be improved. The value loss for hardwoods was much larger than the 5 to 26 percent reported for softwoods. This seems reasonable because hardwood stems contain more sweep and crook and many more defects than softwoods. This, combined with the more complex grading rules, makes the hardwood log bucking problem inherently more complex.

An extensive discussion of ways to use optimal bucking results to improve bucking in the woods was presented by Briggs (1980). One of the suggested approaches is to use a computer to present the bucker with a believable graphic representation of a felled tree, which can be rotated to reveal defects and sweep. The trainee can decide where to buck the tree. The computer then would provide feedback in the form of summaries of the bucked logs and their total economic value, and compare the results with the optimal bucking solution. Repeated use of the simulator, with trees of varying size and quality, increases the trainee's sensitivity to the effect of stem form and defects on log grade and value. These skills are then applicable to real decisions in the forest or at the mill. The Weyerhaueser Company has implemented these suggestions in a decision simulator named VISION for softwoods in the Pacific Northwest, and it is estimated that the operational benefits of the training exceeded $100 million in the period between 1977 and 1984 (Lembersky and Chi 1984; 1986). The use of hand-held computers programmed with an optimization algorithm has been tested in Oregon. The bucker enters diameters, lengths, quality codes, and mandatory buck locations (for sections of sweep, rot, or breakage) into the computer. The computer returns the optimal bucking solution based on adjusted mill prices (Garland et al. 1989; Sessions et al. 1989).

This paper describes a computerized bucking decision simulator developed at Michigan Technological University for training hardwood log bucking skills.

THE HW-BUCK SOFTWARE SYSTEM

The HW-BUCK system is a computerized training tool for teaching improved bucking skills to hardwood buckers and their supervisors. Descriptions of 150 hardwood stems are included with the software. The sawlog grading rules and default veneer specifications used in the system are from the Official Grading Rules for Northern Hardwood Logs and Tie Cuts published by the Timber Producers Association of Michigan and Wisconsin (1988).

The HW-BUCK decision simulator should not be viewed as a stand-alone training tool. It should be used in combination with the more traditional approaches to bucker training. One such approach is to have recognized experts conduct workshops to teach grading, scaling, and bucking skills. Use of the HW-BUCK decision simulator has been integrated with this type of training conducted by Michigan Technological University, and has been well received by the trainees.

Two log scaling options are available (Scribner Decimal C and International 1/4" Log Rules). The trainee is presented with a picture of the tree stem to be bucked. Defects and sweep are represented, and the log can be rotated to better visualize the shape and other characteristics of the tree. The trainee selects cuts, then views the results of their bucking choices and the optimal bucking pattern on the same screen. The user can change prices for both sawlogs and veneer and much of the information concerning veneer grading rules.

The programs are described more completely below.

The Bucking Decision Simulator

The bucking decision simulator, or "bucking game", presents the trainee with the log bucking situation, and allows him or her to buck the tree. The program displays a two-dimensional picture of the tree on the computer screen. Defects and sweep are represented in the picture. This picture can be rotated, which allows the trainee to view all sides of the stem and gives the impression of a three-dimensional view. The trainee can buck the tree, then observe the grade, value, and volume of the resulting logs. This is presented on the same screen as the optimum bucking pattern, which is selected using dynamic programming. The side-by-side comparison allows the trainee to identify differences between his or her choices and the optimum, and to develop heuristics (rules-of-thumb) to improve the choice of cuts.

The user first selects a market that has been previously defined. Markets are defined as a combination of log prices and veneer grading specifications. Although only one market is provided for each of the two log scaling option, others can be defined using the HW-BUCK software. After the market is selected, the trainee can choose which of the 150 stems in the HW-BUCK database to buck. The program then presents the bucker with a picture of the stem. Knots and burls appear as magenta ellipses. Their size can be estimated from a scale given on the screen. The tree can be made larger, which helps to find exact dimensions. Forks and bulges, which cause length deductions and do not permit clear-cuttings, appear as darker gray zones on the stem. End defects (holes, stain, heart) are displayed above the two ends of the stem and above cuts (if they are still present). End defect diameters can be estimated using the same scale as used for knots. Seams are represented by red lines.

Nearly all instructions for the program are input from the cursor keypad on the right side of an AT keyboard. Program operation is straightforward, allowing users to quickly become comfortable with operation even with no prior computer experience.

Cuts can be inserted and deleted at will. A maximum of 7 cuts are permitted. Log lengths allowed are 8, 10, 12, 14, and 16 feet, and all logs must have an 8" trim allowance.

When the trainee has finished bucking a stem, logs are evaluated and presented on the screen with the optimal cutting pattern. Summary information presented below each log includes length, grade, small end diameter, sweep, percent volume deductions due to sweep and total cull, scale volume, and value. Logs are treated as cull if (1) they are not at least 8' 8" (an 8 foot log plus 8 inches of trim allowance), (2) if their scale is less than 20 board feet, or (3) if they have greater than 50 percent cull deduction. After viewing the summary screen, the trainee returns to the game, where cuts can be revised or the user can continue with another tree or exit the program.

Creating New Markets: Changing Default Log Prices and Veneer Grading Rules

The user can replace all of the prices associated with different veneer and sawlog lengths and grades and much of the information used to grade veneer logs. The grading rules for the three grades of sawlogs cannot be changed by the user. Log prices and veneer grading specifications are defined independently. The user later uses combinations of prices and veneer specifications to define markets.

Changing Log Prices

Prices are entered in a spreadsheet-like table. When all the cells are filled, the prices are saved under a name of the user's choice. Zeros are entered in the corresponding cells if certain log lengths or certain grades are not accepted.

Six price sets are already defined based on historical information for the Upper Peninsula of Michigan and Wisconsin (Pickens et al. 1990). Historical sugar maple prices with no length premium are used in the markets provided with the software. These prices are:

Log Grade	Price ($/MBF)
#1 Veneer	450
#2 Veneer	300
#3 Veneer	Not Allowed
#1 Sawlog	180
#2 Sawlog	125
#3 Sawlog	80

Changing Veneer Specifications

The procedure for changing veneer specifications is menu-driven. Veneer specification prompts usually require integer or yes/no responses. The default veneer specification corresponds to those published by the Timber Producers of Michigan and Wisconsin for 1988. The veneer grading specifications that can be altered, along with their values in the default market, are presented in the user's manual (Pickens et al. 1990).

Update Optimal Solutions

New markets are defined as a combination of a price set and a set of veneer grading rules. After a market is defined, the optimal bucking pattern for the 150 sample trees is calculated and stored for use in the bucking game. This process is quite time consuming, and takes about 90 minutes using an IBM AT. The optimal bucking pattern is stored to avoid the need to calculate it during the bucking game, which would require pauses of up to a minute.

Two markets have been provided with the software. The market KEWEENAW uses Scribner Decimal-C log scaling, the default veneer grading rules, and the historical sugar maple prices presented above. The market NATIONAL was created using International 1/4" log scaling, the default veneer grading rules, and the historical sugar maple prices presented above.

DISCUSSION

The HW-BUCK optimal log bucking decision simulator provides a useful tool to train hardwood bucking skills, especially when used in combination with traditional grading, scaling, and bucker training. We believe harvesting crews, their supervisors, and the foresters who work with them would all benefit from training with the simulator. Furthermore, the simulator has been used in classes at Michigan Technological University. In addition to reviewing scaling and grading rules and improving bucking skills, it provides an excellent example of a decision simulator using operations research techniques.

The trainees develop a better understanding of the grading and scaling rules and the value of the various products that can be produced. Repeated use of the decision simulator also allows the trainee to develop heuristics for improving value recovery, which can then be applied when bucking logs. Lee et al. (in process) identify three heuristics developed by comparing the optimal bucking pattern with the field bucker's choice of cuts. First, the optimum patterns included cuts which reduce sweep relative to the actual bucker's choices. Second, many more cull sections were identified in the optimal bucking pattern than by the field buckers. The field buckers tended to retain sections with serious defects, reducing both the grade and scale volume of the resulting logs. By leaving more cull in the woods, better bucking practices can reduce handling and processing costs and improve product yields. Third, the optimization selected cuts which place defects toward the ends of sawlogs to increase clearcuttings, and thus improve log grade.

A user's manual is provided with the software (Pickens et al. 1990). The manual explains the installation and operation of the HW-BUCK programs. The programs were written for IBM AT or compatible computers, and responses are somewhat sluggish on slow machines such as the original IBM PC. An EGA or VGA color monitor is required. An informational packet with specific hardware requirements is available from the authors at the School of Forestry and Wood Products, Michigan Technological University, Houghton, MI, 49931, or telephone number (906) 487-2218. A charge of either $25 or $40, depending on the density of the floppy disks requested, is included to cover the cost of reproduction and distribution. These materials are copyrighted, and it is not legal to receive a copy from any other source.

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TIMBER AND FINANCIAL ASSET PORTFOLIOS: 1937-1986[1]

Thomas A. Thomson[2]

Abstract.--This paper presents multi-period portfolio returns for Douglas-fir and southern pine timber investments combined with common stocks, corporate bonds, U.S. Government bonds and U.S. Government Treasury bills over the 50 year period 1937-1986. When the portfolio optimization model allowed unrestricted choice among assets, it was common to include timber assets in the portfolio. The long run risk-return results, however, were unfavorable. Restricting timber investment each year to be 5-20% for each species, however, increased the long run portfolio returns.

INTRODUCTION

The financial attractiveness of timber growing investments continues to be a major area of study in forest economics. Recent work has incorporated the methods of modern portfolio theory and the capital asset pricing model of finance. Studies that apply the capital asset pricing model to determine the relative attractiveness of timber investments include Thomson (1987, 1989, 1990), Thomson and Baumgartner (1988), Redmond and Cubbage (1988), Zinkhan (1988), and Binkley and Washburn (1988). These papers find that the betas of timber investments, are small or possibly even negative. In most cases, the computed beta was not statistically significant suggesting that the hypothesis of beta equals zero cannot be rejected. Since timber investment betas tend to be small or zero, timber investments can be expected to be desirable components of investment portfolios. These capital asset pricing model studies, however, do not show the proportions of timber investments that will optimize an investment portfolio. Portfolio analysis is required for such optimization.

Mills and Hoover (1982) use a linear approximation technique to compute portfolios of timber, agricultural, and financial assets. Their analysis focuses on the decision of whether to hold timber or non-timber assets and they find that although timber assets had a high risk and relatively low rate of return, they are desirable components of some investment portfolios. Thomson (1987) uses quadratic programming to solve the standard Markowitz mean-variance portfolio problem and analyzes timber investments portfolios both with and without inclusion of the Standard and Poor's 500 common stock index. Thomson and Baumgartner (1988) use the same data to determine how the results of several portfolio solution techniques, including linear approximation and index models, compare to those of quadratic programming. Although other techniques yield similar results, the true mean-variance results are only obtained using quadratic programming. Conroy and Miles (1989), and Zinkhan and Mitchell (1990) study adding a southern pine timber investment to a portfolio of financial investments and find the inclusion of pine to be desirable. Thomson (1990) addresses an expanded portfolio problem by allowing four timber species in the portfolios. One finding is that some timber was held in all portfolios. Thomson (1991) develops short run and long run portfolio results for a mix of timber and financial market investments. He shows that in the long run the riskiest portfolios, which are those containing large proportions of timber, may have a lower return than some less risky portfolios. In a recent survey of pension funds, Harris *et al.* (1989) found that timberland investments were present in some pension portfolios though the number was rather small. Pension funds which invested in timberlands, however, were expecting to hold these investments over a 10-15 year period and perhaps to increase their total timberland holding.

This paper extends earlier work by examining the long run wealth accumulation possible from a portfolio investment strategy which includes Douglas-fir and southern pine in addition to financial assets. The portfolio model employed is the standard Markowitz approach which Thomson (1991) shows to provide a similar result to the long run portfolio model of Grauer and Hakansson (1982). Grauer and Hakansson (1982) determined the historical returns under active portfolio management for common stocks, corporate bonds, U.S. Government bonds and U.S. Government Treasury bills. This paper adds the timber investments of Douglas-fir and southern pine to the domain of assets from which portfolio choices are made.

THE DATA

The data input for portfolio problems are the periodic rates of return for each asset under consideration. A standard method for computing financial returns of a security, as used by Ibbotson and Sinquefield (1982), is:

$$R_t = \left[\frac{V_t + D_t}{V_{t-1}}\right] - 1 \qquad (1)$$

where:

R_t = the rate of return earned in period t

V_t = the value (price) of the security in period t

[1] Presented at the Symposium on Systems Analysis in Forest Resources, Charleston, SC, March 3-7, 1991.

[2] Assistant Professor of Forest Management, School of Natural Resources, The University of Michigan, Ann Arbor, MI 48109-1115.

V_{t-1} = the value (price) of the security in the previous period, t-1
D_t = the dividend received in period t

In period t-1 one invests the value of the security, V_{t-1}, and receives after one period the current value of that security V_t plus the value of the dividend, D_t. These figures are used in equation (1) to determine the return earned over that period. Some modification is required to use this approach for timber investments. Instead of purchasing one security, this paper shall consider the purchase of a 1 acre fully regulated forest. To purchase this forest one must pay the value of the land plus the value of the standing timber (growing stock) at time t-1. After one period, an equivalent forest is returned, plus a dividend in the form of a timber sale receipt from a sustained yield timber harvest. The value of the dividend is reduced by the cost of managing the forest for one year, so the net dividend is the value of the timber harvest minus the cost of managing the forest for one year. As with the security, the value of the one acre fully regulated forest (land plus timber) must be determined. This depends on current stumpage prices. For a fully regulated forest, the amount of growing stock remains constant from period to period; its value depends on the price of stumpage. The LEV of the forest land also depends on the stumpage price. The real annual return for growing a fully regulated timber stand can be estimated as:

$$F_t = \left(\frac{LEV_t + P_tG + P_tH - C}{LEV_{t-1} + P_{t-1}G} \right) - 1 \qquad (2)$$

where:
F_t = real annual return from the timber asset
LEV_t = real value of bare forest land in period t
P_t = real stumpage price in period t
H = constant annual harvest volume from the fully regulated forest
G = growing stock index, which is constant from period to period for a fully regulated forest
C = constant annual real cost of managing the forest including all silvicultural expenditures, land taxes, and other costs associated with forest management

Stumpage price, yield, and management cost information are needed to compute the annual return for each timber investment. P_tG is the current value of the growing stock. The sum of P_tG and LEV_t is the value of the timber plus growing stock in period t and thus is analogous to the value of a security, V_t. The sum of $P_{t-1}G$ and LEV_{t-1} is the value of the timber plus growing stock in period t-1 and thus is analogous to the value of a security in period t-1, (V_{t-1}). The one period earning from managing the forest is the value of the harvest, P_tH, minus the annual forest management costs, C, so P_tH - C is analogous to the dividend, D_t, of a financial security.

Capital market theory implies that the value of a forest's growing stock is the discounted value of its future harvest rather than its immediate harvest value. The growing stock index, G, is calculated as the sum of the discounted growing stock for each age class of the regulated forest. For a 30-year rotation, the growing stock index for a 29-year-old forest is the yield from a 30 year old forest discounted by one year (H/1.05 for a 5% real discount rate). The growing stock index of a 28 year old forest is the growing stock index of a 29 year old forest discounted one year, or the yield of a 30 year old forest discounted two years ($H/(1.05)^2$). The growing stock indices for each age are summed to determine the growing stock index, G, for the fully regulated acre. For a rotation length of N years, this may be expressed as:

$$G = \sum_{n=1}^{N} \frac{H}{(1.05)^n} \qquad (3)$$

Annual real rate of return figures are calculated for growing Douglas-fir forests in the Pacific Northwest and loblolly pine in the south. Because a one acre fully regulated forest is assumed, the number of acres harvested each year is the inverse of the rotation age (N). The per-acre yield at rotation is divided by the rotation age to calculate the annual harvest, H as only 1/N acres can be harvested each year. Similarly, per acre regeneration and stand tending costs are also divided by the rotation age as only 1/N acres will be treated each year. Annual taxes and administrative costs are included on a per acre basis as these costs must be paid for the entire acre whereas planting or other silvicultural activities are done on only a portion of the acre in each year. The forest management cost, incurred annually for a one acre normal forest, is the sum of the planting and other silvicultural costs plus the administrative and tax costs. This cost is computed in real terms and assumed constant throughout the analysis period.

The cost figures for managing southern pine are from Straka *et al.* (1989). All stands are assumed to be planted. Other silvicultural costs such as site preparation, vegetation control, and prescribed burning are assumed to be done in proportion to the acreage of each reported in Straka *et al.* (1989). The seedling cost, which is not included in Straka *et al.*, is \$28 per thousand, the 1990 price of loblolly pine seedlings from the State of Virginia, Waverly nursery. The cost figures for managing Douglas-fir are from Bare (1979). Stands are assumed to receive site preparation prior to planting, a herbicide treatment early in the rotation, and a precommercial thinning at age 15.

The yield of loblolly pine at age 30 is estimated at 12.6 Mbf/acre. The cubic foot yield by diameter class was projected using the North Carolina State University Plantation Management Simulator for site index (age 25) of 65 feet, with 700 trees per acre planted having 85% initial survival. The cubic foot yields were converted to board foot yields by diameter class using conversion ratios in Vardaman (1987). The yield at age 50 for Douglas-fir was projected at 45 Mbf/acre employing the Stand Projection System (Arney 1985) with a site index (breast height age 50) of 125 and a precommercial thinning at age 15 to 225 trees/acre.

The land value (LEV), which depends on the real stumpage price, P_t, was calculated in the usual Faustmann method. A 5% real discount rate was used in the formula:

$$LEV_t = \frac{P_tY_N - \sum_{n=0}^{N} S_n(1.05)^{N-n}}{(1.05)^N - 1} - \frac{A}{0.05} \qquad (4)$$

where:
Y_N = per acre yield of the forest at rotation age N (equals H*N)

S_n = per acre real silvicultural costs in year n such as planting or timber stand improvement

A = per acre real annual costs of forest management such as taxes and administrative costs

and other variables are as defined earlier. The computed LEV figures for the early years were often negative due to the low stumpage prices. In these cases a value of 0 was used. The assumption implicit in the LEV calculations is that growing continuous timber crops of the species under consideration is the financially optimal use of the forest land.

The other data required to compute rates of returns are historical stumpage prices. This study uses stumpage prices for Douglas-fir and southern pine from U.S. National Forest timber sales over the 1926-1986 period. Data for 1926-1957 is from Potter and Christie (1962). Data for 1950-1979 is from Appendix 1 in USDA Forest Service (1982). Data for 1959-1986 is compiled from an annual USDA Forest Service series of stumpage prices. These price series cover overlapping periods, and it was confirmed that all sources encompass a common series as prices corresponded among sources when periods overlapped. Where data was missing from one series it could usually be found in one of the other series. Three data points that could not be identified this way were estimated using regression methods with other price series for the same species. The regression had an R^2 value of 0.99 suggesting that the few estimated points were accurately estimated. The nominal prices given in these reports were adjusted to the common base year of 1967 using the consumer price index as reported in Ibbotson and Sinquefield (1982, 1989) to provide real stumpage prices. The real stumpage prices, real LEV's, and real forest management costs were input, along with the harvest volume and growing stock indices, into equation (2) to compute the annual real rate of return for each timber investment.

Inflation adjusted monthly market return indices through 1981 for common stocks, corporate bonds, U.S. Government bonds, and U.S. Treasury bills are given in Exhibits B-32 - B-36 of Ibbotson and Sinquefield (1982). The more recent figures are derived from Exhibits A-1, A-3, A-4, A-6, and A-7 in Ibbotson and Sinquefield (1989.) These return data serve as the basis for computing an annual return for each of these financial investments. The annual returns computed for timber investments use an annual price series. This annual price series is the composite from averaging prices observed during the year. The market returns given in Ibbotson and Sinquefield, however, are first trading day of the month to first trading day of the month; thus, they represent the return over a precise period. The Ibbotson and Sinquefield data, therefore, were interpreted as 12 monthly estimates. The monthly real return indices were averaged to represent the average return index for that year. The growth in the average return index from one year until the next is used to compute the annual rate of return earned by that investment.

METHODS

The goal of Markowitz portfolio analysis is to maximize expected return for any level of risk where risk is measured by portfolio standard deviation. One way to achieved this goal is to maximize a quadratic function, which is increasing in return, and decreasing in risk. Such a formulation is consistent with maximizing a quadratic utility function (Sharpe 1970) and may be written as:

$$\text{Max } q = \sum_{i=1}^{I} x_i R_i - \lambda \sum_{i=1}^{I} \sum_{j=1}^{I} x_i x_j \sigma_{ij} \qquad (5)$$

subject to:

$$\sum_{i=1}^{I} x_i = 1 \qquad (6)$$

$$x_i \geq 0 \qquad i = 1, 2, \ldots, I \qquad (7)$$

where:

q = the quadratric utility function to be maximized

x_i = the proportion of the portfolio in each of the I assets

R_i = the arithmetic mean (real) rate of return of the i^{th} asset

σ_{ij} = the covariance of the return between the i^{th} and j^{th} asset (if i=j, it is the variance)

λ = a parameter of the function that describes the degree of risk aversion exhibited by the investor ($0 \leq \lambda < \infty$)

Equation (5) is the quadratic utility function to be maximized. Equation (6) requires that the weights sum to 1, the total investment. Equation (7) requires that proportions invested in each alternative be non negative.

The risk aversion parameter, λ, varies among investors. If λ is zero the risk of the portfolio is immaterial and an investor's goal is to maximize return (risk neutrality). If λ is a large number, the goal is to minimize risk (portfolio standard deviation). Values in between these extremes describe investors who are willing to make a trade-off between earning a higher expected rate of return, and being subjected to greater risk. To compute the efficient trade-off frontier between return and risk, equations (5) - (7) are solved parametrically, adjusting the λ coefficient to trace out the result. Optimization calculations were solved using the nonlinear programming software, MP6 from SCI computing (Saigal 1986), using an IBM PC-AT compatible personal computer.

Grauer and Hakansson (1982) maximize an analogous power utility function to determine the optimal portfolios of common stocks, corporate bonds, Government bonds, and Treasury bills for various levels of risk tolerance. They use the observed returns from 1926-35 to compute the portfolio weights to hold during 1936. Then they use the observed returns from 1927-36 to compute portfolio weights for 1937. This process is repeated through 1978. The investor's return for each year is that realized from holding the computed portfolio for that year.

The portfolio analysis reported here follows the Grauer and Hakansson (1982) approach with some modifications. First, this paper maximizes a quadratic utility function rather than a power utility function. Second, the timber investment assets of Douglas-fir and southern pine are added to the choice of investments. Third, the analysis is done using real rates of return rather than nominal rates of return. Fourth, the time period is 1937-86. The return series starts one year later as the 1926 inflation data is needed to compute the real stumpage price for that year so that 1927 is the first year for which a timber return can be computed. The length of the horizon is increased as more recent financial market and timber assets returns data are available.

RESULTS

When the portfolio model is solved, its solution is a set of portfolio weights $x_{i\lambda t}$ for each asset i, for each λ parameter for year t. The 1927-36 period data is used in the first portfolio optimization calculation. Twenty-nine sets of portfolio weights ($x_{i\lambda t}$) are computed, corresponding to the 29 λ parameters used (0.00, 0.05, 0.10, 0.15, 0.20, 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 12.0, 15.0, 25.0, 50.0, 100.0, 999.0). The returns earned by each of these 29 portfolio's ($r_{\lambda t}$) is then calculated for t=1937 using the 1937 return data and the equation:

$$r_{\lambda t} = \sum_{i=1}^{I} x_{i\lambda t}\, r_{it} \qquad \lambda = 1, 2, \ldots, 29 \qquad (8)$$

The return data for the 1928-37 period is then used in the portfolio optimization routine to compute a new set of optimal portfolio weights from which the return earned in 1938 is computed. This process repeats itself, finally using the 1976-85 data to compute portfolio weights needed to choose the 1986 portfolio. The result of these computations is a series of historical rates of return earned over the 1937-86 period for each portfolio of parameter λ.

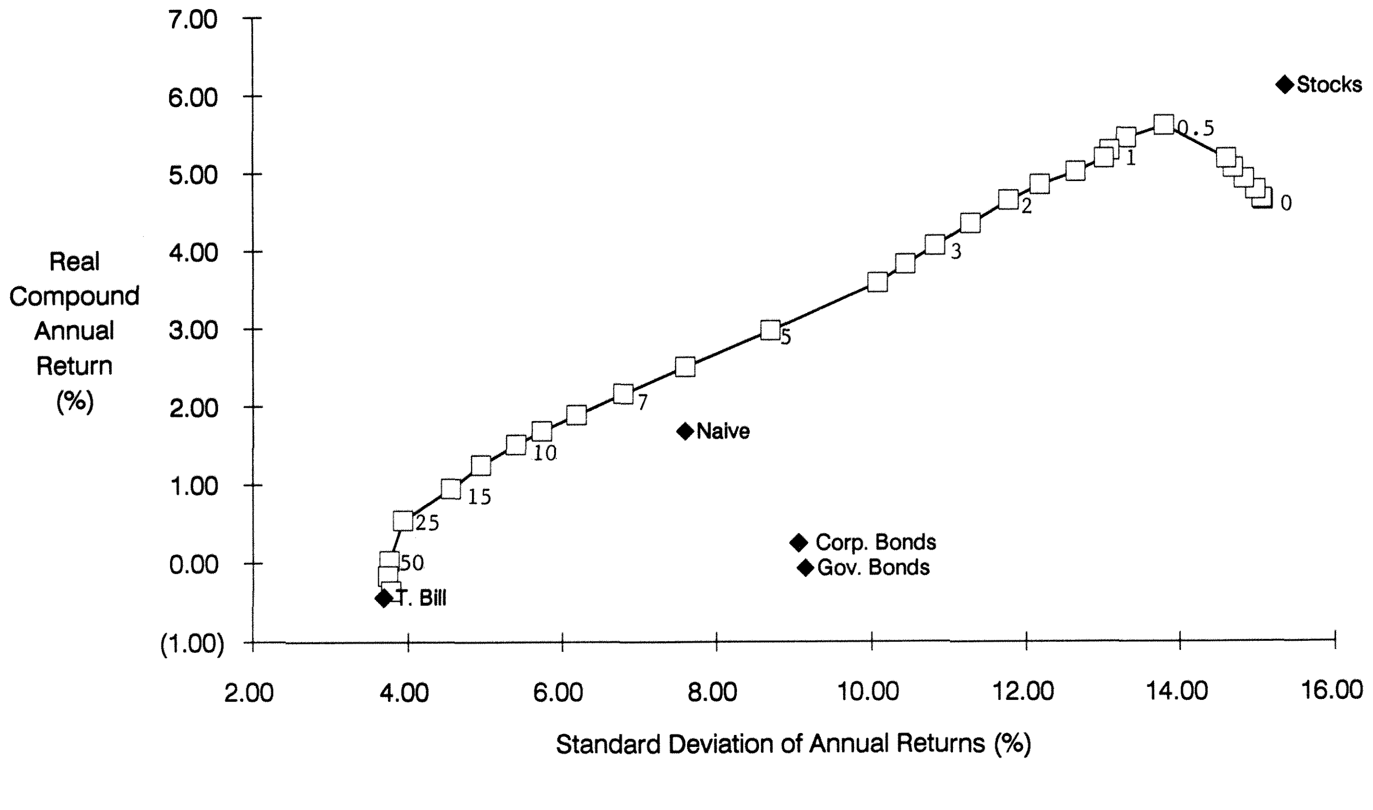
The long run portfolio rate of return for each λ is computed as the compound rate of return for that portfolio strategy which is:

$$g_\lambda = \left[\prod_{t=1}^{50} (1 + r_{\lambda t}) \right]^{1/50} - 1 \qquad \lambda = 1, 2, \ldots, 29 \qquad (9)$$

The compound rate of return from holding each asset individually was also computed for comparison purposes. In addition, the standard deviation of the annual returns was calculated for each portfolio (with parameter λ) and the individual assets.

The above procedure was first applied to the financial market assets. These results, plotted on Figure 1, demonstrate a long term risk-return benchmark available from financial investments. The numeric labels on some of the points of the portfolio results correspond to the λ value of the portfolio strategy that yielded this point. The results also show that if the individual assets were purchased on a buy and hold strategy, an investor would earn a lower rate of return for each level of risk except for holding common stock. Common stock returned somewhat more than that achieved using the portfolio strategy, but it also had a higher standard deviation. A naive portfolio strategy of simply placing 1/4 of one's wealth in each of the 4 financial assets in each period (the naive asset) provides risk reduction, but not to the degree using the portfolio optimization approach provides. Naive portfolio diversification did provide, however, a higher return and lower standard deviation than investing in either corporate or Government bonds. A higher rate of return with about the same risk, however, was achieved by the portfolio strategy with λ=6. The corporate and Government bonds, had about a zero return over this period with a standard deviation of 9% whereas the portfolio strategy with λ=5 had about the same risk, and a 3% rate of return. The λ=0.5 strategy provided the maximum long run portfolio return, although a higher return was achieved (with a higher standard deviation) from investing solely in common stocks. Portfolios with λ<0.5 achieved a lower return and higher standard deviation than some of those with lower λ parameters.

Figure 1. Real compound annual rate of return v. standard deviation of annual returns for financial market investments held singly, or in portfolios (some lambda parameters shown).



Except for the modifications discussed earlier, results analogous to those in Figure 1 are presented in Grauer and Hakansson (1982). As expected, the results shown here are similar to the results of Grauer and Hakansson (1982). Of interest to the readers of these proceedings is what happens when timber assets are included in the portfolio choices. The above analysis was redone with adding the two timber investments to the model. Figure 2 shows these results, including the returns to individual investing in Douglas-fir (return = 7.8%, standard deviation = 39%) or southern pine (return = 6.6%, standard deviation = 31%). Figure 2 reveals a very different pattern than may be expected. The timber assets are shown to be very risky if held singly. More surprising, however, is that when timber assets are included in the portfolio optimization model, the process delimits a risk-return minimizing result only for $\lambda>2$ investors. For lower λ values, risk is increased, but return is not. A higher return and lower risk can be achieved by holding common stocks or the timber assets singly, rather than following the portfolio strategy. Perhaps more disappointing is that the portfolio results which exclude timber assets have about the same return-standard deviation tradeoff as the portfolios which include timber.

Naive diversification (holding 1/6 of ones wealth in each asset in each period) provides a higher return, 5.0%, than the 4.3% achieved with the timber and financial asset portfolio strategy with $\lambda=6$ even though they have about the same risk (standard deviation = 11%). This naive diversification also dominates a portion of the market only portfolio results (i.e either higher return for a given level of risk, or a lower risk for a given level of return, or both) suggesting that including timber assets in portfolios is a viable long run investment strategy. A simple naive diversification in timber (1/2 in each timber species in each period) provides a return of 8.5% with a standard deviation of 31% which is a higher return with somewhat lower risk than either species earned individually, demonstrating that some diversification in timber is desirable.

Figures 3a and b show the timber portfolio proportions chosen over time by the optimization strategy for $\lambda=1$ (return = 6.1%, standard deviation = 20.5%), and $\lambda=50$ (return = 1.1%, standard deviation = 4.3%). From Figure 3a, which shows portfolio weights from a relatively risk tolerant strategy ($\lambda=1$), one can see that for the 1939-1957 period it was common to have about half of ones portfolio invested in timber, first with southern pine, and later with Douglas-fir. For the 1958-68 period no timber was held, then from 1969-82 timber dominated the portfolio. Figure 3b presents similar results for a quite risk averse investor ($\lambda=50$). A similar pattern for timber investing is observed, but the proportions held in timber never exceed 25% of the portfolio and more commonly were less than 10%. Timber holdings were higher in 1937, 1938, and 1959-61 *vis a vis* the $\lambda=1$ result suggesting that timber appeared to be a lower risk investment in these years. Timber investments thus were present for much of the period across risk class, though higher percentages were common in the portfolios of those willing to assume more risk.

Because timber assets offer a higher rate of return on average, and because the capital asset pricing model (CAPM) studies cited earlier have shown that timber returns are not correlated to the returns on common stocks, one would expect timber investments to be valuable additions to a portfolio. The CAPM model, and the previously reported portfolio models all used past realized returns to develop an expected risk-return relationship between timber and financial market investments. The portfolio optimization reported here uses the returns of the previous 10 years to choose a strategy

Figure 2. Real compound annual rate of return v. standard deviation of annual returns for financial and timber investments.

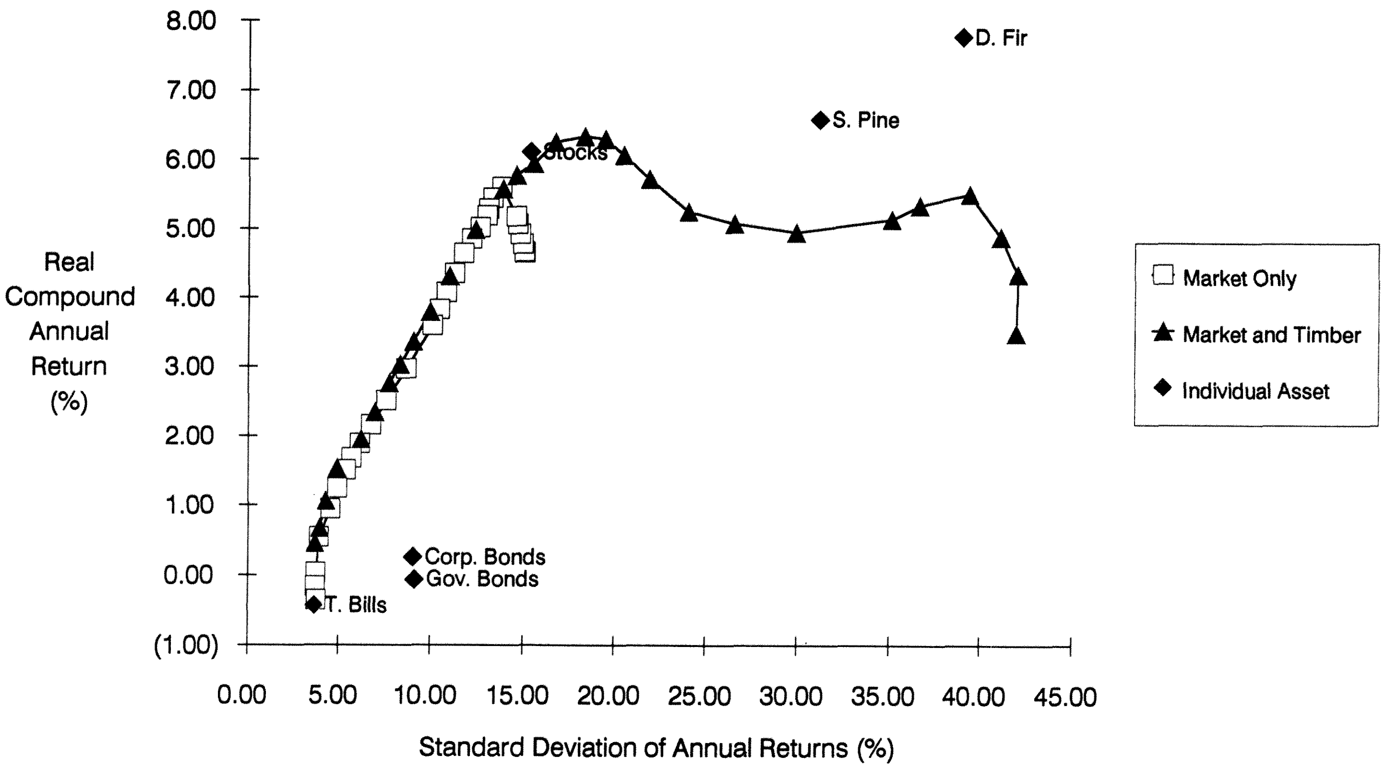


Figure 3a. Portfolio proportions of southern pine and Douglas-fir by year for lambda=1.

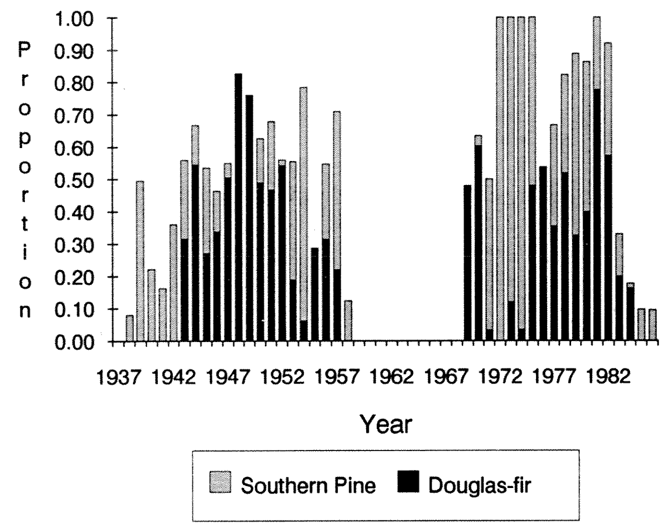
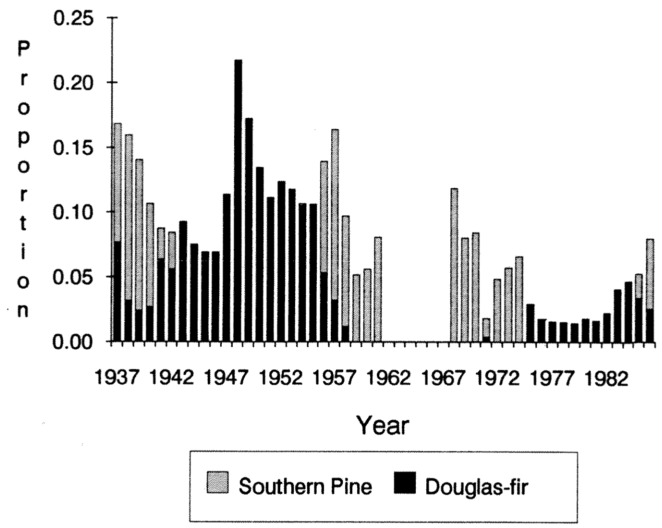


Figure 3b. Portfolio proportions of southern pine and Douglas-fir by year for lambda=50.



which is expected to maximize the returns in the next period, under the assumption that the next period will be like the previous periods. The historically realized return, however, is used to compute the results, rather than the expected return. When timber investments have shown a high rate of return over the past 10 periods, the model may choose high amounts of timber for the next period. Because the return on timber investments swings widely, it appears that the returns earned when timber was included were more often lower than expected resulting in the poor results. Nevertheless one would expect that timber investments can still be valuable additions to portfolios, if the amount of timber one chooses to hold in any period is restricted. The CAPM analyses have the implicit assumption that the timber component is a small part of the portfolio (i.e. that the "market index" is not affected by changing the proportion of one asset in that index).

In light of the large proportions chosen in the timber asset category, the portfolio strategy was recomputed with limits placed on the amount of each timber species that could be held in any period. Limits of 5%, 10%, 15%, 20%, 25%, and 30% for each species were investigated. A 10% limit on each species would allow up to 20% of the portfolio to be timber assets if the model so chose. Figure 4 presents the results for limits of 0% (no timber case), 5%, 10%, and 20%. Results for proportions higher than 20% are dominated by the lower proportions; thus, are not presented. Figure 4 shows that adding timber investments to ones opportunity set does allow a higher return for any level of risk as long as the timber asset proportions are strictly limited. In general, the most desirable risk-return frontier occurs when each timber species is limited to a maximum of 5-10% in each period though for more risk tolerant individuals, a higher return (with higher risk) is possible allowing up to a 20% limit. The outer envelope of points, consisting of results from varying levels of timber restrictions, can be interpreted as the risk-efficient set of investment opportunities. As risk tolerance increases (as measured by a decreasing λ) the optimal portfolio weight limit for timber species increase.

The highest portfolio return (7.7%, with standard deviation = 14.8%) is earned with a 20% limit in each timber species in any year and $\lambda=1$. Higher returns could have been earned by holding timber assets singly, but this would be done with a much higher risk. A low risk portfolio is achieved with the $\lambda=50$ strategy and a 5% limit on each timber species in any year. This strategy provided both a higher return (0.6% vs. -0.4%) and a lower standard deviation (3.6% v. 3.7%) than that of Treasury bills held singly.

Figures 5a and b show the timber portfolio proportions which generated the above results. Figure 5a shows timber weights for the portfolio with the maximum return. The results are somewhat similar to Figure 3a though one can see the timber investment restrictions are binding in many periods. In the early years southern pine enters the portfolio. In the 1943-54 period the maximum amounts of southern pine and Douglas-fir are included. In the unconstrained case, Douglas-fir tended to dominate during this period, but in the constrained scenario, southern pine is an equal portfolio component. In the 1959-68 period, no timber investment is chosen, then in the 1970-82 period, timber is once again often at its maximum level. Figure 5b shows the timber portfolio proportions for the very risk averse $\lambda=50$ parameter, with timber limited to not more than 5% in each species. The pattern is very similar to that of Figure 3b, except the amount of timber is constrained in some periods. There is some substitution between species with more Douglas-fir in the early years and more southern pine in the fifties. These figures show results similar to Figure 3 in that timber is a favored investment except during the 1962-67 period. The amount of timber that may be held in the portfolio, however, is limited.

SUMMARY

This paper has shown the long run wealth building capability of growing Douglas-fir and southern pine in fully regulated forests, along with the standard financial investments of common stocks, corporate bonds, U.S. Government bonds and U.S. Treasury bills. The maximum return earned over the 1937-86 period was from holding Douglas-fir (7.8%) but the standard deviation was also high (39%). A low portfolio risk can be achieved through investing in timber species and financial assets as long as the timber assets held in each period are strictly limited. The lowest risk portfolio was constructed with each timber species limited to a maximum of 5% of one's investment portfolio, and $\lambda=999$. Its return of 0.2% is

Figure 4. Real compound annual rate of return v. standard deviation of annual returns for financial and timber investments with limits placed on timber investments.

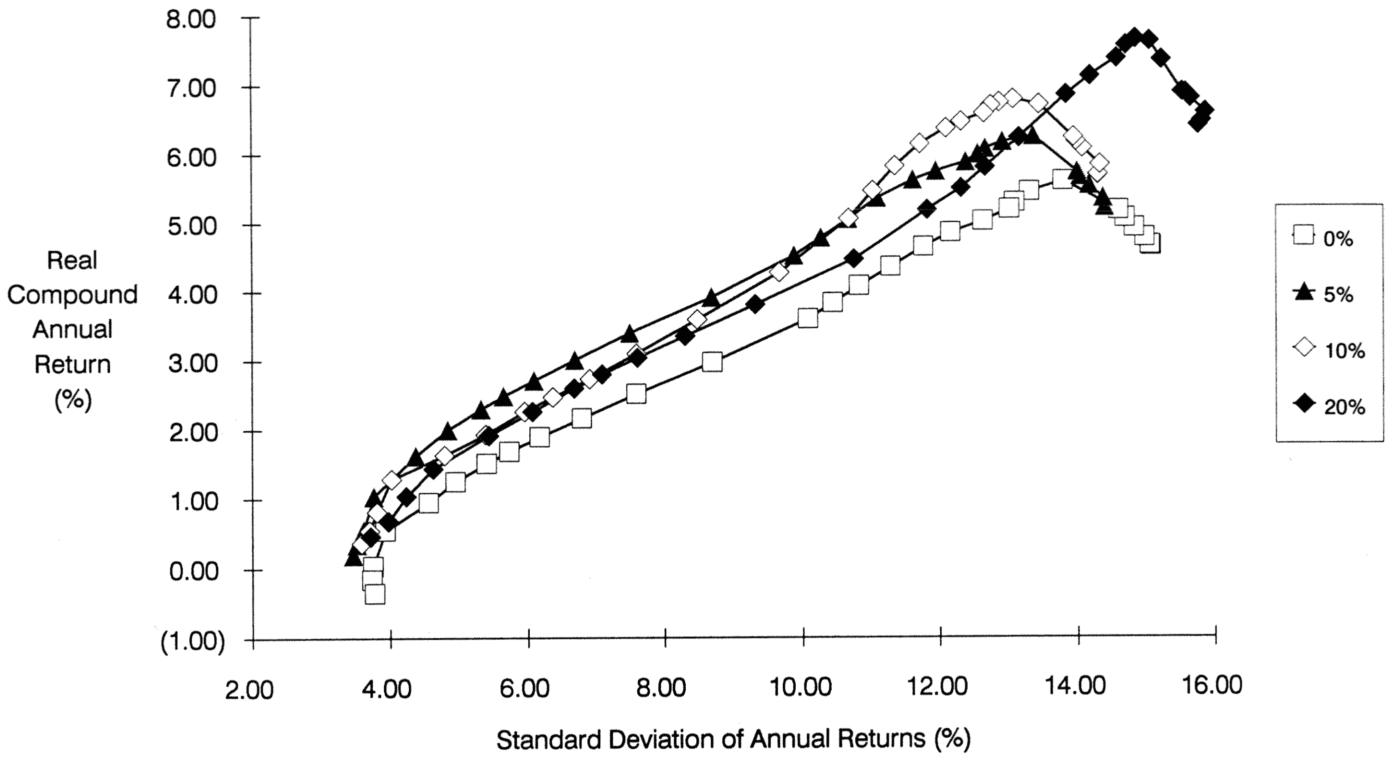


Figure 5a. Portfolio proportions of southern pine and Douglas-fir by year for lambda = 1 with portfolio limits of 20% for each timber species imposed each year.

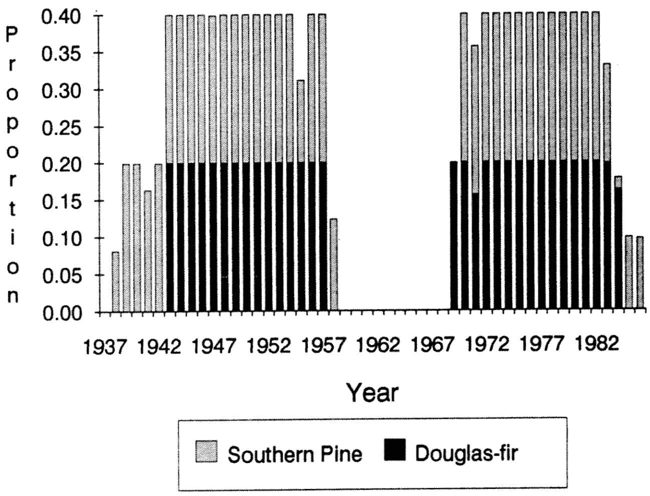
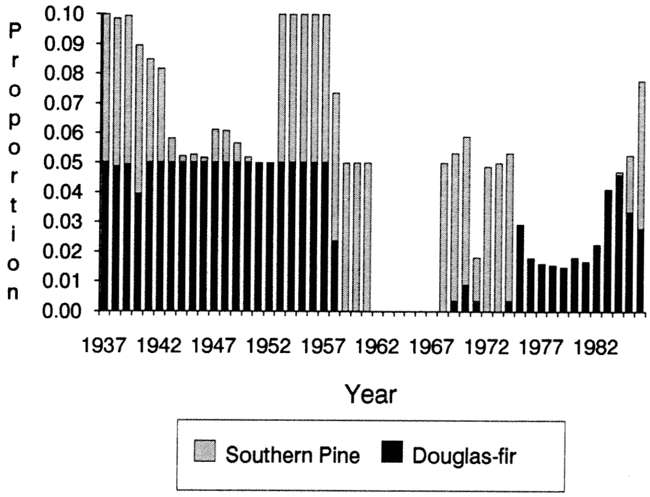


Figure 5b. Portfolio proportions of southern pine and Douglas-fir by year for lambda = 50 with portfolio limits of 5% for each timber species imposed each year.



substantially larger than the -0.4% earned by Treasury bills with a somewhat lower standard deviation (3.5% vs. 3.7%). A portfolio with timber limited to 20% in each species and $\lambda=1$ had the highest return, 7.7% with a standard deviation of 14.8%. This is a higher return, with a lower standard deviation, than was achieved through a buy and hold strategy of common stocks (return = 6.1%, standard deviation = 15.4%) and is almost a high of a return as for holding Douglas-fir singly and has a much lower standard deviation.

In summary, this paper has shown that over a 50-year period, timber investments have been valuable either held singly, or as additions to investment portfolios. When held singly they exhibit a high standard deviation of returns. When held as a part of a portfolio strategy, they should be strictly restricted to constitute to between 5 and 20% of the portfolio, with the higher percentages being appropriate for more risk tolerant investors.

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COST FUNCTION APPROACH FOR ESTIMATING DERIVED DEMAND FOR COMPOSITE WOOD PRODUCTS[1]

Thomas C. Marcin[2]

Abstract.–A cost function approach was examined for using the concept of duality between production and input factor demands. A translog cost function was used to represent residential construction costs and derived conditional factor demand equations. Alternative models were derived from the translog cost function by imposing parameter restrictions.

Keywords: Production economics, economic duality, factor demand

INTRODUCTION

Composite wood products are the fastest growing segment of the forest products industry. The demand for these products is largely a derived demand that arises principally in the construction industry. This paper discusses potential problems in model construction and develops a modeling approach to estimate conditional factor demand based on the translog cost function. A cost function relates the total cost of production for a level of output to input factor prices and technical change. Generally, a translog cost function is paired with its factor-share equations to obtain accurate estimates of parameters. Thus, the factor shares are functions of the same variables and parameters as those of the cost function.

The principle of duality in the theory of production can be used to specify cost functions from which the demand for factor inputs can be derived under certain assumptions of cost minimization and perfect competition (McFadden 1978). The cost function approach has several advantages. First, the cost function can be specified from factor input prices for a given level of output. This leads to computational simplicity in computing factor demands. Second, the conditional factor demand equations can be obtained simply by partial differentiation of the corresponding indirect cost function. Third, the cost function provides a convenient way for specifying empirical functional forms for application to price data where the quantity of factor demands is not known (Fuss 1977a).

This paper first considers the translog cost function as developed by Christensen and others (1973) for representing construction costs and the derived conditional factor demand equations. Previous work by Rockel and Buongiorno (1982) is then reviewed, using the translog cost function to model construction costs. The availability of data for different levels of aggregation is discussed. Finally, alternative model specifications for empirical applications are examined.

COST FUNCTION

The general specification of any cost function begins with the general form

$$\tilde{C} = g(p_1, ..., p_n, Q)$$

where
$\tilde{C}$ is cost function,
p_i is ith input factor price, and
Q is producible output.

Then, using Shephard lemma (Shephard 1970) and the envelope theorem (Beattie and Taylor 1985), the resultant factor demand equation for the ith factor conditional on the output level Q is the conditional factor demand. The conditional factor demand is the partial derivative of p_i on the cost function

$$\partial\tilde{C}/\partial p = x_i(p_i, ..., p_n)$$

where $x_i$is ith input factor demand.

Translog Cost Function

The translog cost function has the advantage of flexibility of specification and can be applied to multiproduct, multifactor production. Unfortunately, it is impossible to provide an explicit solution to the underlying production function mathematically. The translog production function and the translog cost function do not generally correspond to the same technology, although they can

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[2] Economist, USDA Forest Service, Forest Products Laboratory, Madison, WI 53705-2398. The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

e regarded as close approximations for the same technology. Thus, the translog cost function is most useful in studies of factor demand and product supply. However, the translog production and cost functions provide a local second-order approximation to any price frontier, i.e., any arbitrary cost function (Christensen and others 1973). Additionally, for many production and cost functions used in econometric studies, the translog functions does provide a global approximation (Denny and Fuss 1977).

The production structure can be represented by translog cost function and a time trend to represent technology as follows:

$$\ln \tilde{C} = \alpha_0 + \alpha_Q \ln Q = \frac{1}{2}\alpha_{QQ}(\ln Q)^2 = \alpha_t + \frac{1}{2}\alpha_{tt}t^2 + \sum_i \beta_i \ln p + \frac{1}{2}\sum_i \sum_j \gamma_{ij} \ln p_i \ln p_j + \sum_i \delta_{iQ} \ln Q \ln p_i + \sum_i \epsilon_{it} \ln p_i t$$

The factor share equations for each input of the translog cost function are

$$S_i = \beta_i + \delta_{iQ} \ln Q + \gamma_{ij} \ln p_j$$

and

$$S_i = p_i X_i / \sum_j p_j X_j$$

where S is the factor share and X_i is the quantity demanded for the ith factor input.

Because the shares must add to 1, the restrictions on the parameters are

$$\sum_i \beta_i = 1$$

$$\sum_j \gamma_{ij} = 0$$

$$\sum_i \delta_{iQ} = 0$$

In addition, $\gamma_{ij} = \gamma_{ji}$ $(i \neq j)$ must be true; if it is not true, the cross partial derivatives will not be equal and symmetry conditions will be violated.

Thus, the factor shares are functions of the same variables and parameters as those of the cost function. Therefore, if the factor shares are observable, then the equations corresponding to the share equations can be pooled with the cost equation when estimating parameters. In practice, however, it is often difficult to observe the factor shares so that parameters are estimated based upon the cost function alone.

Alternative Models Derived From Translog Function

The translog function is an approximation to the general nonhomothetic cost function, which is assumed to be homogeneous in prices. Since the translog model is complicated, it is useful to look at other possible models that can be derived from it by imposing further restrictions on its parameters. For purposes of identification, the translog cost function is referred to as model I and the subsequent models are called model II, model III, etc. Model II, which is developed by imposing Hicks-neutral technology changes in the cost function over time, requires

$$\alpha_{tt} = 0, \qquad \sum_i \epsilon_{it} = 0$$

The cost function can be further restricted to be homothetic and homogeneous by requiring the cost function to a separable function of prices. This model, model III, requires

$$\sum_i \delta_{iQ} = 0, \qquad \alpha_{QQ} = 0$$

Further constraints may be added to make the second-order price terms equal to zero, which results in unitary elasticity of substitution between factor inputs. This is model IV, which implies that

$$\gamma_{ij} = 0 \qquad \text{for every } i, j$$

This, in fact, is the cost function corresponding to a generalized Cobb–Douglas production function. Finally, the cost function can be reduced to that of an ordinary Cobb–Douglas production function by adding constant returns to scale. This requires $\alpha_Q = 0$ and is model V.

Estimation of Cost Function

Data

The data available for estimating cost functions may be classified as either macro- or microdata. Macrodata or aggregate data are available from the U.S. Department of Commerce. Previous work by Rockel and Buongiorno (1982) used monthly observations from the Construction Review published by the U.S. Department of Commerce to estimate the demand for wood and other inputs in residential construction. These authors used the Boeckh index of building costs for residences as an index of the average cost of residence in the United States. This index is based upon a survey of local costs for materials and labor for 20 selected cities. These costs are then used to calculate the cost of building a typical wood-framed house and a typical brick house (Levy 1977). The index excludes the cost of land and financing, and it is weighted based upon actual labor and material costs observed from 1926 to 1929. The Boeckh index has at least two major drawbacks. First, the weights for the various shares of construction costs have surely been much different in recent years than they were in the period 1926–1929. Second, the index does not incorporate any adjustments for technical change, which reduce the cost per unit of output. The Boeckh index overstates increases in the cost per housing unit to the extent that technological progress has occurred in the industry.

In a sense, Rockel and Buongiorno estimated the weights of the Boeckh index. The output variable used in their model was the number of housing starts. A major problem with this measure of output is the heterogeneity of housing starts—the type, size, and quantity of housing starts vary. A better measure of the aggregate output of the construction sector is the value of new construction in constant dollars. Similarly, the current dollar value of new construction is a reasonably accurate measure of total construction costs.

The producer price index is used to provide measures for material input prices. These measures are reasonably good estimates for existing products. The price of labor used by Rockel and Buongiorno is the average weekly earnings of special trade construction workers. A better alternative is to use an hourly wage rate because it provides a constant unit of measure.

Additional data on factor shares are provided by input–output tables for the United States, in which factor shares can be calculated from the I/O tables. These tables provide a checkpoint for other data sources. Unfortunately, these tables are not available in a frequent or timely manner.

The use of monthly data entails statistical problems related to autocorrelation, seasonality, collinearity, and data aggregation. Autocorrelation can be tested by several procedures. The common test is the Durbin–Watson statistic. Values <1 or >2 indicate strong autocorrelation. Methods are also available for correcting autocorrelation (for example, see Maddala (1977), pp. 257–291). Monthly data can exhibit strong autocoorelation tendencies, which need to be tested and corrected. The use of dummy variables in the model can be used to test for seasonality. Construction material prices may exhibit strong seasonal patterns because the construction industry has strong seasonal patterns of activity. Problems of collinearity also exist for prices of many materials used in construction. Finally, there are problems with data aggregation. For example, there is no clear data set for composite wood products. Denny and May (1978) suggest the use of a two-stage estimation procedure: a microfunction of a particular set of disaggregated inputs is estimated in the first stage and aggregate inputs are used in the second stage. Fuss (1977b) applied such a procedure to his work on energy.

Other studies to estimate production technologies and factor demand equations have used annual data. For example, Christensen and others (1973) used annual data from the United States private domestic economy to fit parameters to the translog production and price possibility frontiers. Denny and May (1978) used price and quantity input from Statistics Canada to measure prices and quantities of inputs and output of the Canadian manufacturing sector to fit and test a translog cost function.

Monthly data were used in this study to examine the cost function approach. The output measure was residential construction expenditures in constant dollars. The current dollar value of residential construction was used as a measure of costs. Producer price indexes were used as a measure of input prices. Factor prices were used for lumber and plywood, and combined indexes were used for hardboard, particleboard, and fiberboard and for other construction materials. Hourly wage rates for construction workers were used for measures of labor input price. Monthly data were compiled for 1960 to 1990 (U. S. Department of Commerce 1960–1990).

Parameters

Parameters for the various restricted forms of the translog cost functions were estimated with generalized nonlinear least square estimation procedures using version 4.1C of TSP (TSP International 1987). Single equation methods were used to directly estimate the family of restricted cost function forms. Because monthly data were used, it was not possible to estimate factor input cost share. Therefore, the cost function was estimated by itself.

Results of the regression estimates of the parameters of the translog cost function and its various restricted forms are presented in Table 1. These preliminary results indicate that the use of monthly data for this type of analysis is complicated by several problems. Autocorrelation, seasonality, and collinearity of input variables lead to problems in obtaining expected signs and consistent parameter estimates.

The models presented in the Appendix provide a useful starting point for additional analysis of the cost function approach. The Durbin–Watson statistic indicates significant autocorrelation (Maddala 1977). The parameters for the proxy for composite products was positive and significant in the generalized Cobb–Douglas cost function and in all unitary elasticity models.

CONCLUSION

The cost function approach has several advantages. First, it provides a convenient way to obtain supply and demand equations, which is consistent with traditional (primal) economic theory. Second, the dual approach is useful in generating a functional specification for supply and demand equations for econometric estimation. Finally, the cost function approach provides a sound theoretic approach for using price and cost data to estimate a consistent set of factor demand equations.

Preliminary results using the duality approach were not completely satisfactory using monthly data. The variable for composite products, which included particleboard, fiberboard and hardboard, was significant and positive for all five models examined. This seems to indicate a significant variation in price trends for this variable. A promising direction for future research is to develop a more refined data base using microdata or regional data and to specify a simultaneous-equations model that would include factor share equations related to alternative costs of factor inputs and end–use markets.

Future directions for use of the duality theory for estimating factor demand can be divided into two categories: (1) improvements in the data base for use in model estimation and (2) refinements in the application of theory for model specification. Problems associated with the use of monthly data could be avoided by developing an alternative data set based upon microdata from the construction industry or other end–use industries. Regional data might also be useful because much contemporary demand analysis focuses on panel data sets from individual firms or industrial surveys. An example of this type of work is the work of Caves and others (1981) for the transportation sector. In addition, it may de difficult to separate the effects of changes in construction activity from trends in factor prices in a monthly model because prices tend to move with trends in activity. Thus, explanatory variables are probably not truly exogenous when national data are used. Therefore, simultaneous estimation methods may be worthwhile. It would be useful to add a variable for construction financial costs and to examine the possible effects of changes in real estate value on construction expenditure data. Theoretical considerations in model specifications include using a profit function approach because the output is not a fixed quantity as specified in

...e cost function. The use of factor share equations in a simultaneous-equations model might eliminate some anomalies present in monthly data analysis. For example, it may be more useful to use annual data or cross-sectional data with factor share estimates even with as few as 30 observations.

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Table 1.—Average cost functions of residential construction expenditures in the United States, January 1960 to December 1989

Coefficient[a]	Model I	Model II	Model III	Model IV	Model V
α_0	35.1680	67.7820	12.3960	-3.2565	5.8137
α_Q	-0.1603×10^{-1}	-4.9788	0.9964	0.9404	-
α_{QQ}	-0.4613	0.5166×10^{-1}	-	-	-
α_T	-0.1435×10^{-1}	-0.4364×10^{-3}	-0.3276×10^{-3}	-0.1756×10^{-3}	0.1511×10^{-2}
α_{TT}	0.1700×10^{-4}	-	-	-	-
β_1	-11.9720	-33.5770	-12.2160	0.8461	0.9172×10^{-1}
β_2	-7.0928	-1.7484	-6.6678	-0.2808	0.6725×10^{-1}
β_3	1.2154	2.9357	0.6256	-0.1273	-0.1541
β_4	-1.6815	5.9459	10.0660	0.3146	0.4683
β_5	20.5310	27.4444	9.1930	0.2474	0.5268
γ_{11}	1.0156	7.2212	5.4500	-	-
γ_{22}	-1.5147	-0.6273	-0.4935×10^{-1}	-	-
γ_{33}	1.7419	0.9602	1.9361	-	-
γ_{44}	-2.5229	-2.1427	-0.8693	-	-
γ_{55}	1.2369	3.3229	2.4301	-	-
γ_{12}	2.4055	1.6883	2.8610	-	-
γ_{13}	-1.0129	-1.2163	-1.7101	-	-
γ_{14}	0.1818	-1.4439	-2.9022	-	-
γ_{15}	-2.5900	-6.2493	-3.6986	-	-
γ_{23}	0.6742×10^{-1}	-0.2753	-0.9065	-	-
γ_{24}	-0.7214	-0.7692	0.8023×10^{-1}	-	-
γ_{25}	-0.2368	-0.1649×10^{-1}	-1.9854	-	-
γ_{34}	0.3381	0.9722	0.5590	-	-
γ_{35}	-1.1345	-0.4408	0.1215	-	-
γ_{45}	2.7244	3.3837	3.1324	-	-
δ_1	0.3747	1.5264	-	-	-
δ_2	0.7067	0.1495	-	-	-
δ_3	-0.5993	-0.4608	-	-	-
δ_4	1.1769	0.5255	-	-	-
δ_5	-1.6589	-	-	-	-
ϵ_1	0.3999×10^{-2}	-	-	-	-
ϵ_2	-0.4917×10^{-3}	-	-	-	-
ϵ_3	0.2719×10^{-2}	-	-	-	-
ϵ_4	-0.3173×10^{-2}	-	-	-	-
ϵ_5	-0.3054×10^{-2}	-	-	-	-
r^2	0.9963	0.9952	0.9944	0.9916	0.9471
Durbin–Watson statistic	0.6752	0.6224	0.6265	0.3631	0.2711

[a] Q is residential construction expenditures in constant dollars.
1 is other construction materials; 2 is softwood lumber;
3 is plywood; 4 is particleboard, fiberboard, and hardboard; and
5 is wages.

APPENDIX—TSP PROGRAM

```
          PROGRAM

LINE  ****************************************************************

        1  FREQ M $
        2  IN FPLPROD $
        3  ? YEAR 1955 MONTH 1 = 1 $
        3  SMPL 1960:01 1989:12 $
        4  AVCOST = AVCOST/100 $
        5  LNACN = LOG(ACN) $
        6  LNDF = LOG(DF) $
        7  LNPL = LOG(PL) $
        8  LNHW = LOG(HW) $
        9  LNW = LOG(WAGES)$
       10  LQ = LOG(VNCON)$
       11  LAC = LOG(VNCUR)$
       12  TREND T$
       13  OPTION SIGNIF=2 $
       14  ? PRINT ACN WAGES PL HW DF AVCOST HUNITS VNCUR VNCON T $
       14  FRML EQ1 LAC = A0 + AQ*LQ + .5*AQQ*(LQ*LQ) + AT*T + .5*ATT*(T*T) +
       14  B1*LNACN + B2*LNDF + B3*LNPL + B4*LNHW + (1-B1-B2-B3-B4)*LNW + .5*
       14  {C11*LNACN*LNACN + C22*LNDF*LNDF + C33*LNPL*LNPL + C44*LNHW*LNHW +
       14  (C11+C22+C33+C44+2*C12+2*C13+2*C14+2*C23+2*C24+2*C34)*LNW*LNW } +
       14  C12*LNACN*LNDF + C13*LNACN*LNPL + C14*LNACN*LNHW +
(-C11-C12-C13-C14)*LNACN*
       14  LNW + C23*LNDF*LNPL + C24*LNDF*LNHW + (-C12-C22-C23-C24)*LNDF*LNW +
       14  C34*LNPL*LNHW + (-C13-C23-C33-C34)*LNPL*LNW +
(-C14-C24-C34-C44)*LNHW*LNW
       14  + D1*LNACN*LQ + D2*LNDF*LQ + D3*LNPL*LQ + D4*LNHW*LQ +
(-D1-D2-D3-D4)*LNW*LQ
       14  + E1*LNACN*T  + E2*LNDF*T  + E3*LNPL*T    + E4*LNHW*T  +
(-E1-E2-E3-E4)*LNW*T
       14  $
       15  PARAM A0 1 AQ 1 AQQ 1 AT 1 ATT 1 B1 1 B2 1 B3 1 B4 1 C11 1 C12 1
       15  C13 1 C14 1 C22 1 C23 1 C24 1 C33 1 C34 1 C44 1 D1 1 D2 1 D3 1 D4 1
E1 1
       15  E2 1 E3 1 E4 1 $
       16  LSQ EQ1 $
       17  COPY @FIT,CFIT $
       18  FRML EQ2 B5 = 1 - B1 - B2 - B3 - B4 $
       19  FRML EQ3 C15 = -C11 - C12 - C13 - C14 $
       20  FRML EQ4 C25 = -C12 - C22 - C23 - C24 $
       21  FRML EQ5 C35 = -C13 - C23 - C33 - C34 $
       22  FRML EQ6 C45 = -C14 - C24 - C34 - C44 $
       23  FRML EQ7 C55 = C11 + C22 + C33 + C44 + 2*(C12 + C13 + C14 + C23 +
C24 + C34)
       23  $
       24  FRML EQ8 D5 = -D1 - D2 - D3 - D4 $
       25  FRML EQ9 E5 = -E1 - E2 - E3 - E4 $
       26  ANALYZ EQ7 EQ8 EQ2 EQ3 EQ4 EQ5 EQ6 EQ9 $
       27  FSH1 = B1 + C11*LNACN + C12*LNDF + C13*LNPL + C14*LNHW + C15*LNW +
D1*LQ + E1*T
       27  $
       28  FSH2 = B2 + C12*LNACN + C22*LNDF + C23*LNPL + C24*LNHW + C25*LNW +
D2*LQ + E2*T
       28  $
       29  FSH3 = B3 + C13*LNACN + C23*LNDF + C33*LNPL + C34*LNHW + C35*LNW +
D3*LQ + E3*T
       29  $
       30  FSH4 = B4 + C14*LNACN + C24*LNDF + C34*LNPL + C44*LNHW + C45*LNW +
D4*LQ + E4*T
       30  $
       31  FSH5 = B5 + C15*LNACN + C25*LNDF + C35*LNPL + C45*LNHW + C55*LNW +
D5*LQ + E5*T
       31  $
       32  N11 = C11/FSH1 + FSH1 - 1 $
       33  N12 = C12/FSH1 + FSH2 $
       34  N13 = C13/FSH1 + FSH3 $
```

```
|     35  N14 = C14/FSH1 + FSH4 $
|     36  N15 = C15/FSH1 + FSH5 $
|     37  N21 = C12/FSH2 + FSH1 $
|     38  N22 = C22/FSH2 + FSH2 - 1 $
|     39  N23 = C23/FSH2 + FSH3 $
|     40  N24 = C24/FSH2 + FSH4 $
|     41  N25 = C25/FSH2 + FSH5 $
|     42  N31 = C13/FSH3 + FSH1 $
|     43  N32 = C23/FSH3 + FSH2 $
|     44  N33 = C33/FSH3 + FSH3 - 1 $
|     45  N34 = C34/FSH3 + FSH4 $
|     46  N35 = C35/FSH3 + FSH5 $
|     47  N41 = C14/FSH4 + FSH1 $
|     48  N42 = C24/FSH4 + FSH2 $
|     49  N43 = C34/FSH4 + FSH3 $
|     50  N44 = C44/FSH4 + FSH4 - 1 $
|     51  N45 = C45/FSH4 + FSH5 $
|     52  N51 = C15/FSH5 + FSH1 $
|     53  N52 = C25/FSH5 + FSH2 $
|     54  N53 = C35/FSH5 + FSH3 $
|     55  N54 = C45/FSH5 + FSH4 $
|     56  N55 = C55/FSH5 + FSH5 - 1 $
|     57  LIST L1 N11 N12 N13 N14 N15 N21 N22 N23 N24 N25 N31 N32 N33 N34 N35
N41 N42
|     57  N43 N44 N45 N51 N52 N53 N54 N55 $
|     58  ? PRINT L1 $
|     58  CFIT = EXP(CFIT) $
|     59  FITX1 = CFIT*FSH1/ACN $
|     60  FITX2 = CFIT*FSH2/DF $
|     61  FITX3 = CFIT*FSH3/PL $
|     62  FITX4 = CFIT*FSH4/HW $
|     63  FITX5 = CFIT*FSH5/WAGES $
|     64  M11 = (CFIT/(ACN*ACN))*((FSH1*FSH1)-FSH1+C11)$
|     65  M12 = (CFIT/(ACN*DF))*(FSH1*FSH2 + C12)$
|     66  M13 = (CFIT/(ACN*PL))*(FSH1*FSH3 + C13)$
|     67  M14 = (CFIT/(ACN*HW))*(FSH1*FSH4 + C14)$
|     68  M15 = (CFIT/(ACN*WAGES))*(FSH1*FSH5 + C15)$
|     69  M22 = (CFIT/(DF*DF))*(FSH2*FSH2 - FSH2 + C22)$
|     70  M23 = (CFIT/(DF*PL))*(FSH2*FSH3 + C23)$
|     71  M24 = (CFIT/(DF*HW))*(FSH2*FSH4 + C24)$
|     72  M25 = (CFIT/(DF*WAGES))*(FSH2*FSH5 + C25)$
|     73  M33 = (CFIT/(PL*PL))*(FSH3*FSH3 - FSH3 + C33) $
|     74  M34 = (CFIT/(PL*HW))*(FSH3*FSH4 + C34) $
|     75  M35 = (CFIT/(PL*WAGES))*(FSH3*FSH5 + C35) $
|     76  M44 = (CFIT/(HW*HW))*(FSH4*FSH4 - FSH4 + C44) $
|     77  M45 = (CFIT/(HW*WAGES))*(FSH4*FSH5 + C45 ) $
|     78  M55 = (CFIT/(WAGES*WAGES))*(FSH5*FSH5 + C55 - FSH5) $
|     79  LIST L2 M11 M12 M13 M14 M15  M22 M23 M24 M25 M33 M34
|     79  M35 M44 M45 M55 $
|     80  ? PRINT L2 $
|     80  PMDET M11 M12 M13 M14 M15
|     80        M12 M22 M23 M24 M25
|     80        M13 M23 M33 M34 M35
|     80        M14 M24 M34 M44 M45
|     80        M15 M25 M35 M45 M55 $
|     81  ?
|     81  ?
|     81  ?  ADD RESTRICTION TO GET HICKS-NEUTRAL CHANGE
|     81  ?
|     81  FRML EQ11 LAC = A0 + AQ*LQ + .5*AQQ*(LQ*LQ) + AT*T +
|     81  B1*LNACN + B2*LNDF + B3*LNPL + B4*LNHW + (1-B1-B2-B3-B4)*LNW + .5*
|     81  {C11*LNACN*LNACN + C22*LNDF*LNDF + C33*LNPL*LNPL + C44*LNHW*LNHW +
|     81  (C11+C22+C33+C44+2*C12+2*C13+2*C14+2*C23+2*C24+2*C34)*LNW*LNW } +
|     81  C12*LNACN*LNDF + C13*LNACN*LNPL + C14*LNACN*LNHW +
(-C11-C12-C13-C14)*LNACN*
|     81  LNW + C23*LNDF*LNPL + C24*LNDF*LNHW + (-C12-C22-C23-C24)*LNDF*LNW +
|     81  C34*LNPL*LNHW + (-C13-C23-C33-C34)*LNPL*LNW +
(-C14-C24-C34-C44)*LNHW*LNW
|     81  + D1*LNACN*LQ + D2*LNDF*LQ + D3*LNPL*LQ + D4*LNHW*LQ +
(-D1-D2-D3-D4)*LNW*LQ
```

```
|     81  $
|     82
|     82  PARAM A0 1 AQ 1 AQQ 1 AT 1 B1 1 B2 1 B3 1 B4 1 C11 1 C12 1
|     82  C13 1 C14 1 C22 1 C23 1 C24 1 C33 1 C34 1 C44 1 D1 1 D2 1 D3 1 D4 1
|     82  $
|     83
|     83  LSQ EQ11 $
|     84  COPY @FIT,CFIT $
|     85  FRML EQ2 B5 = 1 - B1 - B2 - B3 - B4 $
|     86  FRML EQ3 C15 = -C11 - C12 - C13 - C14 $
|     87  FRML EQ4 C25 = -C12 - C22 - C23 - C24 $
|     88  FRML EQ5 C35 = -C13 - C23 - C33 - C34 $
|     89  FRML EQ6 C45 = -C14 - C24 - C34 - C44 $
|     90  FRML EQ7 C55 = C11 + C22 + C33 + C44 + 2*(C12 + C13 + C14 + C23 +
C24 + C34)
|     90  $
|     91  FRML EQ8 D5 = -D1 - D2 - D3 - D4 $
|     92  ANALYZ EQ7 EQ8 EQ2 EQ3 EQ4 EQ5 EQ6 $
|     93  ?
|     93  ? ADD RESTRICTIONS TO GET HOMETHETIC PRODUCTION TECHNOLOGY
|     93  ?
|     93  FRML EQ21 LAC = A0 + AQ*LQ + AT*T +
|     93  B1*LNACN + B2*LNDF + B3*LNPL + B4*LNHW + (1-B1-B2-B3-B4)*LNW + .5*
|     93  {C11*LNACN*LNACN + C22*LNDF*LNDF + C33*LNPL*LNPL + C44*LNHW*LNHW +
|     93  (C11+C22+C33+C44+2*C12+2*C13+2*C14+2*C23+2*C24+2*C34)*LNW*LNW } +
|     93  C12*LNACN*LNDF + C13*LNACN*LNPL + C14*LNACN*LNHW +
(-C11-C12-C13-C14)*LNACN*
|     93  LNW + C23*LNDF*LNPL + C24*LNDF*LNHW + (-C12-C22-C23-C24)*LNDF*LNW +
|     93  C34*LNPL*LNHW + (-C13-C23-C33-C34)*LNPL*LNW +
(-C14-C24-C34-C44)*LNHW*LNW  $
|     94
|     94
|     94  PARAM A0 1 AQ 1  AT 1  B1 1 B2 1 B3 1 B4 1 C11 1 C12 1
|     94  C13 1 C14 1 C22 1 C23 1 C24 1 C33 1 C34 1 C44 1
|     94  $
|     95
|     95  LSQ EQ21 $
|     96  COPY @FIT,CFIT $
|     97  FRML EQ2 B5 = 1 - B1 - B2 - B3 - B4 $
|     98  FRML EQ3 C15 = - C11 - C12 - C13 - C14 $
|     99  FRML EQ4 C25 = - C12 - C22 - C23 - C24 $
|    100  FRML EQ5 C35 = - C13 - C23 - C33 - C34 $
|    101  FRML EQ6 C45 = - C14 - C24 - C34 - C44 $
|    102  FRML EQ7 C55 = C11 + C22 + C33 + C44 +2*(C12 + C13 + C14 + C23 +
C24 + C34) $
|    103  ANALYZ EQ2 EQ3 EQ4 EQ5 EQ6 EQ7 $
|    104  ?
|    104  ?  ADD UNITARY ELASTICITY OF SUBSTITUTION RESTRICTION
|    104  ?
|    104
|    104  FRML EQ31 LAC = A0 + AQ*LQ + AT*T +
|    104  B1*LNACN + B2*LNDF + B3*LNPL + B4*LNHW + (1-B1-B2-B3-B4)*LNW $
|    105  PARAM A0 1 AQ 1  AT 1  B1 1 B2 1 B3 1 B4 1 $
|    106
|    106  LSQ EQ31 $
|    107  COPY @FIT, CFIT $
|    108  FRML EQ B5 = 1 - B1 - B2 - B3 -B4 $
|    109  ANALYZ EQ2 $
|    110  FRML EQ41 LAC = A0 + AT*T +
|    110  B1*LNACN + B2*LNDF + B3*LNPL + B4*LNHW + (1-B1-B2-B3-B4)*LNW $
|    111  PARAM A0 1 AQ 1   B1 1 B2 1 B3 1 B4 1 $
|    112
|    112  LSQ EQ41 $
|    113  COPY @FIT, CFIT $
|    114  FRML EQ B5 = 1 - B1 - B2 - B3 - B4 $
|    115  ANALYZ EQ2 $
|    116  END $
```

```
         EXECUTION

*******************************************************************************


CURRENT SAMPLE :  1960:1 TO 1989:12

                              NONLINEAR LEAST SQUARES
                              ***********************


EQUATIONS: EQ1

NOTE => The model is linear in the parameters.
Working space used: 30819
                                  STARTING VALUES

                    A0          AQ          AQQ         AT          ATT
             ------------------------------------------------------------
 VALUE    |        1.00        1.00        1.00        1.00        1.00


                    B1          B2          B3          B4          C11
             ------------------------------------------------------------
 VALUE    |        1.00        1.00        1.00        1.00        1.00


                    C22         C33         C44         C12         C13
             ------------------------------------------------------------
 VALUE    |        1.00        1.00        1.00        1.00        1.00


                    C14         C23         C24         C34         D1
             ------------------------------------------------------------
 VALUE    |        1.00        1.00        1.00        1.00        1.00


                    D2          D3          D4          E1          E2
             ------------------------------------------------------------
 VALUE    |        1.00        1.00        1.00        1.00        1.00


                    E3          E4
             --------------------------
 VALUE    |        1.00        1.00

F=    13.317     FNEW= -0.25550     ISQZ=  0 STEP=  1.0000     CRIT=  333.00

CONVERGENCE ACHIEVED AFTER    1 ITERATIONS


    2 FUNCTION EVALUATIONS.

                LOG OF LIKELIHOOD FUNCTION =     640.660
                    NUMBER OF OBSERVATIONS =    360
```

PARAMETER	ESTIMATE	STANDARD ERROR	T-STATISTIC
A0	35.168	10.897	3.2273
AQ	-0.16032E-01	1.6724	-0.95866E-02
AQQ	-0.46130	0.15691	-2.9398
AT	-0.14355E-01	0.49230E-02	-2.9160
ATT	0.17002E-04	0.32637E-05	5.2095
B1	-11.972	5.1898	-2.3068
B2	-7.0928	2.0305	-3.4932
B3	1.2154	3.5205	0.34524
B4	-1.6815	2.7550	-0.61033
C11	1.0156	2.2263	0.45617
C22	-1.5147	0.42056	-3.6016
C33	1.7419	0.98633	1.7661
C44	-2.5229	0.80919	-3.1178
C12	2.4055	0.69304	3.4710
C13	-1.0129	1.1284	-0.89765
C14	0.18181	1.0175	0.17869
C23	0.67423E-01	0.50934	0.13237
C24	-0.72143	0.49145	-1.4680
C34	0.33812	0.74743	0.45238
D1	0.37469	0.33703	1.1117
D2	0.70667	0.16442	4.2979
D3	-0.59934	0.20149	-2.9745
D4	1.1769	0.26662	4.4139
E1	0.39999E-02	0.22416E-02	1.7844
E2	-0.49173E-03	0.86028E-03	-0.57159
E3	0.27192E-02	0.15896E-02	1.7106
E4	-0.31734E-02	0.17146E-02	-1.8508

STANDARD ERRORS COMPUTED FROM QUADRATIC FORM OF ANALYTIC FIRST DERIVATIVES (GAUSS)

```
                    EQUATION    EQ1
                    ***************

DEPENDENT VARIABLE: LAC

           SUM OF SQUARED RESIDUALS =    0.599897
      STANDARD ERROR OF THE REGRESSION =    0.424440E-01
         MEAN OF DEPENDENT VARIABLE =    9.40706
                 STANDARD DEVIATION =    0.671206
                          R-SQUARED =    0.996293
                 ADJUSTED R-SQUARED =    0.996004
            DURBIN-WATSON STATISTIC =      0.6752


               RESULTS OF PARAMETER ANALYSIS
               *****************************

INPUT PARAMETERS WERE: A0 AQ AQQ AT ATT B1 B2 B3 B4 C11 C22
    C33 C44 C12 C13 C14 C23 C24 C34 D1 D2 D3 D4 E1 E2 E3 E4

    FRML EQ7 C55 = (((C11+ C22)+ C33)+ C44)+ 2* (((((C12+ C13)+ C14)+ C23)+
C24)+ C34)

    FRML EQ8 D5 = ((- D1- D2)- D3)- D4

    FRML EQ2 B5 = (((1- B1)- B2)- B3)- B4

    FRML EQ3 C15 = ((- C11- C12)- C13)- C14

    FRML EQ4 C25 = ((- C12- C22)- C23)- C24

    FRML EQ5 C35 = ((- C13- C23)- C33)- C34

    FRML EQ6 C45 = ((- C14- C24)- C34)- C44

    FRML EQ9 E5 = ((- E1- E2)- E3)- E4
```

PARAMETER	ESTIMATE	STANDARD ERROR	T-STATISTIC
C55	1.2369	0.80792	1.5310
D5	-1.6589	0.23856	-6.9536
B5	20.531	3.5185	5.8350
C15	-2.5900	1.1689	-2.2157
C25	-0.23683	0.46862	-0.50538
C35	-1.1345	0.82678	-1.3722
C45	2.7244	0.66442	4.1004
E5	-0.30540E-02	0.15512E-02	-1.9688

WALD TEST FOR THE HYPOTHESIS THAT THE GIVEN SET OF PARAMETERS ARE JOINTLY ZERO:

CHI-SQUARED = 371.50925 WITH 8 DEGREES OF FREEDOM.
P-VALUE = 0.00000000

NONLINEAR LEAST SQUARES
****

EQUATIONS: EQ11

NOTE => The model is linear in the parameters.
Working space used: 25937

STARTING VALUES

	A0	AQ	AQQ	AT	B1
VALUE	1.00	1.00	1.00	1.00	1.00

	B2	B3	B4	C11	C22
VALUE	1.00	1.00	1.00	1.00	1.00

	C33	C44	C12	C13	C14
VALUE	1.00	1.00	1.00	1.00	1.00

	C23	C24	C34	D1	D2
VALUE	1.00	1.00	1.00	1.00	1.00

	D3	D4
VALUE	1.00	1.00

F= 9.0363 FNEW= -0.12899 ISQZ= 0 STEP= 1.0000 CRIT= 338.00

CONVERGENCE ACHIEVED AFTER 1 ITERATIONS

2 FUNCTION EVALUATIONS.

LOG OF LIKELIHOOD FUNCTION = 595.118
NUMBER OF OBSERVATIONS = 360

PARAMETER	ESTIMATE	STANDARD ERROR	T-STATISTIC
A0	67.782	11.606	5.8404
AQ	-4.9788	1.7739	-2.8067
AQQ	0.51659E-01	0.16086	0.32113
AT	-0.43640E-03	0.13268E-03	-3.2891
B1	-33.577	5.0143	-6.6963
B2	-1.7484	1.7838	-0.98011
B3	2.9357	2.8278	1.0382
B4	5.9459	2.8384	2.0948
C11	7.2212	2.0343	3.5496
C22	-0.62729	0.38425	-1.6325
C33	0.96021	0.43069	2.2295
C44	-2.1427	0.86445	-2.4787
C12	1.6883	0.50206	3.3627
C13	-1.2163	0.68281	-1.7813
C14	-1.4439	0.96157	-1.5016
C23	-0.27526	0.28026	-0.98217
C24	-0.76924	0.38885	-1.9782
C34	0.97217	0.54941	1.7695
D1	1.5264	0.34931	4.3697
D2	0.14946	0.16492	0.90628
D3	-0.46082	0.21036	-2.1906
D4	0.52546	0.27752	1.8934

STANDARD ERRORS COMPUTED FROM QUADRATIC FORM OF ANALYTIC FIRST DERIVATIVES (GAUSS)

EQUATION EQ11
****

DEPENDENT VARIABLE: LAC

SUM OF SQUARED RESIDUALS = 0.772610
STANDARD ERROR OF THE REGRESSION = 0.478103E-01
MEAN OF DEPENDENT VARIABLE = 9.40706
STANDARD DEVIATION = 0.671206
R-SQUARED = 0.995227
ADJUSTED R-SQUARED = 0.994931
DURBIN-WATSON STATISTIC = 0.6224

RESULTS OF PARAMETER ANALYSIS
****

INPUT PARAMETERS WERE: A0 AQ AQQ AT B1 B2 B3 B4 C11 C22 C33
C44 C12 C13 C14 C23 C24 C34 D1 D2 D3 D4

```
    FRML EQ7 C55 = (((C11+ C22)+ C33)+ C44)+ 2* (((((C12+ C13)+ C14)+ C23)+
C24)+ C34)

    FRML EQ8 D5 = ((- D1- D2)- D3)- D4

    FRML EQ2 B5 = (((1- B1)- B2)- B3)- B4

    FRML EQ3 C15 = ((- C11- C12)- C13)- C14

    FRML EQ4 C25 = ((- C12- C22)- C23)- C24

    FRML EQ5 C35 = ((- C13- C23)- C33)- C34

    FRML EQ6 C45 = ((- C14- C24)- C34)- C44
```

PARAMETER	ESTIMATE	STANDARD ERROR	T-STATISTIC
C55	3.3229	0.85411	3.8905
D5	-1.7405	0.25908	-6.7180
B5	27.444	3.8052	7.2122
C15	-6.2493	1.1426	-5.4694
C25	-0.16492E-01	0.40222	-0.41002E-01
C35	-0.44084	0.56726	-0.77715
C45	3.3837	0.72676	4.6559

WALD TEST FOR THE HYPOTHESIS THAT THE GIVEN SET OF PARAMETERS ARE JOINTLY ZERO:

CHI-SQUARED = 253.16107 WITH 7 DEGREES OF FREEDOM.
P-VALUE = 0.00000000

NONLINEAR LEAST SQUARES
****

EQUATIONS: EQ21

NOTE => The model is linear in the parameters.
Working space used: 21257

STARTING VALUES

	A0	AQ	AT	B1	B2
VALUE	1.00	1.00	1.00	1.00	1.00

	B3	B4	C11	C22	C33
VALUE	1.00	1.00	1.00	1.00	1.00

	C44	C12	C13	C14	C23
VALUE	1.00	1.00	1.00	1.00	1.00

	C24	C34
VALUE	1.00	1.00

F= 8.6268 FNEW= -0.48123E-01 ISQZ= 0 STEP= 1.0000 CRIT= 343.00

CONVERGENCE ACHIEVED AFTER 1 ITERATIONS

2 FUNCTION EVALUATIONS.

LOG OF LIKELIHOOD FUNCTION = 566.005
NUMBER OF OBSERVATIONS = 360

PARAMETER	ESTIMATE	STANDARD ERROR	T-STATISTIC
A0	12.396	4.3574	2.8448
AQ	0.99642	0.19368E-01	51.448
AT	-0.32761E-03	0.13598E-03	-2.4092
B1	-12.216	3.7211	-3.2830
B2	-6.6678	0.93315	-7.1455
B3	0.62565	1.8117	0.34535
B4	10.066	2.2994	4.3775
C11	5.4500	2.0951	2.6013
C22	-0.49350E-01	0.29856	-0.16529
C33	1.9361	0.34375	5.6324
C44	-0.86929	0.89416	-0.97219
C12	2.8610	0.43562	6.5676
C13	-1.7101	0.65917	-2.5944
C14	-2.9022	0.98666	-2.9415
C23	-0.90649	0.24072	-3.7657
C24	0.80231E-01	0.32933	0.24362
C34	0.55895	0.46645	1.1983

STANDARD ERRORS COMPUTED FROM QUADRATIC FORM OF ANALYTIC FIRST DERIVATIVES (GAUSS)

EQUATION EQ21
****

DEPENDENT VARIABLE: LAC

SUM OF SQUARED RESIDUALS =	0.908241
STANDARD ERROR OF THE REGRESSION =	0.514581E-01
MEAN OF DEPENDENT VARIABLE =	9.40706
STANDARD DEVIATION =	0.671206
R-SQUARED =	0.994391
ADJUSTED R-SQUARED =	0.994130
DURBIN-WATSON STATISTIC =	0.6265

RESULTS OF PARAMETER ANALYSIS
****

INPUT PARAMETERS WERE: A0 AQ AT B1 B2 B3 B4 C11 C22 C33 C44 C12 C13 C14 C23 C24 C34

FRML EQ2 B5 = (((1- B1)- B2)- B3)- B4

FRML EQ3 C15 = ((- C11- C12)- C13)- C14

FRML EQ4 C25 = ((- C12- C22)- C23)- C24

FRML EQ5 C35 = ((- C13- C23)- C33)- C34

FRML EQ6 C45 = ((- C14- C24)- C34)- C44

FRML EQ7 C55 = (((C11+ C22)+ C33)+ C44)+ 2* (((((C12+ C13)+ C14)+ C23)+ C24)+ C34)

PARAMETER	ESTIMATE	STANDARD ERROR	T-STATISTIC
B5	9.1930	2.7846	3.3013
C15	-3.6986	1.1364	-3.2548
C25	-1.9854	0.30054	-6.6061
C35	0.12153	0.57157	0.21263
C45	3.1324	0.74219	4.2204
C55	2.4301	0.89423	2.7176

WALD TEST FOR THE HYPOTHESIS THAT THE GIVEN SET OF PARAMETERS ARE JOINTLY ZERO:

CHI-SQUARED = 194.90973 WITH 6 DEGREES OF FREEDOM.
P-VALUE = 0.00000000

NONLINEAR LEAST SQUARES
****

EQUATIONS: EQ31

NOTE => The model is linear in the parameters.
Working space used: 12047

STARTING VALUES

	A0	AQ	AT	B1	B2
VALUE	1.00	1.00	1.00	1.00	1.00

	B3	B4
VALUE	1.00	1.00

F= 8.3435 FNEW= 0.15229 ISQZ= 0 STEP= 1.0000 CRIT= 353.00

CONVERGENCE ACHIEVED AFTER 1 ITERATIONS

2 FUNCTION EVALUATIONS.

LOG OF LIKELIHOOD FUNCTION = 493.855
NUMBER OF OBSERVATIONS = 360

PARAMETER	ESTIMATE	STANDARD ERROR	T-STATISTIC
A0	-3.2565	0.25076	-12.987
AQ	0.94038	0.21699E-01	43.337
AT	-0.17564E-03	0.10772E-03	-1.6305
B1	0.84613	0.74609E-01	11.341
B2	-0.28080	0.33138E-01	-8.4737
B3	-0.12729	0.64397E-01	-1.9767
B4	0.31458	0.46458E-01	6.7713

STANDARD ERRORS COMPUTED FROM QUADRATIC FORM OF ANALYTIC FIRST DERIVATIVES (GAUSS)

EQUATION EQ31
****

DEPENDENT VARIABLE: LAC

SUM OF SQUARED RESIDUALS =	1.35607
STANDARD ERROR OF THE REGRESSION =	0.619802E-01
MEAN OF DEPENDENT VARIABLE =	9.40706
STANDARD DEVIATION =	0.671206
R-SQUARED =	0.991624
ADJUSTED R-SQUARED =	0.991482
DURBIN-WATSON STATISTIC =	0.3631

RESULTS OF PARAMETER ANALYSIS
****

INPUT PARAMETERS WERE: A0 AQ AT B1 B2 B3 B4

FRML EQ2 B5 = (((1- B1)- B2)- B3)- B4

PARAMETER	ESTIMATE	STANDARD ERROR	T-STATISTIC
B5	0.24738	0.45127E-01	5.4818

WALD TEST FOR THE HYPOTHESIS THAT THE GIVEN SET OF PARAMETERS ARE JOINTLY ZERO:

CHI-SQUARED = 30.050615 WITH 1 DEGREES OF FREEDOM.
P-VALUE = 0.00000000

NONLINEAR LEAST SQUARES
****

EQUATIONS: EQ41

NOTE => The model is linear in the parameters.
Working space used: 10521

STARTING VALUES

	A0	AT	B1	B2	B3
VALUE	1.00	-1.76D-04	1.00	1.00	1.00

	B4
VALUE	1.00

F= 4.7579 FNEW= 1.0742 ISQZ= 0 STEP= 1.0000 CRIT= 353.78

CONVERGENCE ACHIEVED AFTER 1 ITERATIONS

2 FUNCTION EVALUATIONS.

LOG OF LIKELIHOOD FUNCTION = 161.977
NUMBER OF OBSERVATIONS = 360

PARAMETER	ESTIMATE	STANDARD ERROR	T-STATISTIC
A0	5.8137	0.34672	16.768
AT	0.15113E-02	0.25215E-03	5.9936
B1	0.91716E-01	0.18213	0.50357
B2	0.67250E-01	0.80711E-01	0.83322
B3	-0.15408	0.16166	-0.95313
B4	0.46833	0.11629	4.0273

STANDARD ERRORS COMPUTED FROM QUADRATIC FORM OF ANALYTIC FIRST DERIVATIVES (GAUSS)

A LEAST-COST ANALYSIS OF TRANSITION IN NORTH AMERICA'S UPHOLSTERED, WOOD HOUSEHOLD FURNITURE INDUSTRY[1]

Eric J. Todd and Steven H. Bullard[2]

Abstract.--Factors influencing the location of the North American upholstered, wood household furniture industry are undergoing many changes.[3] This paper presents a least-cost linear programming approach to determining optimal furniture production and shipment patterns. The results suggest that Mexico and the East South Central region of the U.S. are well-poised to increase their shares of the North American market as consumption patterns and factors of production change in the next decade.

INTRODUCTION

The furniture industry is an important part of the manufacturing sector in the United States. The upholstered, wood household furniture industry in the U.S. grew 16 percent from 1982 to 1987 to 82.1 thousand employees, approximately 30 percent of total U.S. household furniture employment (USDC Bureau of the Census 1990).[4] The furniture industry is the largest consumer of hardwood lumber in the U.S. (Koch 1985). In 1987 alone, U.S. upholstered, wood household furniture manufacturers used over $375 million in wood-based raw materials.

During the 1980's, the baby-boom generation entered the 25-44 year old age bracket, where many major consumption decisions are made. This age bracket now accounts for one-third of the U.S. population, and will continue to be an important consumer group in the 1990's. More than half of these consumers own their own homes and many households have more than one income (Standard and Poors 1986). The growth of this segment of this population, coupled with the economic prosperity of the 1980's, led to an increased demand for upholstered furniture. North American producers enjoy the benefits of this expansion, since shipment costs keep foreign manufacturers from being competitive.

Three factors have played a role in the historic location of the furniture industry in the U.S. As noted, upholstered furniture is expensive to ship so the industry has tended to locate near the consuming population. Also important are a plentiful hardwood supply and low-cost labor pool. Total payroll results in nearly 50 percent of the value added by manufacture (USDC International Trade Administration 1985). Each of these factors has played a role as the industry has shifted from Jamestown, NY, to Grand Rapids, MI, and then to High Point, NC. While High Point is still the major production center, we are seeing significant shifts in production westward into Mississippi, Tennessee, and even into Mexico.

Other changes, particularly those that relate to production, are resulting in geographic shifts in the furniture industry's location within North America. The free trade agreement between the U.S. and Canada, for example, is changing the

[1]Presented at the Symposium on Systems Analysis in Forest Resources, Charleston, SC, March 3-7, 1991.

[2]The authors are, respectively, Graduate Research Assistant and Associate Professor of Forest Economics, School of Forest Resources, Mississippi State University, Mississippi State, MS.

[3]For the purposes of this study, North America does not include Alaska, the Yukon, or the Northwest Territories.

[4]Throughout this paper, "furniture and fixtures" refers to Standard Industrial Classification (SIC) 25, the "household furniture industry" is SIC 251, and "upholstered, wood household furniture" refers to SIC 2512 (see Office of Management and Budget 1987).

relative cost of doing business in the two countries as the tariffs are reduced. Because of an advantage in economies of scale and slightly lower wage rates in the U.S., some Canadian manufacturers are expanding into the U.S. or moving their facilities to the United States.

Mexico is growing in importance as a furniture producing region. The lower wage rates and the lack of environmental regulations are causing some U.S. furniture firms to set up production facilities in Mexico. The maquiladora program also is encouraging expansion into Mexico.[5/] This program is especially benefitting California firms who otherwise would encounter environmental regulations and worker's compensation costs that may be prohibitive.

The U.S. population is expected to shift from the northeast and midwestern sections of the nation to the western and southwestern regions (USDC Bureau of the Census 1989b). Combining regional population projections with known furniture consumption patterns based on age (Epperson 1989) will yield forecasts of consumption patterns as the population ages and concentrations shift. Similar information for Canada and Mexico allow forecasts to be made for the entire continent (Statistics Canada 1989, Direccion General de Estadistica 1980).

OBJECTIVE

The overall objective of this study was to assess the current potential for geographic shifts in the manufacture of upholstered, wood household furniture in the U.S., Canada, and Mexico. Specific objectives were to (1) identify all geographic areas that currently are important producers of upholstered, wood household furniture, (2) identify areas where demand currently is concentrated, and (3) investigate potential shifts in the geographic distribution of production during the next 5 to 10 years.

METHODS

The transportation algorithm of linear programming was used to evaluate optimal patterns of upholstered furniture production and shipment in North America. The model was designed to estimate the patterns of shipment between production regions and consumption regions that minimized the combined costs of production and transportation. This section will explain how the source and destination regions were determined and how the relevant costs were calculated.

Regions

Twelve regions were used to represent production and twelve were defined for consumption of upholstered household furniture in North America (Figure 1). The nine census regions of the Census Bureau were used as the production and consumption regions of the United States. Canada was split into two regions, with the division occurring along the Manitoba-Ontario border. This is near the middle of the country and passes through a relatively unpopulated area; thus it divides the markets without splitting a major population center. Mexico was included as a single region since the only area of concern in this study is the border region where the furniture maquiladoras are located. The maquiladoras are the only Mexican furniture plants that affect the U.S. furniture market; furniture plants in the interior of the country are oriented entirely toward the domestic market (Evans 1990).

Production Indices

Determining actual production costs for each region is difficult since comparable data are not available for all of the regions shown in Figure 1. For that reason, production costs were represented by manufacturing cost indices. The Seventh Annual Study of the General Manufacturing Climates of the Forty-Eight Contiguous States of America was selected as a source of production cost indices for the U.S. (GrantThornton 1986). This index is based on 22 factors that are pertinent to industries such as furniture manufacturing.[6/] In fact, states traditionally associated with furniture production score quite well on this index (Kunkel 1989). Since GrantThornton scores apply only to U.S. states, production indices for regions in Canada and Mexico were calculated relative to the U.S. regional scores (Garreau 1981, Evans 1989a). The 12 regional scores then were indexed with the average score being assigned a value of one.

Transportation Indices

Production and consumption centroids were identified within each region to represent the sources and destinations of furniture flow. Transportation costs were estimated from every production centroid to every consumption centroid, resulting in 144 transportation costs. These transportation costs are a weighted average of truck and railroad shipping costs. The weight assigned to each method of transportation varies

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[5/]The maquiladora program was established in 1965 by Mexico and the U.S. to create jobs for Mexico. The program was designed to encourage U.S. companies to open plants in Mexico and use U.S.-made parts. When the finished product is shipped to the U.S., the company is taxed only on the value-added in Mexico (Evans 1989b).

[6/]The 22 factors used to determine this index are: Wages, Unionization, Energy Costs, Worker's Compensation Insurance (WCI), Taxes, Manhours Lost, Value Added, Change in Wages, Unemployment Compensation (UC) Benefits, Change in Taxes, Change in Unionization, Expenditure vs. Revenue Growth, High School Educated Adults, UC Net Worth, Maximum WCI Payment, Environmental Control, Voc-Ed Enrollment, Debt, Hours Worked, Population Change, Population Density, and Welfare Expenditure.

Figure 1.--The twelve regions defining regional production and consumption of upholstered household furniture in North America.

by region (USDC Bureau of the Census 1981, U.S. Department of Transportation 1980).[7]

The 144 costs also were indexed by assigning the average cost a value of one.

Total Indices

The final step in representing costs was to combine production and consumption indices into an overall index. Rubin and Zorn (1986) state that transportation costs comprise 22.92 percent of the total costs in the furniture and fixtures industry. We used this percentage to determine a weighted average of the indices for each region. Each production index was combined with 12 separate transportation indices, depending on the furniture destination, resulting in a 12 by 12 matrix that serves as the technical coefficients table of the model.

Production and Consumption Data

Regional furniture production was represented as a percentage of total North American production. The number of upholstered household furniture employees in each region was used as a proxy for production since actual data on a comparable basis for all three countries is not available (USDA Bureau of the Census 1990, Statistics Canada 1989, Direccion General de Estadistica 1979).

Regional consumption figures were measured as a percent of total consumption in North America. Retail sales estimates for each region were usedas a measure of consumption for the region (USDC Bureau of the Census 1989a, Statistics Canada 1989, Direccion General de Estadistica 1980). Percentages allow easy examination of model results, and they also obviate the need for assumptions about production estimates (such as dollar value of shipments) versus retail (marked-up) consumption estimates.

Comparisons of regional production and consumption percentages reveal that 3 regions are net producers of upholstered furniture. These are the South Atlantic region, the East South Central region, and Mexico. The two U.S. regions contain the two major furniture producing markets in the U.S. These are High Point, NC, in the South Atlantic region, and Tupelo, MS, in the East South Central region.

RESULTS

Upholstered, wood household furniture industry shipments resulting from the base model specifications show the South Atlantic region to be the primary furniture supplier to the eastern half of the U.S. and eastern Canada (Figure 2). The East South Central region is the second largest producing region and, given the model's assumptions, most efficiently serves the south central and southeastern United States.

---

[7]Percentages of furniture shipments by truck and rail within Canada were provided by Jennifer Allen, Marketing Representative for CP Rail, Toronto.

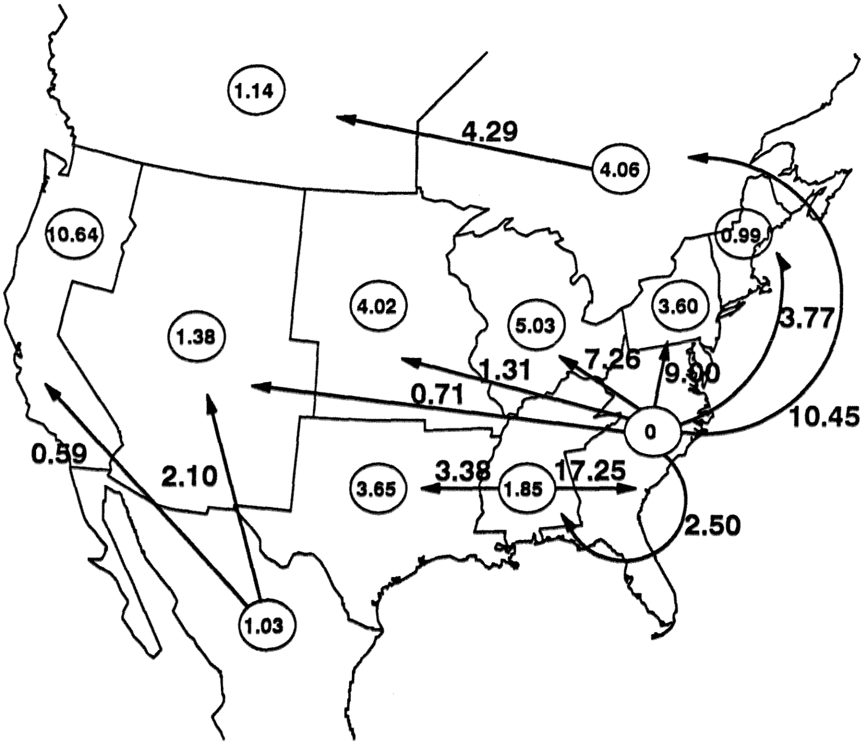

Figure 2.--Optimal furniture shipment pattern yielded by the initial model. Each number is a percent of all upholstered household furniture produced and consumed in North America. Numbers inside a circle represent furniture produced and consumed in the same region, while those along the arrows represent shipments between regions.

Scenarios

Several of the base model parameters and assumptions were altered to help assess potential changes in the geographic distribution of production in North America. These alterations also helped identify any regional comparative advantages that may exist. We present each of the six scenarios separately, although in reality several of these could be acting simultaneously on the industry in the 1990's.

Increasing Transportation Costs

Rising fuel costs are increasing the costs of furniture transportation, and as a result, the transportation component of total costs may increase above the 22.92 percent we used in the initial model. An increase in the transportation index of 10 percent resulted in significant shifts in the least-cost furniture distributions. The South Atlantic region would now most efficiently serve the U.S. markets along the East Coast and those in eastern Canada. The East South Central region is forecast to expand its shipment pattern to include those regions in the central portion of the United States.

This pattern does not change even as the transportation index is increased by 50 percent. This reveals a potential comparative advantage for the East South Central region that may prove to be extremely important in the 1990's. With rising fuel and transportation costs, this region becomes the most efficient long-term supplier to the central regions of the United States.

Diminishing Transportation Advantage

The eastern half of the U.S. dominates total furniture and home furnishings sales with 76 percent of total U.S. sales occurring in the Midwest, Northeast, and South (Bullard 1990). The population is shifting, however, away from the Northeast and Midwest to the western and southwestern states (USDC Bureau of the Census 1989b). To reflect the decrease in transportation advantage that these regions may experience in the 1990's, the importance of the transportation advantage was decreased to 10 percent. Any transportation advantage they now enjoy would therefore play less of a role in determining the least-cost shipment pattern.

As the transportation component becomes less significant, the South Atlantic region is able to serve eastern Canada more efficiently. As a result, the Middle Atlantic region receives most of its furniture from the East South Central region. The East South Central region, as before, becomes the least-cost supplier to the central portion of the U.S., suggesting that their comparative shipping advantage to this portion of the nation is quite stable.

Increasing Labor Costs

The upholstered, wood household furniture industry has tended to migrate towards the southeastern U.S. for several reasons. One of the most important of these has been relatively low labor costs. In the last 15-20 years, however, manufacturing wages in these states have risen as a percentage of the U.S. average, reflecting a greater competition for labor (USDC International

Trade Administration 1985). To model the effects of increased wages, we increased the manufacturing indices in the southeastern U.S. by 10, 25, and 50 percent.

The shift in shipment patterns for the East South Central and South Atlantic regions, as a result of a 10 percent increase, is the same as the shift resulting from an increase in transportation costs. This implies that base model distribution is more sensitive to both labor and transportation cost increases. Again, the East South Central region appears to have an advantage that makes it the least-cost supplier to the central portion of the nation. Further cost increases have little effect on this distribution.

Decreasing Canadian Employment

Since the Free-Trade agreement has gone into effect between the U.S. and Canada, the Canadian furniture manufacturing industry has experienced plant closures in response to the changing manufacturing climate. For this scenario, we assumed that the upholstered furniture industry employment and production decrease in Canada would result in a comparable 1.75 percent increase in the production capacity of the southeastern U.S..

As would be expected with this scenario, more furniture is shipped from the U.S. into Canada. Rather than receiving all of their furniture from the South Atlantic region, as in the base model, the Canadian markets also are served by the East South Central region and Mexico. This pattern of production and shipment is especially beneficial for the East South Central region since it allows producers in that region to serve many other regions, giving them a broad consumer base.

Increasing Mexican Production

Conditions seem to favor the expansion of Mexican production as they work to penetrate the U.S. market. The expanding maquiladora program, in addition to the stabilization of the Mexican government and the curbing of inflation, have helped increase the level of exports by the Mexican furniture industry (Evans 1990). To examine how this expansion may impact the U.S. industry, we included a scenario with an increased production percentage for Mexico.

In response to incremental increases in Mexican production, the South Atlantic and East South Central regions' shipments were shifted to areas where they have a greater relative transportation advantage over Mexico. The East South Central region, for example, decreased their shipments to the west and increased shipments to the East North Central region and eastern Canada. The South Atlantic region, meanwhile, showed increased shipments to the Middle Atlantic and New England regions as a result of Mexican production increases.

Consumption Projections

Relationships between consumer age and yearly expenditures on specific types of home furnishings were published by Epperson (1989). Combining this information with regional population projections for the U.S. (USDC Bureau of the Census 1989b) and Canada (Industry, Science and Technology Canada 1988) yields a forecast of consumption patterns.

The model was modified to project consumption projections for the year 2000. As a result, the East South Central region increased shipments to the west while decreasing shipments to the shrinking markets in the north. The South Atlantic region increased its shipments into Eastern Canada, which is a growing market, while shipping less to the regions on the East Coast of the U.S., which are projected to have decreasing consumption percentages due to population shifts.

SUMMARY

The least-cost distributions yielded by the base model appear to be quite sensitive. Cost increases as low as 10 percent, in production or transportation costs, result in significant shifts in distribution patterns. As these costs increase, the East South Central region is forecast to serve a larger market area. This region seems to have comparative advantages that favor it becoming the long-term least-cost producer for the central portion of the United States.

As the U.S. population shifts westward, we expect the South Atlantic region's share of the market to decrease. If the upholstered furniture manufacturing industry follows this population shift, production in the South Atlantic region may decrease. Accordingly, we expect the East South Central region to increase its market share due to a comparative transportation advantage and a projected population growth within the region.

Finally, Mexican production could very well play a larger role in the future U.S. market. The forecasted westward population shift would give it a comparative advantage over the producing regions in the southeastern United States. This advantage would be in addition to the low-cost production advantage the region already enjoys.

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APPLICATION OF ROCKY MOUNTAIN STATION MICROCOMPUTER FORPLAN ON NATIONAL FORESTS IN THE PACIFIC NORTHWEST REGION[1]

Alan Ager, Brian Kent, Jim Merzenich, and Richard Phillips[2]

Abstract. The use of FORPLAN as tool for forest planning on national forests was vastly simplified by the development of the microcomputer (RMS) FORPLAN system. This software became available in 1989 and found immediate application in the Pacific Northwest Region of the USDA Forest Service. The migration of FORPLAN to the microcomputer eliminated numerous operational constraints associated with remote mainframe systems, and substantially reduced the time and effort needed to complete forest plans. The use of RMS FORPLAN and LINDO/386 also reduced mainframe computer costs to the national forests in Region 6 by 0.5 million dollars over a one year period. This paper describes the development of RMS FORPLAN and its application in Region 6.

Keywords: FORPLAN, LINDO, linear programming, land management planning.

INTRODUCTION

FORPLAN is the primary tool used by the USDA Forest Service for analyzing economic and production tradeoffs in the development of comprehensive forest plans (Iverson and Alston, 1986, Johnson et al., 1986, Barber and Rodman, 1990). The Agency, in cooperation with Norm Johnson, developed the FORPLAN system on a UNISYS mainframe at the National Computer Center in Fort Collins. Given the computer technology available at that time, the system required mainframe-sized hardware to solve the large linear programming models generated for forest-wide analyses. Like many mainframe applications, FORPLAN was expensive and difficult to run. Furthermore, solving the linear programs (LP's) that some FORPLAN users created was even a greater challenge (Kent et al., 1987). As a result, the system contributed significantly to the difficulty and cost of conducting forest planning analysis.

In 1989, Brian Kent and others at the Rocky Mountain Forest and Range Experiment Station ported the FORPLAN system to a Intel 80386/MS-DOS based microcomputer platform. This was done in an effort to reduce the costs of running FORPLAN to make it a more economical research tool. The new microcomputer system was called "RMS (Rocky Mountain Station) FORPLAN". It was subsequently released to national forests in Region 6, where it found immediate application.

In this paper, we briefly describe the development of RMS FORPLAN, and discuss its impact on forest planning efforts in Region 6.

DEVELOPMENT OF RMS FORPLAN

RMS FORPLAN was created by compiling the source code for the eight FORPLAN executable programs that comprise the Version 2, release 13 matrix generator and report writer using the NDP FORTRAN compiler (Microway, Kingston, MA) and the Phar Lap DOS extenders (Phar Lap Software, Cambridge, MA). Use of the DOS extenders allowed the compiled code to take advantage of high memory (RAM in excess of the 640 Kb limit associated with MS-DOS). Only minor code modifications were necessary to successfully recompile FORPLAN in the new environment. Two versions of RMS FORPLAN were developed, these being specific to either the Intel 80387 or Weitek mathematical coprocessors.

Initial testing indicated that virtually any FORPLAN model could be generated using this new system, and that reports could be prepared for virtually any model once it was solved. As was the case with the mainframe, the greater challenge was in solving FORPLAN models once they were generated. Initial testing demonstrated that many of the more reasonable sized FORPLAN models could be solved on a microcomputer using LINDO/386 (LINDO Systems, Chicago, IL). A modified version of LINDO/386 was developed for the Forest Service that had row and column limits expanded to accommodate large models.

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[2] Planning Analyst, USDA Forest Service, Pendleton, OR 97801; Project Leader, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO 80524; Planning Analysts, USDA Forest Service, Portland, OR. 97208. Mention of trademarks in this paper does not imply endorsement by the USDA Forest Service.

Like RMS FORPLAN executables, LINDO/386 came in both the Intel 80387 and Weitek versions. In order to permit communication between FORPLAN and LINDO/386, two utilities were developed. The first modified outputs from the RMS FORPLAN matrix generator to convert them to a format that could be input in LINDO/386. The second modified solution output from LINDO/386 so that it could be read and interpreted by the RMS FORPLAN report writer.

The Intel 80386 microprocessor coupled with DOS extenders provided the first of two keys to the success of RMS FORPLAN. An earlier attempt to create a microcomputer version of FORPLAN was severely limited by the existing technology. Specifically, FORPLAN source code could not be compiled within the MS-DOS 640 Kb RAM limit, and DOS extenders were not yet developed. In the earlier project, this problem was solved by splitting the FORPLAN executables into separate programs, and reducing the maximum size of the FORPLAN data sets. This seriously compromised the capability of the package, as the maximum data set size was reduced well below that required by even the smallest FORPLAN model in Region 6. With the DOS extenders, these modifications to reduce the FORPLAN program size were not necessary.

The second key to the success of RMS FORPLAN was the development of LINDO/386 software, which was also capable of accessing high memory. On the mainframe, the most significant computational problem and cost associated with FORPLAN analysis stemmed from solving the models. When the RMS FORPLAN project began, it was not clear whether solving the larger models could be accomplished. The release of LINDO/386, and the subsequent finding that it was capable of solving these large FORPLAN models set the stage for the operational use of RMS FORPLAN in Region 6.

APPLICATION OF RMS FORPLAN IN REGION 6

Several national forests obtained the RMS FORPLAN executables and purchased LINDO/386 for beta testing in late 1989. Early results from this testing showed that many forest wide models could be generated and solved in a matter of hours. Other advantages were also realized that made RMS FORPLAN a very attractive alternative to FORPLAN on the Unisys mainframe. Within the next year, the majority of Region 6 national forests acquired the necessary hardware and software, and were using RMS FORPLAN as an operational tool.

The microcomputer systems acquired in Region 6 to run RMS FORPLAN reflected the large RAM requirements of both RMS FORPLAN and LINDO/386, and the extensive mass storage (hard drive) needed to process the FORPLAN data files. All forests acquired systems that were beyond the minimum hardware (80386, math coprocessor, 4 MB RAM, 100 MB mass storage) required to run RMS FORPLAN (Table 1). Larger systems were found to be necessary to generate and solve the large and more complex models developed on many of the forests. Furthermore, the larger systems have shown markedly faster FORPLAN and LINDO/386 execution times for a given model.

The amount of RAM seems to have been particularly important, especially for solving LP's. LINDO/386 resorts to virtual memory paging when RAM is insufficient to load the entire LP matrix, which slows computations.

Several of the machines acquired to run RMS FORPLAN were also configured with ram disks, disk caching, and a Weitek coprocessor (Table 1). In limited testing, the disk caching reduced the time required for matrix generation and report writing by over twenty percent. The Weitek coprocessor reduced LP processing time by over one-half in many cases, and provided objective function values that more closely resemble those obtained from the mainframe.

Six of the 13 Region 6 forests using Version 2 FORPLAN models migrated entirely to RMS FORPLAN shortly after its release (Table 2). On each forest, run times were highly variable, and depended on the model size and density. The other six forests (Mount Baker-Snoqualmie, Rogue River, Siskiyou, Siuslaw, Umpqua, Wenatchee, and Winema) either had models that could not be easily solved with LINDO, or for other reasons, chose not to migrate entirely to RMS FORPLAN. However, most of these forests did use the matrix generator as a debugging tool, and the report writer for reporting tasks. Even this limited application of RMS FORPLAN resulted in significant time and cost savings. Several models that were not initially solvable with LINDO/386 were reduced in size by removing unnecessary prescriptions and harvest timing choices. In their original form, these models were in the range of 40,000 - 100,000 columns and 4,000 - 8,000 rows, and took several days of processing on the UNISYS mainframe to solve. In all cases, models were reduced to a size accommodated by LINDO/386 without significant changes in model solutions. In our estimation, all the models in the Region could be scaled to run within the LINDO/386 limits.

Table 1 Summary of Microcomputer Hardware for the application of FORPLAN and other analysis tools[a].

Forest	Type	RAM	Drive Size	MC
Deschutes	386/25	9	320	W
Giff. Pinch.	386/33	10	320	I/W
Mt. Baker	386/16	4	100	I
Mt. Hood	386/33	12	320	I/W
Olympic	386/33	8	330	I/W
Rogue River	386/33	8	320	I
Siskiyou	386/20	6	80	I
Siuslaw	386/33	8	330	W
Umatilla	386/33	16	320	W
Umpqua	386/20	5	130	I
Wenatchee	486/33	12	320	I
Willamette	386/33	14	420	I/W
Regional Off.	386/33	16	320	I/W

[a] RAM is random access memory in megabytes, drive size is in megabytes, MC refers to math coprocessors: I = Intel, W = Weitek.

Table 2. Example model sizes, densities, and solution times, for Region 6 national forests[a].

Forest	Size (RxC)	Non Zero Density	Solution Time (Hrs)
Deschutes	3.5x60	0.03%	12
Giff. Pinch.	3.5x40	0.1%	1-36
Mt. Hood	3.5x50	0.4%	2-72
Olympic	2.0x30	0.1%	1-4
Umatilla	3.0x13	0.2%	2-8
Willamette	8.0x40	0.2%	2-48

[a] Only forests that used LINDO/386 in conjunction with RMS FORPLAN are listed. Six other forests used the matrix generator and report writer, but solved the models on the UNISYS mainframe.

INTEGRATION OF RMS FORPLAN WITH OTHER MICROCOMPUTER SOFTWARE

Perhaps the most useful result of migrating FORPLAN to the microcomputer is that FORPLAN now resides on the same system as the software tools needed to build data sets and interpret solutions. These tools include both commercial and in-house (Forest Service) software. For instance, the use of commercially-available word processors, spreadsheets, and relational databases has streamlined the construction of FORPLAN data and yield files. In addition to commercial packages, an extensive library of microcomputer software has been developed in Region 6 to further integrate FORPLAN data files with the raw input data. These programs convert FORPLAN data sets to a database format where modifications can be easily performed. In addition, programs have been developed to reformat database information to the format required by FORPLAN. These programs have proven to be especially useful for converting FORPLAN data from Version 1 to Version 2 formats.

One of the most useful programs developed in Region 6 extracts and organizes raw output data from the FORPLAN report writer into several logical databases. These databases can be used to display, interpret, and summarize the FORPLAN solution at any level of resolution desired, which vastly simplifies analyzing FORPLAN results.

CONCLUSIONS

RMS FORPLAN has significantly enhanced the Pacific Northwest Region's capability to conduct planning analysis. The microcomputer environment has eliminated numerous operational constraints associated with using the mainframe system, and has substantially reduced the time and effort to make a typical FORPLAN run. Steps such as accessing the mainframe via the Forest Service Data General network, logging on to the mainframe, transferring data, using the mainframe submittal system, etc. have been eliminated. More importantly, FORPLAN input and output files can now be easily processed with microcomputer software, allowing for more efficient model development, debugging, reporting, and interpreting results. Finally, significant cost reductions have been realized.

In the future, RMS FORPLAN will make the FORPLAN system a more usable tool. Less time will be devoted to the mechanics of building and running models, and proportionately more time will be spent on interpreting solutions and conducting sensitivity analysis designed to explore a broader range of model formulations and resource allocation issues. The microcomputer platform will also facilitate integrating FORPLAN analysis with other planning such as those developed to disaggregate FORPLAN solutions to a meaningful spatial scale (e.g. Merzenich, this proceedings).

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SPATIAL DISAGGREGATION PROCESS:
Distributing Forest Plan Harvest Schedules to Subareas[1/]

James P. Merzenich[2/]

Abstract. The Spatial Disaggregation Process (SDP) is a means of distributing a planned, scheduled timber harvest quantity to subareas of a National Forest. SDP serves as a bridge between the Forest-wide FORPLAN model and projects conducted on Ranger Districts. With SDP one can calculate the harvest potential of geographic areas while considering constraints designed to protect or manage other resources. The process utilizes user-friendly relational data base and graphic support systems that work in "real-time" mode on microcomputers. This enables land managers to better understand resource relationships and contributes to more informed decisions.

Keywords: land management planning, integrated resource analysis, hierarchical planning, timber management, area-level analysis.

INTRODUCTION: THE NEED FOR SDP

Since 1980, the FORPLAN linear programming model has been used to determine sustainable, or nondeclining, levels of timber harvest on each National Forest.[3/] FORPLAN typically schedules harvests for 15 decades using an economic efficiency objective, while considering nondeclining yield and other resource goals. Because of the complexity of this problem when applied to areas that often exceed a million acres, Forest-wide FORPLAN models often cannot contain sufficient detail to ensure that an "optimal" solution can be implemented.

The timber base acreage on National Forests in the Pacific Northwest is declining. Since mostly uncut roadless areas, old-growth stands, and riparian zones are being removed from the base, the areas that remain available for timber production have generally been harvested. Issues such as biodiversity and the consideration of cumulative effects may place limits on the rate and quantity of harvest from any given geographic area. These concerns, when coupled with the effects of past harvests, limit the absolute attainable harvest volume within the next decade. On most National Forests in the Pacific Northwest, environmental considerations as reflected in Standards and Guidelines reduce the first-decade harvest level below the long-term sustained yield level.[4/]

An intermediate level of analysis is needed to build a bridge between the Forest Plans and resource projects (Barber 1990, Wood et al. 1989). This paper describes a process for estimating realizable timber harvest levels while considering standards and guidelines to manage other resources on Forest subareas. This Spatial Disaggregation Process, termed SDP, is intended to:

1. Strengthen FORPLAN by estimating an implementable harvest acreage which best fits the capabilities of subareas of a National Forest and

2. Serve as a tactical planning tool to help implement the Forest Plan and conduct sensitivity analysis on emerging issues.

[1/] Presented at the Symposium on Systems Analysis in Forest Resources, sponsored by the Society of American Foresters, Charleston, SC, March 4-6, 1991.

[2/] Planning Analyst, Forest Service, U.S. Department of Agriculture, Portland, OR.

[3/] The FORest PLANning linear programming model, or FORPLAN, was initially developed by K. Norman Johnson, currently Professor of Forest Management, Oregon State University, Corvallis, OR.

[4/] In the Forest Service, U.S. Department of Agriculture, land management planning process, the **Standards and Guidelines** direct all resource management activities and uses on the Forest, provide standards for performance, and establish bounds and constraints for these activities and uses.

THE DESIGN OF SDP

The initial purpose of Spatial Disaggregation was to determine whether a given FORPLAN solution could or could not be implemented. The process is now an integral part of Forest Plan development and implementation. In Spatial Disaggregation the unique characteristics of each subarea are used to fit a harvest schedule to the land. These subareas, or Plan implementation units, may be watersheds, timber compartments, project areas, or other areas as determined on a particular National Forest.

The use of relational data base technology enables Spatial Disaggregation to work effectively. The models described here have been developed on microcomputers using a widely known commercial data base application named Paradox.[5]

To enhance SDP as a decision support tool, a graphics program is used to perform analysis and map the results. This map display and decision visualization tool was developed jointly by Richard Church and David Lantner of the University of California, Santa Barbara, and personnel of Regions 5 and 6 of the Forest Service.[6] It operates using a map boundary file and a data file which contains thresholds for each subarea. These thresholds are the maximum acres and volume that can be harvested in a subarea over a given length of time while meeting a specific standard and guideline. Up to six thresholds may be considered simultaneously in a given problem. The program has powerful "what-if" editors that enable the user to edit data and change relationships. The program then instantly calculates and maps the results of these changes. Figure 1 shows a sample display screen produced by the program.

In brief, the following general sequence of events is used to "solve" a Spatial Disaggregation problem:

1. Data tables are built to describe the land base. Normally obtained from a Geographic Information System (GIS), they contain the acreage by subarea, vegetative class, management area, and other relevant strata.

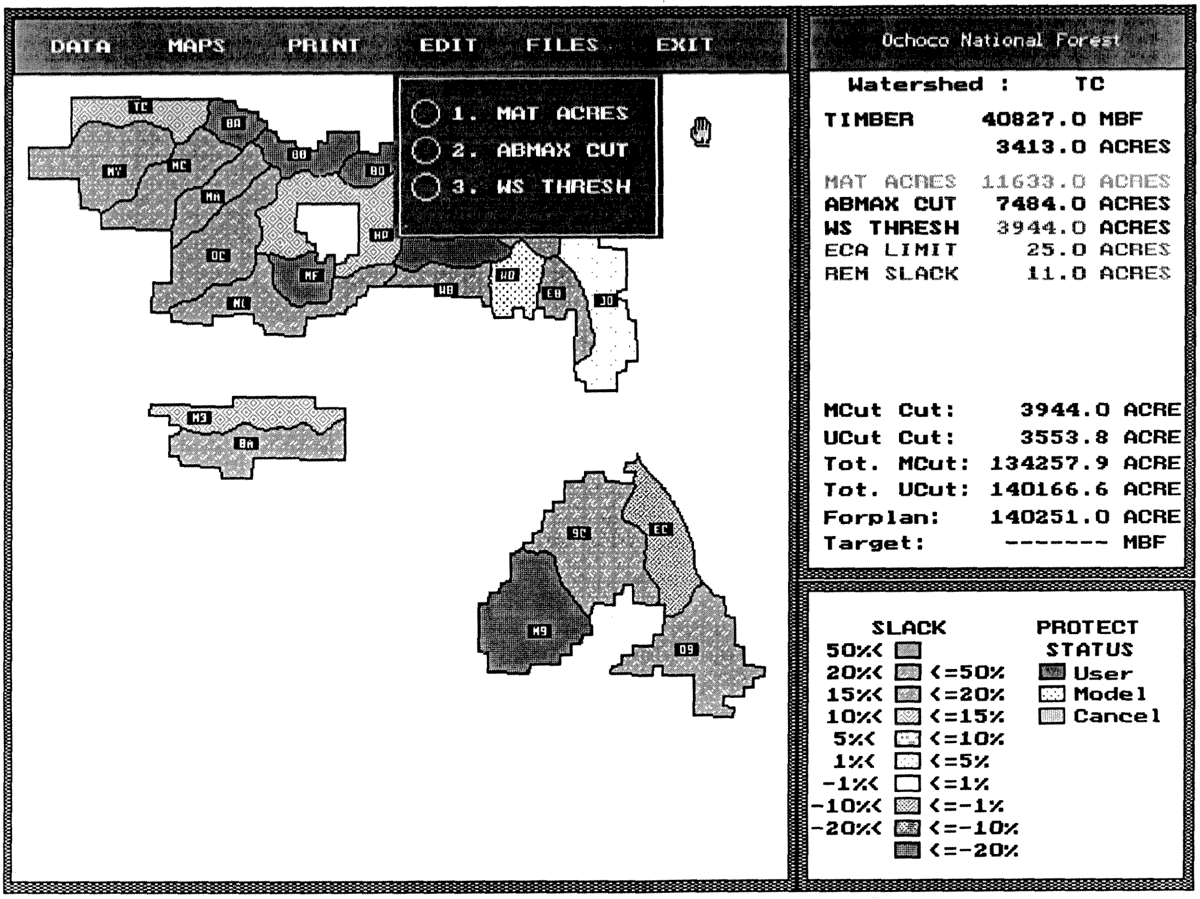

Figure 1.--Sample map display screen.

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[5]Paradox, version 3.5, is a software copyright of Borland International, Scotts Valley, CA.

[6]Richard Church and David Lanter are Professors of Geography, University of California, Santa Barbara. Klaus Barber and Malcolm Kirby (Forest Service, U.S. Department of Agriculture, Region 5) and Richard Dyrland (Forest Service, U.S. Department of Agriculture, Region 6) have been instrumental in designing and carrying out this cooperative agreement.

2. Tables containing resource information, such as harvest volumes per acre, watershed recovery rates, and constraint limits are built and linked to the base tables.

3. Scripts, i.e., repeatable data base query sequences, are developed to process subarea data and prepare input for the map display program.

4. The FORPLAN solution is distributed on a prorated basis to each subarea, and these data are displayed in map form. Subareas which can sustain additional harvests above the prorated share are colored in shades of green, while areas of potential shortage are flagged in red.

5. The harvest is redistributed such that no subarea violates the threshold bounds. If a harvest quantity cannot be totally redistributed, the maximum feasible harvest level is calculated for each subarea. Maps and reports depicting the redistribution are immediately created.

FOREST EXAMPLES:

Spatial disaggregation models have been or are being developed for all National Forests in California, Oregon, and Washington and for some Forests in other Regions. A brief description of models for two National Forests follows.

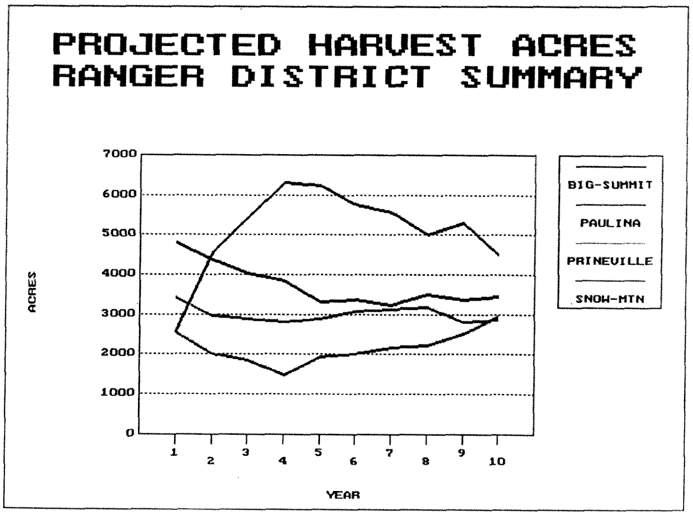
Ochoco National Forest

Unique "equivalent clearcut" acreage limits applied to watersheds control the timber harvest level on the Ochoco National Forest. The Ochoco SDP model distributes harvests from a Forest-wide FORPLAN solution to 24 watersheds. Historic timber harvest data for each watershed, and clearcut recovery curves specific to harvest types, are used to project watershed condition and to calculate potential harvests. The model makes either decadal or annual calculations. A Paradox script interactively graphs annual projected harvests, equivalent clearcut percentages, and remaining harvest balances by watershed or Ranger District. Sample graphs produced by this script are shown in figure 2.

The present SDP model for the Ochoco Forest calculates that the planned harvest level derived from FORPLAN is approximately 90 percent of the total watershed potential for the first decade. In other words, if all watersheds were cut to their absolute limit, with economic and nondeclining yield considerations set aside, the total harvest could be increased 10 percent. Several factors suggest that the planned harvest level calculated using FORPLAN should continue to be evaluated.

1. The existing watershed conditions vary greatly within and across Ranger Districts. To achieve the FORPLAN output level for the decade, harvests would have to be concentrated on the better-than-average Districts and watersheds in the early years, then switched to the remaining watersheds as conditions improved. The ability to quickly increase or decrease harvest levels on a District or watershed may be limiting. The annual projected District harvest levels are shown in figure 2 for a schedule calculated with SDP.

2. The average size of watersheds analyzed in the current model is 35,000 acres. The Forest Plan will be implemented on subbasins averaging 5,000 acres. Because of an uneven distribution of past harvests, the total available harvest acreage will probably decline when the analysis is done at this level.



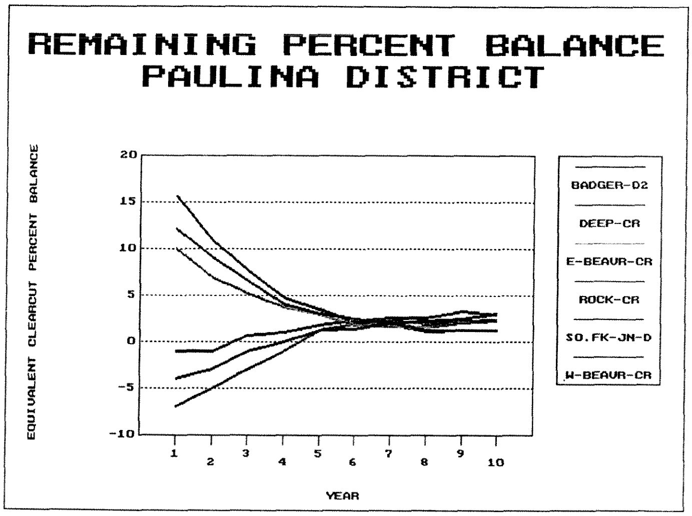


Figure 2.--Sample graphs produced by interactive Paradox Script.

3. Many watersheds are presently in good condition because of included roadless areas. Legal requirements to further analyze environmental impacts before entering roadless areas (e.g., Environmental Impact Statements), makes this acreage unavailable for harvest for several years.

4. A significant portion--64,000 acres, or 7 percent--of the Ochoco Forest burned in the severe drought conditions of 1990. This burn area will be generally unavailable for harvest

in the planning decade, further reducing the Forest's ability to redistribute the planned harvest.

The preliminary SDP model results, combined with these factors, suggest that the first-decade Forest Plan harvest quantity may need to be reevaluated. Forest personnel are presently incorporating subbasin and roadless area boundaries into GIS, updating the land strata to reflect burned areas, and validating the assumptions of the watershed model. They are also developing a FORPLAN model which includes the 24 major watersheds. Their next step will be to distribute FORPLAN harvest levels to the subbasins of each watershed while considering factors such as the year in which roadless areas can be entered. This process will result in a more refined calculation of the potential harvest level and provide a guide for plan achievement. The Ochoco SDP model has been instrumental in identifying data needs and bringing the potential problems of implementing the Forest Plan to the immediate attention of managers.

<u>Willamette National Forest</u>

On the Willamette National Forest the major factors limiting the potential harvest in the first decade are watershed recovery goals, the dispersion of harvest units, maintenance of habitat for spotted owls, and controls on the rate of harvest in visual management areas. The Willamette FORPLAN model controls harvests on 33 major watersheds, while the Forest Plan will be implemented on 454 subbasins.

The Willamette SDP model schedules suitable timber acres for harvest using unique watershed protection controls for each subbasin. The model also uses subbasin-specific management area, working group, and condition class data to determine the potential harvest level with visual management, harvest-unit dispersion, and spotted owl habitat limitations. Each of these factors has been found to be limiting on some subbasins.

With standards and guidelines modeled in FORPLAN at the watershed level, 102,000 acres are scheduled for clearcut harvest in the first decade. The SDP model, which uses the same modeling constraints applied to 454 subbasins, calculates that only 92,000 acres can be harvested. There is thus a 10-percent reduction in the allowable harvest acreage when the analysis is done at the more detailed level. This reduction is primarily a result of an uneven distribution of past harvests. Using the Willamette model as an example, K. Norman Johnson explained why FORPLAN models have generally overestimated the sustainable level of timber harvest (Johnson, 1990).

On the Willamette National Forest, these SDP-derived harvest acreage limits were used in determining the appropriate Forest Plan harvest level. The Willamette Forest allowable sale quantity is thus based on the spatial aggregation of data calculated by subbasin.

With SDP one may quickly determine the change in potential harvest acreage that would result from changes in model parameters. This sensitivity testing could include changes in watershed recovery rates, reaggregation of the base data, and varying the time period for which the analysis applies. The current Willamette FORPLAN model takes several hours to solve such a problem for 33 watersheds. In SDP the same problem, calculated for 454 subbasins, can be solved in a few minutes.

Recently, a requirement was established to maintain 50 percent of each subbasin in stands over 11 inches in diameter, to protect spotted owls. With an existing SDP model, Willamette Forest personnel were able to analyze the potential effect of this requirement in a single workday. Those Forests within the Region who were not prepared to run SDP took up to a month to achieve comparable results.

Willamette Forest personnel are presently developing an SDP implementation model that will be more useful to the Ranger Districts. This model will use stand-specific data from GIS to calculate annual harvest levels and determine potential timber sale areas. Concurrently, a multidecadal SDP model is being developed to help determine the sustainability of an SDP-derived harvest level.

SUMMARY

Spatial Disaggregation serves as a bridge between the Forest planning model and projects conducted on Ranger Districts. The primary purpose is to determine how to achieve the projected timber harvest level for a National Forest and its Districts. Analysis can be conducted on a decadal, annual, or other temporal basis using the level of detail needed to solve the problem. With the incorporation of visual displays which map data and analytical results in "real time" mode, SDP enables land managers to better understand resource relationships on a Forest or District and contributes to more informed decisions.

SDP Models are simple but powerful and can be easily modified to reflect new data and to evaluate the effects of changing situations. SDP analysis increases understanding of the Forest Plan by showing relationships between timber harvesting and other management activities. The Spatial Disaggregation Process makes the effects of Forest Plan assumptions apparent to managers. These assumptions can then be critiqued, evaluated, and modified to respond to management objectives and new information.

Spatial Disaggregation is an intermediate, or tactical stage, analytical tool and does not consider the juxtaposition of potential harvest units. Models such as SNAP II (Sessions 1990) and IRAS (Jones et al. 1986) are designed to schedule harvest chances while considering such factors as the adjacency of harvest units and economic efficiency. Spatial Disaggregation helps to identify problems in Forest subareas that require more intensive evaluation, and establishes bounds on the expected production level of each subarea.

As such, SDP is a necessary precursor to integrated resource analysis conducted on specific project areas. The shortcomings of current Forest data often become evident as the Spatial Disaggregation Process is conducted. SDP should be done now using existing data so the results can help identify immediate and future data needs.

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HARVEST BLOCKING, ADJACENCY CONSTRAINTS AND TIMBER HARVEST VOLUMES

Mark S. Jamnick and Karl Walters[1/]

Abstract.--Twelve harvest blocking patterns are developed from a strata-based timber harvest schedule for a 12,393 hectare forest in New Brunswick. A Monte-Carlo integer programming model is used to analyze the expected timber harvest volumes from each blocking pattern under different combinations of adjacency delay and maximum opening size. For this particular forest, the differences between blocking patterns are relatively small and forest managers have considerable flexibility in choosing a blocking pattern which best meets operational and other resource value criteria without sacrificing timber harvest volumes.

Keywords: Monte-Carlo integer programming, timber harvest scheduling, spatial allocation.

INTRODUCTION

The spatial feasibility of strata-based timber harvest schedules is a major forest management concern which has been the subject of a number of recent research initiatives (Nelson, et al., 1988; O'Hara, et al., 1989; Clements, et al., 1990). The emphasis in these studies has been to determine timber harvest volumes in the presence of "adjacency constraints" which restrict the time that must elapse before contiguous forested areas of a given maximum size may be harvested. These contiguous areas will be referred to as harvest blocks.

These studies have presumed that a particular harvest blocking pattern has been established. Given this pattern, the objective has been to use Monte-Carlo integer programming to determine a near optimal integer solution. It is apparent, however, that there are many ways to allocate a given strata-based timber harvest schedule on-the-ground, and that there are many potential harvest blocking patterns. Blocking patterns may differ in their sensitivity to adjacency constraints, provision of wildlife habitat or visual quality, or logging and road construction costs. Thus, alternative blocking patterns should be developed and evaluated so that forest managers can be assured that they are taking full advantage of their management opportunities.

This paper presents an analysis of twelve alternative harvest blocking patterns for a small New Brunswick forest. The analysis is limited to the expected timber harvest volumes that result from each blocking pattern under different combinations of maximum harvest openings and amount of time between harvest of adjacent blocks. The results indicate that differences in timber harvest volumes between blocking patterns are relatively small for the particular forest and patterns examined in this study, and that forest managers may be able to exploit opportunities for management of multiple resources without sacrificing timber harvest volumes.

DATA AND METHODS

Study Area

The study forest was defined to be four contiguous New Brunswick Forest Development Survey map sheets. Inventory and geographic information were obtained from the New Brunswick Department of Natural Resources and Energy. The forest is comprised of 3,241 stands which total 17,458 hectares of forested and non-forested land. Following standard wood supply analysis procedures used in New Brunswick, the forest was divided into components which were primarily softwood and primarily hardwood. The harvest schedule was developed only for the 12,393 hectare softwood component. Stand types (strata) were defined based on attributes in the provincial geographic information system database and were described by seven levels of identifiers: cover type, condition class, age, management unit, soil group, silviculture code, and management emphasis. The forest was divided into 57 stand types which ranged in size from 2 to 1921 ha. Silvicultural prescriptions for each of the 57 stand types included clearcutting followed by natural regeneration or planting to either black spruce (*Picea mariana* Mill.) or jack pine (*Pinus banksiana* Lamb.). If the regenerated stand was naturally regenerated then it was eligible to be sprayed with herbicides at age five and to be precommercially thinned at age 15. In the case of planting,

[1/]Assistant Professor of Forestry, Faculty of Forestry, The University of New Brunswick, Fredericton, N.B.; and Regional Planning Coordinator, Carleton-Victoria Wood Producers Association, P.O. Box 159, Bristol, N.B.

options for either light or heavy scarification were considered. Costs for all silvicultural activities (except harvesting) were considered in the problem. Yield information for each of the stand types and alternative silvicultural prescriptions required 167 yield tables for existing stand types and 42 yield tables for regenerated stand types.

Strata-Based Timber Harvest Schedule

A 70-year strata-based timber harvest schedule, consisting of 14 five-year planning periods, was developed for the forest using PC FORPLAN Version 2 (Johnson 1986). This harvest schedule maximized first period softwood timber harvest volume subject to nondeclining yield, FORPLAN's "perpetual timber harvest" ending inventory constraint, an annual silvicultural budget of $75,000, and a constraint which limited jack pine plantations to 15% of the area planted. Softwood fiber was the objective of management and hardwood volume merely a by-product of softwood harvests. No constraints were placed on hardwood volumes, but hardwoods were assumed to remain unharvested in any stand that contained less than 50 m^3 per hectare of hardwood volume.

The solution to this model indicated a periodic allowable softwood harvest of 123,231 m^3. The annual silviculture budget was completely utilized in each planning period except the twelfth period. A summary of the first five planning periods of the linear program solution is presented in tables 1 and 2.

Table 1. Forest outputs by planning period.

Output (m^3 per period)	Period 1	2	3	4	5
Softwood gross volume	123,231	123,231	123,231	123,231	123,231
Softwood pulp volume	87,119	86,462	85,302	84,366	84,138
Softwood sawlogs	36,112	36,769	37,929	38,865	39,093
Hardwood gross volume	21,556	21,967	33,115	70,060	24,593

Allocation of the Strata-Based Solution

Alternative harvest blocking patterns for the first five periods of the strata-based solution were developed using CRYSTAL (Walters 1991). CRYSTAL is a model that has been specifically designed to spatially and temporally allocate a strata-based harvest schedule. CRYSTAL is a conceptually simple model in which a stand eligible for harvest is initially chosen as a "seed." Then the neighbors of the seed are examined to determine if any of them are also eligible for harvest at this time. If so, the seed and the neighboring stands are aggregated into a potential harvest block. As each eligible neighbor is added to the potential harvest block, other stands which become neighbors are examined for harvest eligibility and are added if appropriate. This process continues until no additional eligible neighbors are found or until the maximum block size is reached. After exhausting all possibilities, if the potential block exceeds the minimum block size it is assigned a block number and a harvest period which coincides with the harvest period of the seed stand, and its component stands are withdrawn from further consideration by the algorithm. If the harvest block is smaller than the minimum block size, then the stands are released and considered for later inclusion in other blocks. Finally, a new seed stand is chosen and the process of aggregation and allocation begins again. The algorithm continues until the entire strata-based solution, that can be allocated within the constraint of the minimum block size, has been allocated.

Table 2. Silvicultural activities by planning period.

Activity (ha per period)	Period 1	2	3	4	5
Precommercial thinning	338	459	55	494	512
Planting jack pine	46	10	49	0	0
Planting black spruce	262	55	278	0	0
Light scarification	308	65	172	0	0
Heavy scarification	0	0	155	0	0
Herbicide application	0	802	885	956	974
Clearcutting	1,599	1,508	1,649	1,760	1,374

Although conceptually simple, CRYSTAL is a relatively complex model that provides numerous options to guide the harvest blocking process. CRYSTAL allows the user to develop alternative harvest blocking patterns by specifying (1) minimum and maximum harvest block sizes, (2) criteria for choosing seed stands, (3) the allowable deviation from the timing choices determined in the strata-based schedule, and (4) the pattern of the search for stands adjacent to the seed. Because there are numerous combinations of these user defined parameters, each of which results in a unique harvest blocking pattern, only a small subset of the many possible harvest blocking patterns that can be developed were examined in this study.

CRYSTAL was designed to allocate the strata-based solution as closely as possible. Because of the spatial distribution of stands, however, it may be impossible to completely allocate a harvest schedule without violating harvest block size constraints. Therefore, deviations from the exact timing of harvest specified in the harvest schedule may be allowed in order to permit allocation of more of the harvest schedule by selecting tolerance limits that govern how much deviation in timing choices are acceptable.

A user specified tolerance value of ± 1 would allow consideration of any stands adjacent to the seed stand which are within one period of the timing choice for the seed stand. Since the intent of the program is to follow the harvest schedule as closely as possible, the program will deviate from the harvest schedule only if it is not possible to adhere to scheduled periods. This is accomplished by forcing the program to first select any adjacent stand eligible for harvest in the same period as the seed stand. There is also an option whereby the user may wish to make the selection of adjacent stands more restrictive by allowing the use of timing deviations only up to the point where the potential block reaches minimum size, thereafter, only true contemporaries may be included in the harvest block.

Once all of the eligible stands have been determined, the program must select which ones will be included in the harvest block. Each stand has three attributes associated with it, one of which may be used as a selection criteria: allocation potential, stand proximity, and stand area.

The allocation potential is calculated as:

$$AP = \sum_{i=1}^{n} X_1$$

where:

AP = allocation potential

X_i = number of eligible stands contiguous to seed stand in period i

i = period of allocation

n = number of periods to be allocated.

Selecting stands on the basis of increasing allocation potential will bias the solution to first allocate those stands that have few eligible neighbors.

Stand proximity is calculated as the linear distance between the centroids of a particular stand and the seed stand. By selecting nearest stands first, harvest blocks delineated by CRYSTAL will tend to be circular in shape. This may be advantageous because it will tend to reduce the ratio of perimeter to area within a harvest block. Although other factors such as terrain affect the operability of a harvest block, large perimeter to area ratios generally increase extraction costs and windthrow damage of residual trees (Smith 1962, pp. 413-414).

If stand area is chosen as the selection criteria, CRYSTAL will select the stand with the smallest area. By building harvest blocks with the smallest stands first, the number of small stands allocated will be maximized. Since small stands tend to have low allocation potentials, the overall allocation of the harvest schedule may be increased using this criterion.

CRYSTAL selects the eligible stand with the lowest value for the chosen attribute. If a tie exists between two or more eligible stands, the program selects the stand belonging to the stand-type with the largest area remaining to be allocated. Biasing the solution toward unallocated area helps to distribute the allocation across stand-types and harvest periods.

Harvest Blocking Patterns

Twelve different harvest blocking patterns were developed from the strata-based solution (table 3). This table also shows the percentage of the strata-based solution that was allocated by the CRYSTAL model. In each case, harvest block size was restricted to be between 15 and 55 hectares. The first seven models differ in the criteria used to select seed stands. These criteria are (A) stand area in ascending order, (B) stand area in descending order, (C) stand perimeter in ascending order, (D) stand perimeter in descending order, (E) stand identification number in ascending order, (F) stand type identifier, and (G) allocation potential.

The remaining five harvest blocking patterns all use stand area in descending order as the selection criteria for seed stands, but differ with respect to (1) whether CRYSTAL was allowed to deviate from the timing choices in the harvest schedule when generating harvest blocks (unrestricted search), or was restricted to stands eligible for harvest in the same period as the seed stand once the block exceeded the minimum block size (restricted search), and (2) the criteria for selection of adjacent stands.

Estimation of Harvest Volumes

CRYSTAL does not consider adjacency as it allocates harvest blocks, but does keep track of adjacent blocks. This information was used to estimate maximum timber harvest volumes for each of the blocking patterns described above using a Monte-Carlo integer programming model named BLOCK (Dallain 1989; Clements, et al., 1990). BLOCK allows the user to specify both maximum opening sizes and adjacency delays. Two or more adjacent blocks may be harvested at the same time if their combined area does not exceed the user specified maximum opening size.

BLOCK assigns a harvest period to each block based on the objective function and adjacency constraints used in the model. Thus, even though CRYSTAL assigns a harvest period based on the harvest period of the seed stand in the strata-based solution, this timing choice may be changed in the

BLOCK model. For all the runs presented in this paper, the objective was to maximize the five-period average timber harvest volume and harvest timing choices in BLOCK were restricted to be no less than the harvest timing choice assigned for that block by CRYSTAL. For example, if a block was assigned to be harvested in the second period in CRYSTAL, then it could be scheduled for harvest in periods two through five by BLOCK, but could not be harvested in the first period.

Table 3. Description of the twelve harvest blocking patterns and percent of the strata-based solution allocated by CRYSTAL.

Harvest Blocking Pattern	Seed Selection Criterion	Search for Stands	Adjacent Stand Criterion	Percent Allocated
A	Area (ascending)	Unrestricted	Allocation Potential	90.89
B	Area (descending)	Unrestricted	Allocation Potential	92.38
C	Perimeter (ascending)	Unrestricted	Allocation Potential	90.96
D	Perimeter (descending)	Unrestricted	Allocation Potential	91.75
E	Stand Number	Unrestricted	Allocation Potential	92.54
F	Stand Type	Unrestricted	Allocation Potential	91.30
G	Allocation Potential	Unrestricted	Allocation Potential	91.59
B1	Area (descending)	Unrestricted	Stand Area	90.97
B2	Area (descending)	Unrestricted	Stand Proximity	92.41
B3	Area (descending)	Restricted	Allocation Potential	92.38
B4	Area (descending)	Restricted	Stand Area	91.19
B5	Area (descending)	Restricted	Stand Proximity	92.57

One hundred feasible solutions were generated for each of the 12 blocking patterns for various combinations of adjacency delays and maximum opening sizes. In the first set of runs, timber harvest volumes were estimated for each blocking pattern without adjacency delays. These runs were used to estimate the effect of timing choice deviations introduced in the harvest blocking process and the reductions in harvest that result from the incomplete allocation of the strata-based timber harvest schedule. Even in the absence of adjacency constraints and with complete allocation of the strata-based schedule, timber harvest volumes from a given harvest blocking pattern are almost always less than timber harvest volumes in a strata-based timber harvest schedule because some blocks contain one or more stand types which were not scheduled for harvest in the same period that the block is scheduled for harvest (Jamnick, _et al._, 1990). These timing choice deviations are necessitated by operational considerations not considered in the long-term strata-based schedule.

Timber harvest volumes were also estimated for adjacency delays of 1 and 2 five-year periods in combination with maximum opening sizes of 55 and 125 hectares. The purpose was to determine if there were any significant differences in the timber harvest volumes from different blocking patterns. If no significant differences occur, then this indicates that, for this particular case study, managers have a lot of flexibility and can choose a harvest blocking pattern on some basis other than timber harvest volume. If, on the other hand, there are significant differences, then a manager can choose a blocking pattern with full knowledge of the trade-offs between timber harvest volumes and other resources considerations.

RESULTS

The best of the 100 feasible solutions generated from the various runs of the BLOCK model are presented in tables 4 through 8. There are relatively small differences in the five-period average timber harvest volumes between different blocking patterns for a given maximum opening size and adjacency delay. It should be noted, however, that this is a very small and consequently relatively uniform forest. Differences, when expressed as a percentage of the strata-based allowable cut, can vary by over 5%. On a larger forest, with a higher annual allowable cut, a 5% difference in timber harvest volumes could be substantial and influence the selection of a blocking pattern.

Table 4. Timber harvest volume (m^3) per period without adjacency delays.

Blocking Pattern	Period 1	2	3	4	5	Average
A	114,717	118,115	110,619	112,992	112,334	113,755
B	112,072	111,924	111,203	110,532	111,107	111,368
C	110,530	114,424	120,400	117,883	112,660	115,719
D	113,250	110,228	110,476	115,259	116,112	113,065
E	110,355	118,936	118,623	115,456	112,051	115,084
F	110,125	110,814	116,689	113,435	111,849	112,582
G	110,480	114,531	110,796	116,258	110,186	112,450
B1	110,235	110,261	110,533	110,072	111,011	110,422
B2	111,238	112,796	111,484	115,006	117,029	113,511
B3	111,588	110,292	111,483	112,185	114,625	112,035
B4	101,062	107,525	108,885	110,564	117,343	109,076
B5	111,839	112,679	115,140	114,257	114,631	113,709

Table 5. Timber harvest volume (m^3) per period with one period adjacency delay and maximum opening size of 55 hectares.

Blocking Pattern	Period 1	2	3	4	5	Average
A	100,874	100,226	104,779	123,072	111,018	107,994
B	100,432	101,881	104,786	109,088	104,345	104,106
C	100,888	101,233	109,241	110,550	121,378	108,658
D	100,038	102,113	108,923	109,974	104,901	105,190
E	100,261	102,422	106,782	117,075	113,811	108,070
F	102,595	100,917	100,676	115,657	105,796	105,128
G	90,653	93,288	99,671	127,543	109,407	104,112
B1	101,257	100,970	100,523	101,097	115,156	103,801
B2	101,615	105,287	106,038	108,686	109,365	106,198
B3	100,715	102,303	103,467	103,515	111,574	104,315
B4	91,543	95,424	98,702	113,105	108,199	101,393
B5	103,616	103,866	103,335	111,247	109,964	106,406

Table 6. Timber harvest volume (m^3) per period with two period adjacency delay and maximum opening size of 55 hectares.

Blocking Pattern	Period 1	2	3	4	5	Average
A	76,616	78,173	87,599	85,053	102,735	86,035
B	76,412	75,208	77,757	85,796	113,091	85,653
C	78,264	75,864	80,060	97,627	99,166	86,196
D	76,966	77,995	77,193	89,219	116,333	87,541
E	78,401	76,958	77,551	97,547	94,800	85,051
F	79,236	76,232	76,121	101,472	109,680	88,548
G	75,967	75,292	75,414	88,394	121,131	87,240
B1	76,171	76,960	77,794	98,860	100,003	85,958
B2	78,164	80,864	78,697	93,720	103,595	87,008
B3	78,100	78,528	80,052	88,197	109,617	86,899
B4	77,593	77,850	81,785	87,127	105,078	85,887
B5	81,090	75,484	75,555	91,849	108,703	86,536

Periodic timber harvest volumes show somewhat more variation between blocking patterns than do the five-period averages. This is particularly evident in periods four and five where there is somewhat more flexibility in the allocation process because only the first five periods of the stratabased solution were blocked. As an example, with a two period adjacency delay, blocks assigned to be harvested in period five will only present a problem if they are adjacent to blocks assigned to be harvested in period three, four or five, whereas blocks that are assigned to be harvested in period three can present a problem if they are adjacent to blocks assigned to be harvested in periods one through five.

Table 7. Timber harvest volume (m^3) per period with one period adjacency delay and maximum opening size of 125 hectares.

Blocking Pattern	Period 1	2	3	4	5	Average
A	101,753	102,088	104,868	121,504	122,662	110,575
B	106,983	100,999	102,381	124,094	108,210	108,533
C	109,520	109,526	103,971	116,390	122,354	112,352
D	100,155	109,430	111,034	117,178	109,359	109,431
E	103,606	104,371	106,599	116,138	130,252	112,185
F	104,182	103,210	104,332	119,517	116,506	109,549
G	100,660	101,047	107,346	121,573	120,096	110,144
B1	100,234	104,953	106,847	110,967	118,633	108,327
B2	101,144	104,382	110,365	114,478	117,385	109,551
B3	105,977	108,639	110,744	107,896	110,798	108,811
B4	100,722	108,728	105,076	113,392	113,095	108,203
B5	106,007	116,842	100,099	112,990	116,546	110,497

Periodic timber harvest volumes, particularly the first period, may be more important to the selection of a blocking pattern than the five-period average volume because it will actually be implemented. On this basis, for example, patterns G and B4 are clearly inferior to the other patterns when the maximum opening size is 55 hectares and there is a one period adjacency delay (table 5), and patterns A, C, F and B1 inferior to the other patterns when there is a two period adjacency constraint and a maximum opening of 125 hectares (table 8).

Adjacency Constraints and Maximum Opening Sizes

As expected, adjacency constraints and maximum opening sizes had a substantial impact on timber harvest volumes. A one period adjacency delay with a maximum opening size of 55 hectares reduced average periodic timber harvest volumes by approximately 7,000 m^3 for each blocking pattern as compared to the runs without adjacency constraints, and a two period adjacency delay further reduced timber harvest volumes by approximately 20,000 m^3. When the maximum opening size was increased to 125 hectares the effect of the adjacency constraints was diminished and average periodic timber harvest volumes decreased by approximately 3000 m^3 with one period adjacency and an additional 8000 m^3 with two period adjacency.

These results are relatively consistent across the various blocking patterns, but the relative rankings of the average periodic harvest volumes show more sensitivity to the adjacency delay than to the maximum opening size (table 9). No single seed selection criteria consistently outperformed the others, but pattern C (perimeter ascending) had the highest objective function value without adjacency constraints and with one period adjacency constraints. When two period adjacency constraints were used pattern F (stand type) had the largest average periodic timber harvest volume with a maximum opening size of 55 hectares, and pattern E (stand number) the largest average periodic timber harvest volume with a maximum opening size of 125 hectares.

Table 8. Timber harvest volume (m^3) per period with two period adjacency delay and maximum opening size of 125 hectares.

Blocking Pattern	Period 1	2	3	4	5	Average
A	91,506	94,924	101,855	114,133	106,364	101,756
B	96,028	91,653	99,344	100,947	113,365	100,267
C	91,045	96,863	100,016	116,431	108,081	102,487
D	93,421	94,422	98,829	97,082	123,092	101,369
E	92,554	90,398	97,138	108,565	125,659	102,863
F	91,484	100,091	97,118	101,552	123,153	102,680
G	93,999	90,095	96,991	109,672	119,821	102,116
B1	90,609	98,008	92,224	100,273	125,000	101,223
B2	94,788	100,449	94,089	114,174	105,375	101,775
B3	95,790	96,189	101,393	96,413	111,950	100,347
B4	95,877	94,754	94,808	96,581	123,076	101,019
B5	92,633	106,270	97,440	97,636	119,792	102,754

Search for Adjacent Stands

Patterns based on restricted searches performed slightly better than patterns based on unrestricted searches when allocation potential and stand proximity were used as the adjacent stand criteria. Patterns based on unrestricted searches performed slightly better than patterns based on restricted searches when stand area was used as the adjacent stand criteria. Overall, however, there was very little difference between restricted and unrestricted searches. It is unclear why there was not a larger difference between unrestricted and restricted searches, but it may be attributable to the particulars of the case study.

Adjacent Stand Selection Criteria

Patterns based on stand proximity had larger average periodic timber harvest volumes than patterns based on allocation potential or stand area regardless of the adjacency constraints, maximum opening sizes or search for adjacent stands. This result may be attributable to the shape of the blocks when this criterion is used. Since stand proximity tends to produce circular blocks, it may be that there are fewer adjacent blocks than if stand area or allocation potential are used.

Once again, however, the differences in average periodic harvest volumes are relatively small indicating that forest managers have considerable flexibility in allocating harvest blocks. Since each criteria produces different block shapes, but nearly the same harvest volumes, considerations which are influenced by block shape such as logging costs might guide the selection of a particular blocking pattern.

Table 9. Rankings of average periodic timber harvest volumes.

Blocking Pattern	Adjacency Constraints: No Adjacency	55 ha One Period	55 ha Two Periods	125 ha One Period	125 ha Two Periods
A	3	3	8	3	7
B	10	10	11	10	12
C	1	1	7	1	4
D	6	6	2	8	8
E	2	2	12	2	1
F	7	7	1	7	3
G	8	9	3	5	5
B1	11	11	9	11	9
B2	5	5	4	6	6
B3	9	8	5	9	11
B4	12	12	10	12	10
B5	4	4	6	4	2

CONCLUSIONS

Harvest blocking patterns do vary in their sensitivity to adjacency delays and maximum opening sizes. In this particular study the differences in timber harvest volumes between blocking patterns were relatively small. Thus, for this forest, managers should be able to consider operational criteria and other resource values in their selection of a blocking strategy. On other forests there may be greater differences in harvest volumes and managers may be required to examine the tradeoffs between timber harvest volumes, operational considerations and other resource values in selecting a harvest blocking pattern. In any case, this study has clearly demonstrated that there are many alternatives for harvest schedule allocation and that managers are severely limiting themselves if they do not develop and evaluate these alternatives.

Some patterns in the results are evident and may be generally applicable. As an example, Nelson and Finn (1991) also concluded that adjacency delay had more of an effect on timber harvest volumes than maximum opening size. How generally applicable the results are, however, is an area for future research. As more researchers start to examine these types of questions it should be possible to determine which results are general, and which are sensitive to particular forest structures.

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SILVICULTURAL PLANNING USING A BAYESIAN FRAMEWORK [1]

David R. Larsen[2]

Abstract. -- Silvicultural management planning can be aided by the use of adaptive growth models which utilize a Bayesian statistical framework. Adaptive growth models are designed to predict stand structure change both in treated and untreated stands. Adaptive growth models are based on stand dynamic theories, parameterized to given stands, and utilize additional data as it is measured over the years.

Keywords: Adaptive growth models, Adaptive management.

SILVICULTURAL MANAGEMENT

Silviculture, the manipulation of forest stand structure to alter stand development patterns to meet desired objectives, has been practiced in many forms. Silvicultural systems have been developed to produce particular forest stand structures in different parts of the world (Matthews, 1989). These systems have, often become regimented to the point that forest managers invoke a "standard practice" with little thought about site-specific conditions. As foresters become more familiar with the processes of stand dynamics (Oliver and Larson, 1990) they can design site-specific variations of silvicultural systems for individual stands. The successes of these site-specific treatments depend on the extent of the manager's knowledge of how stands grow and on the care taken in implementation of stand-specific manipulations. Obviously, unforeseen occurrences such as fires, wind storms, and insect and disease outbreaks can also greatly affect the success of management.

Silviculturists use many types tools to determine a management scenario. These tools include static stand assessment tools known as diagnostic criteria, dynamic tools such as growth models, and economic tools to evaluate returns from the various alternatives. Diagnostic criteria such as height-diameter ratios (Abetz, 1976), stand stocking diagrams (Gingrich, 1964), and stand density diagrams (Reineke, 1933; Drew and Flewelling, 1979) are used to assess the need for site-specific treatments. Traditionally, diagnostic criteria have been designed to be specific to conditions that require treatment (e.g. thinning). Growth models have been designed to give point estimates of tree or stand volume. Often, foresters need more information that point estimates provide. More general growth models are needed to predict future stand development patterns as forest management objectives diversify from wood volume production to wood quality and management of other resources such as riparian habitats (Oliver et al., 1991), wildlife habitats (Thomas, 1979), and aesthetics. Properly designed, these tools could allow silviculturists to project stand structures to be produced by a proposed management regimes and to assess the suitability of those structures for stated management objectives.

Silviculturists need predictive tools that best take advantage of available information and data. Ideally, these tools should be easy to use, provide estimates of ranges of outcomes, and produce didactic output easy for managers to use in assessing management alternatives. Adaptive growth models can fit these criteria and are discussed here. Growth models have been developed to project volume growth over large

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[1] Presented at the Systems Analysis in Forest Resources Symposium, Charleston, SC, March 3-7, 1991.

[2] Graduate Research Assistant in the College of Forest Resources, University of Washington, Seattle, WA 98195.

forested areas for forest planning and inventory update. Growth models do not always work well for stand level projections of silvicultural treatments, primarily because limited treatment effects are included in many modeling data sets. Further, the inability of most models to predict non-commodity resource outputs, because physical biological relationships have not been developed, reduces the usefulness of these traditional growth models in multi-resource problems.

Adaptive growth models take a different approach to modeling and fulfill different purposes than traditional growth models. Adaptive growth models are designed to project stand development in response to treatments applied and one based on biologically based stand dynamics theories (Oliver and Larson, 1990). They have a Bayesian statistical framework, and depend on monitoring systems for results.

BAYESIAN FRAMEWORK

Many desired features of adaptive growth models do not fit easily within a standard statistical framework. Bayesian statistics permits the systematic biasing of equations with relevant additional information external to the modeling data set. The concept is that information outside a given data set is known and can improve growth model predictions. The equation is biased through the assumption of prior frequency distributions about some component of the equation. In the case where "prior" assumptions provide no new information, the result is the same obtained from unbiased methods. Bayesian statistics have had a poor reputation since the methods can be easily misused. Additionally, the methods have not been as widely taught as the more common "frequentist" methods (Berger, 1985); however, the results of using a Bayesian approach can be quite useful when the priors are formulated in a systematic and rational way.

Why would foresters want to use a Bayesian approach? Foresters are often faced with a collection of <u>information</u> and <u>data</u> that differ in time, resolution, and quality. <u>Information</u> in this context is compiled data or equations such as height-age curves, height-diameter curves, height growth equations, and site index equations. <u>Data</u> are individual measurements taken from forest samples (Baskerville and Moore, 1988). Often, foresters would like to take advantage of all information and data available, while allowing for differences in time and quality. The Bayesian approach permits one to do this. Other advantages include the ability to use assumed error distributions to simulate ranges of potential outcomes of the models, as well as the ability to integrate new information and data easily through the assumed prior distribution. The biggest disadvantage to Bayesian statistics is the inclusion of known bias, since bias can be abused. This disadvantage can be overcome with careful and conscientious definition of prior distributions.

ADAPTIVE GROWTH MODELS

Adaptive growth models are designed as a tool to understand stand development patterns and how silvicultural treatments affect those patterns. An example of one such flexible tool is an adaptive growth model developed by the author. The adaptive growth model can be used to project stand structure changes based on the principles of stand dynamics. The model can be easily parameterized for different areas and species. Similar adaptive growth models can be designed to be whole stand or individual tree, just as with any other forest growth model. The example presented here is an individual tree model. This type of model is designed for a different purpose than traditional growth models. It is designed to predict tree sizes and spatial patterns with emphasis on height and crown dimensions.

Adaptive growth models are adaptive because they are designed to utilize additional data and information as they becomes available. This type of tool is designed to be part of an adaptive management system in forestry (Baskerville, 1985; Walters, 1986).

<u>An Example</u>

The following simulation was produced by the individual tree, distance-dependent adaptive growth model described above. Input data were distilled into a set of parameters, and a hypothetical stand of the same structure as an original stand was generated and grown. All equations are designed to reflect biological relationships at the whole tree level. The following are explicit assumptions and conditions:

- Stand responses are simply the aggregate of individual tree responses to their immediate environments.
- Crown size is the dominant force in changing tree size.
- Root systems, while important, are not considered in this example.
- Stem area increment at crown base is a function of crown size regardless of tree size.

- Stem area increments at other points on the stem follow a function similar to that described by Long, et al. (1981; see figure 1).
- Leaf area is related by some proportion to surface area of a solid representing the crown shape of that species (Maguire and Hann, 1987).

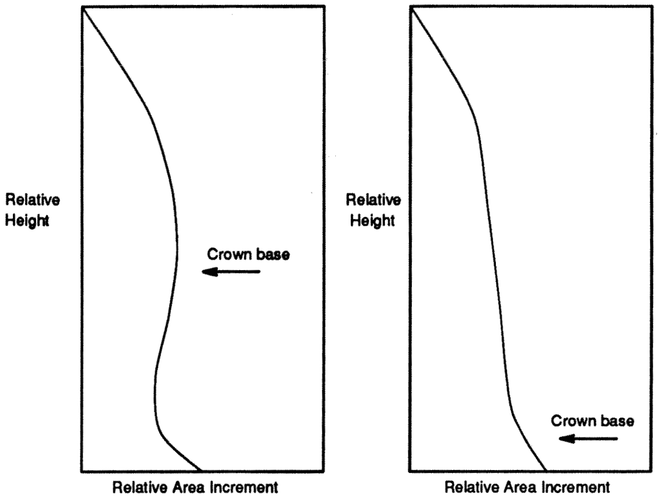

Figure 1: The assumed shape of the stem area increment. This shape is similar to functions described by Long, et al. (1981)

An example model based on these assumption is configured in several major parts: stand generation, stand growth, utilities, parameter setting routines, and display. The general approach is a "run and display" model since the modeled sequence is run, stored, and then displayed at any time or across time. Additionally, the model is designed to be unitless,

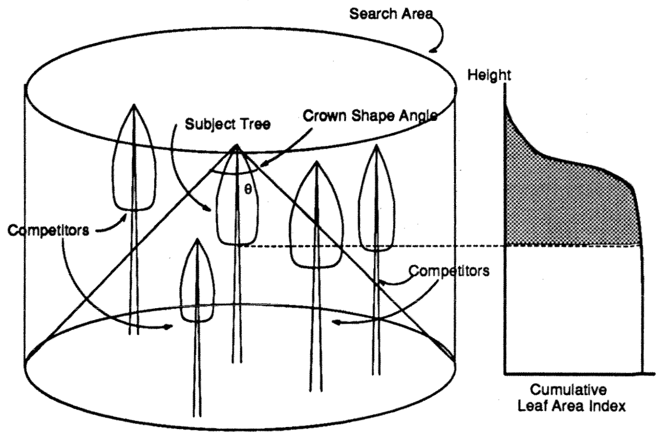

Figure 2: Illustration of the search area for a subject tree

allowing users to define units of prediction within a range of one or more years.

Stand generation is accomplished through determining distributions for key dimensions such as tree heights and spatial patterns and then drawing from these distributions a set of simulated trees. Remaining variables are defined through relationships to the key variables.

Stand growth uses the following set of components to determine new tree sizes:

- Height grow predicts height increment based on each tree's current crown and stem size. These variables are considered analogous to a tree's photosynthetic potential and respirative cost as it becomes larger.
- Crown change is predicted using a probabilistic model. This model predicts the probability of crown recession of one height

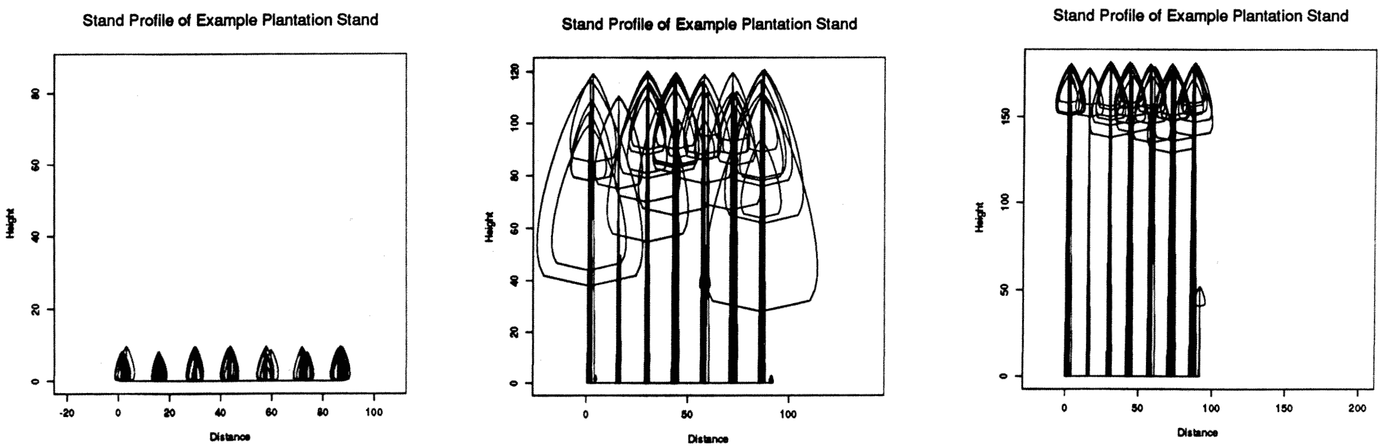

Figure 3: Simulated stand profile at initial, 50, and 100 years. Trees on the edge of the plot have more exposed surface area and therefore longer crowns.

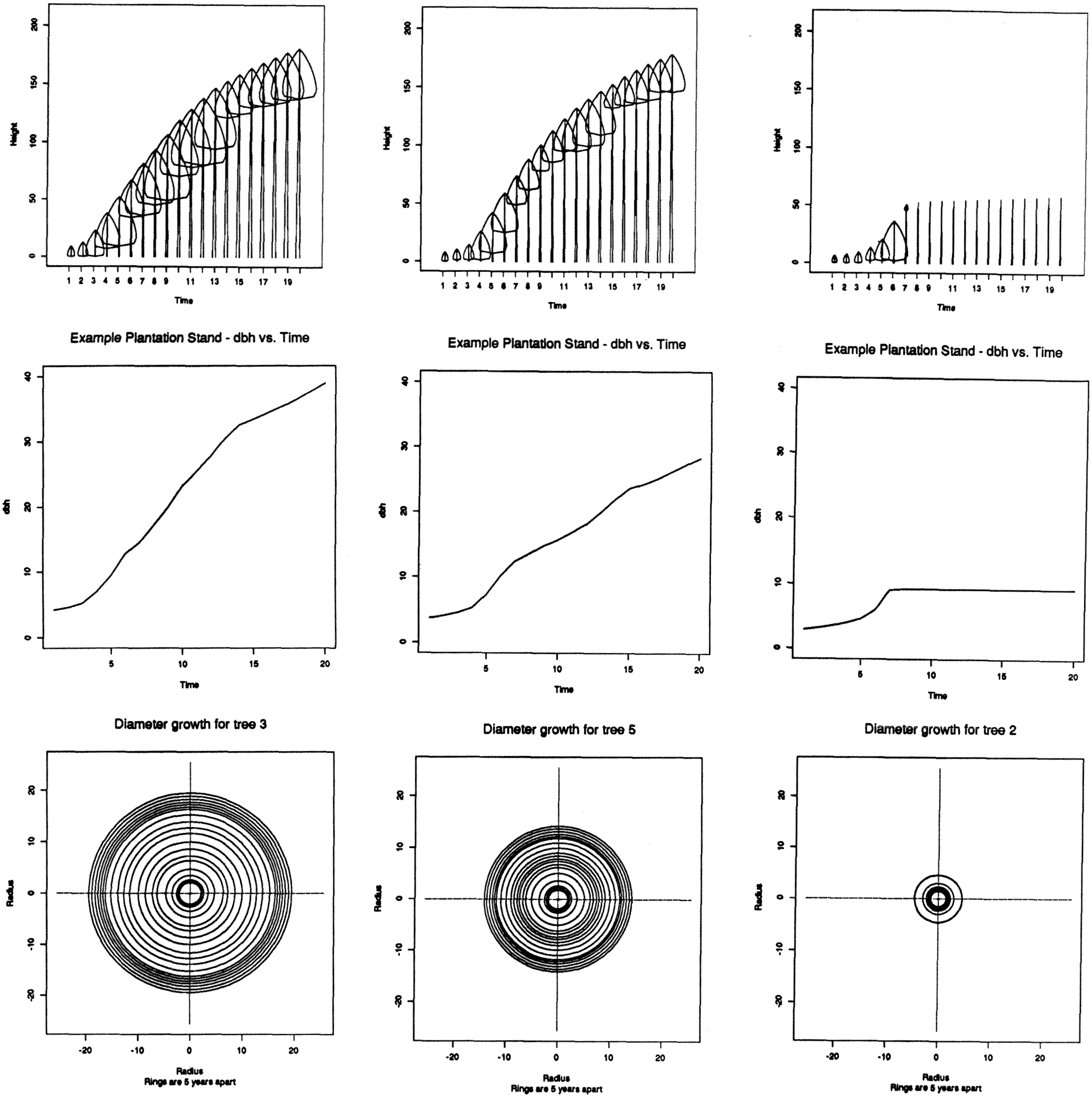

Figure 4: Tree 3, 5, and 2 from the simulated stand, tree profiles and diameter growth.

unit given the cumulative leaf area index above the crown base within a size- related search distance around the subject tree. This concept is described visually in figure 2. The size of the search area is defined by a crown angle, which is very similar to maximum crown width. All trees within the area are cumulatively summed from the top of the canopy to the ground to provide a cumulative leaf area index profile. Leaf area index as used here means the amount of leaf surface area above a unit ground surface area. The leaf area index value at the current crown base is used to predict crown recession, and the process is repeated at higher intervals on a tree's stem until the crown does not recede.

- Regeneration is predicted by generating potential seedlings at x, y coordinates and then determining the cumulative leaf area index above the seedling within a large search distance. If the competition is less than a threshold amount, the seedling is established; otherwise it is discarded (e.g. assumed not to live).

- Mortality in the current version is simply caused by the loss of crown below a threshold. Other types of mortality may be important but have not been considered in this example.

- Stem area increment, as stated previously, follows the assumption of a shape similar to that published by Long et al. (1981). Admittedly these functions are hard to parameterize, but they were designed to follow the biological functioning of stem growth.

The sequence of steps through the model is in the same order as it is are presented in this list.

"Utilities" are the routines that allow stand manipulations such as thinning and pruning. Thinning is specified by selecting individual trees by number or location. Pruning can be specified as either a relative height lift of a fixed height lift.

"Parameter setting" routines aid the user in building a parameter set for the stand of interest by stepping through the procedures. The overall design of the growth model has emphasized relationships that are common among trees and has avoided relationships that are species or form specific.

This model has been implemented within the S statistical package (Becker et al., 1988). One advantage of the package is the flexible and extensive nature of the S environment. Additionally, the environment provides may tools to analyze the output of the growth model. The S package is an ideal experimental development environment but may not be practical for users that do not have access to, or are not interested in, learning the Unix operating system. A 386 version is being developed as well.

"Display" routines are extensive beyond the generic routines within the statistical package. They are designed to display the growth data visually. Additionally, it is a simple matter to revise existing display routines to display relationships not originally considered.

Figure 3 is an example of the stand profile function in the display package. Figure 4 is an example of the profile of an individual tree displayed over time. Figure 5 is a plot of di-

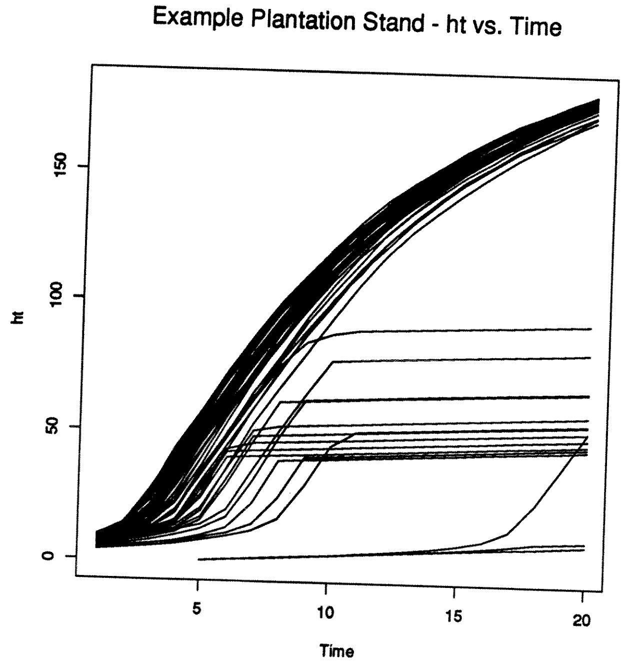

Figure 5: Height growth for all trees in the simulated stand. Horizontal lines show trees that are dead.

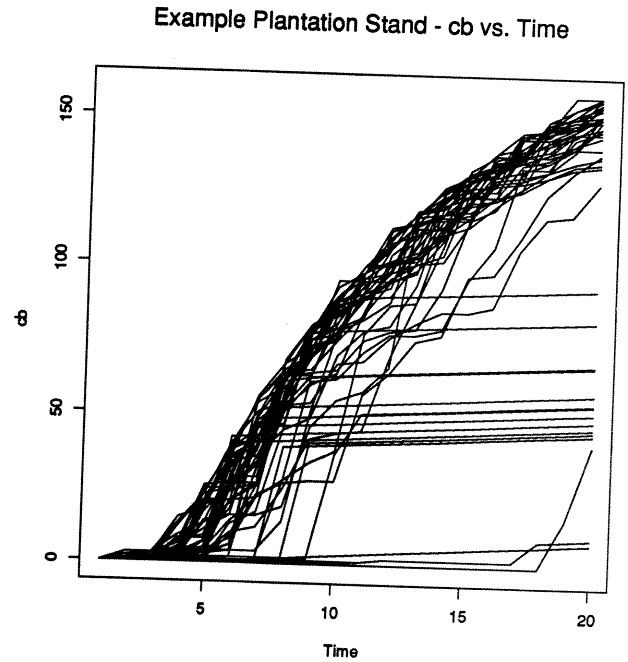

Figure 6: Height of live crown base for all trees in simulated stand.

ameter growth at breast height for the same three trees. Figure 6 is a plot of height age curves for all trees. Figure 7 is a plot of crown base change curves for all trees.

DECISION PROCESS

The main reason for building any stand growth model is to provide a tool for understanding a system under consideration and for using that understanding in a decision process. Foresters must choose a management scenario with incomplete knowledge about their outcome. A large amount of general knowledge has been derived about the trends of forest systems, and the challenge is to take advantage of this general knowledge in making decisions.

Adaptive growth models can play a role in the decision making process in a number of ways. Adaptive growth models can facilitate the identification of desirable alternatives and provide measurable criteria to determine periodically if the stand is meeting the desired objectives. Trees are long lived by human standards. It is hard for people to visualize changes in trees and stands as well as their possible development paths. Often desired forests structures can not be developed from an existing stand. Here, an adaptive growth model can aid in the understanding of feasible alternatives. Adaptive growth models can be used to identify how feasible alternatives relate to stated goals.

Once suitable management alternatives are identified, they can be analyzed economically for value returned by a variety of techniques, which best suit the manager's needs. At this point the analyses must be organized for presentation to decision makers for action.

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INVENTORY DESIGN FOR HARVEST SCHEDULING [1]

JOHN C, WELKER [2]

Abstract.-- Large scale forest inventories designed to support forest planning and harvest scheduling models differ from conventional forest inventories in several respects. Rather than providing an estimate of current volume, the main objective is to provide information about initial state conditions of each strategic planning stratum. This information is used to project yields under alternative management and harvest regimes. The value of information in a strategic planning model varies by stratum based on age, stand conditions, yield modeling techniques, and available management alternatives. The inventory design objective is to maximize the value of strategic planning information for a given inventory budget. Mead Coated Board uses a sampling design based on cluster sampling to meet this objective.

Keywords: Cluster sampling, Strategic Planning

INTRODUCTION

Forest inventories can be grouped into three broad categories based on the type of information they provide: (1) Information for considering strategic planning alternatives; (2) Information for making tactical decisions; and (3) Information for making operational decisions. Stand and tract cruises are examples of inventories which provide operational or tactical planning information. Information requirements are often immediate and related to the distribution product volume or value on the tract.

The main reason for inventories to support strategic planning is to estimate the necessary attributes to project future volume distributions by strategic planning stratum. For each planning stratum there is a need to project yields for alternative silvicultural and harvest regimes. Due to the relatively high cost of these inventories and the potential value of the information, careful inventory design is more important than in most cruises. Nevertheless, articles relating to strategic planning seldom mention the inventory information required to support such models. Persons dealing with strategic planning issues are usually interested in either methodology or implementation. The perception of both groups may be that inventory design and the source of inventory information are not very important. However, both the usefulness of planning methodology and its feasible implementation can be severely limited by bad data. Another reason for the lack of interest may be that planners feel they have little or no control over the data gathering process. They are happy with whatever data that might be available.

This paper discusses inventory design issues as they relate to large-scale inventories for strategic planning. The strategic planner is assumed the principal "customer" for whom inventories are carried out. Throughout the discussion inventory design issues are related to strata level inventories being carried out by the Mead Coated Board Division as part of our Timberlands Planning Model.

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2/ Senior Business Analyst, Mead Coated Board Division, 1200 Brookstone Centre, Columbus, GA 31904

INVENTORY OBJECTIVES

More often than not the first thing asked when considering an inventory is what to measure and how many plots to put in. Maybe this is due to our desire to get out in the woods as soon as possible and get the job done. Whatever the reasons, these should be the last questions asked and answered, not the first. The first question should be: Why and for whom are we doing this inventory? At Mead this is usually expressed by asking who our internal customers are and discussing their needs.

Figure 1 shows the main components of the Mead Timberlands Planning Model. The chief objective of our large-scale forest inventory is to give initial state conditions relating to the Fee and Long-term Contract lands in the model. For both company and non-company lands the model requires projections of stand and stock tables by species and product class. For company plantations, it is desirable to be able to project these yields for alternative planting densities, hardwood release, thinning, and clearcut management regimes.

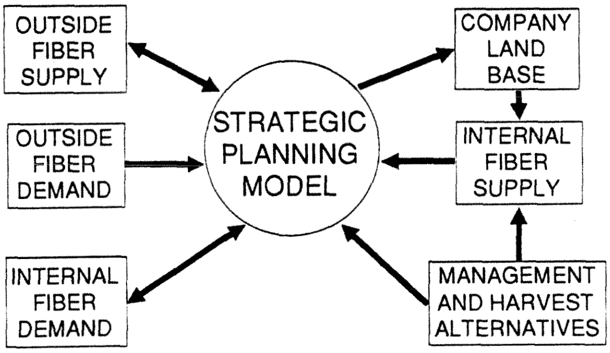

Figure 1. Timberlands Planning Model Information Components

As with most forest companies in the United States, fee lands provide a relatively small portion of our total fiber needs. Given the importance of fiber supply from non-company lands, it is reasonable to ask how much inventory and analysis time should be spent modeling supply from company-controlled lands. As we consider alternative strategic plans using the Timberlands Planning model, we hope to have some answers to that question.

In the meantime we decided to develop a Geographic Information System (GIS) for Fee and Leased lands. We also decided to carryout a Strata Level Inventory (SLI) to provide data for the Timberlands Planning Model. These decisions were based on the following working hypotheses:

(1) Company lands have larger strategic significance than their percentage of total fiber supply implies;

(2) Company lands represent a large continuing investment on the part of our stockholders. More detailed inventory information will help us manage these lands more efficiently.

Development of the GIS began in 1989 and is expected to be completed by the middle of 1991. The purpose of the GIS is to provide geographically based stand level information for making tactical and operational management and harvesting decisions. The system is based on identifying stands in each compartment which are of sufficient size to form manageable operating units. "Walk-thru" (Recon) inventories carried out during the stand mapping process are used to record approximate stand condition information, e.g. vegetation type, age class, site index, density.

Because it is desirable to have preliminary results from the Timberlands Planning Model prior to completing the GIS, the decision was made to conduct SLI in each of the three years that the GIS is being completed. Also, a secondary objective of the SLI is to have a statistically based method for evaluating the accuracy of the stand level Recon inventories. The examples and procedures discussed in this paper are primarily from the 1990 SLI.

INVENTORY DESIGN

Based on the SLI objectives outlined above, there are four sets of questions that should be considered prior to beginning field work:

(1) **Target Population -**
What part of the GIS database should be considered in the target population? Are there stands in the database in which the value of information is less than the inventory cost? Are there other, less expensive sources of information for projecting yields of stands in these planning strata?

(2) **Stand Attributes -**
What stand attributes should be measured to provide the projected yields for each management and harvesting alternative? What yield models will be used in the present and future Planning Models? What is the accuracy and precision of these models?

(3) **Stratification -**
What stand condition attributes from the GIS database should be used to form inventory strata? Should inventory strata and strategic planning strata be the same?

(4) **Sampling Design -** What sampling design should be used for the inventory as a whole? What criteria should be used to determine the sampling intensity in each individual stratum?

The questions are interrelated. Also, theoretically correct answers to some of these questions can only be obtained at a prohibitive cost. Nevertheless, the guiding principle for obtaining working answers is to focus on the original inventory objectives. In this respect inventory design for strategic planning is similar to any other inventory. In other respects strategic planning inventories differ:

(1) The mission is to maximize the value of information as it relates to current and future decisions. Therefore, the customer's prior expectations about the importance of certain inventory strata in the planning process play an important part in inventory design;

(2) The current stand and strata attributes are only of interest as they affect decisions resulting from the planning model's implementation.

(3) Inventory stratification is a necessity due to the wide range of stand conditions encountered and the need to make yield projections which are tied to individual planning units on the ground.

Target Population

For some stands in the GIS database the value of the additional information is less than the expected inventory cost. The obvious case is for clearcut stands which have not yet been regenerated. Stands recently regenerated may be another case. Final percent survival is still largely a function of unpredictable factors. At Mead the percent survival of young stands regenerated within the last three years is being monitored as part of a regeneration quality control program. No better information about survival can be gathered by including these stands in a SLI. The 1990 SLI target population was reduced about 25% by excluding clearcut and recently regenerated stands.

For the remaining stands, the Recon Inventory information contains some of the data required for yield projection. Future analysis of the accuracy of this information may indicate that other strata can be excluded from the SLI population. Alternatively, double sampling schemes which make the best use of both the Recon and Strata Level Inventories may be used in the future.

Stand Attributes

The stand attributes of interest are those initial conditions required by the various models to project product yields under alternative management and harvesting regimes. Suffice it to say that there are a wide variety of yield models available in both the public and private sectors. The attributes measured and the data processing methods chosen should be sufficiently flexible to be useful as inputs to current and future yield models. Below are the various types of yield models used to project results from the 1990 SLI:

STAND TYPE-AGE CLASS	PROJECTION TYPE	% ACRES
Planted Pine 1-14 yr.	Dbh Distr. Recovery	45%
Planted Pine 15+ yr.	Stand Projection	11%
Seeded Pine 15+ yr.	Individual Tree	7%
Natural Pine 15+ yr.	Individual Tree	12%
Natural Hdwd 15+ yr.	Individual Tree	25%

The yield model used to transform current stand attributes to future yields is as important as the initial attributes themselves. **Figure 2** gives an example of two direct-seeded strata which have almost identical initial attributes. A plantation yield model was used to project yields in one case and a natural stand, individual tree yield model was used in the other case. The plantation model gives higher total merchantable yields and lower sawtimber yields than. Subsequent analyses using remeasured plot data indicated that the individual tree growth model is more accurate for direct seeded stands. In either strategic or tactical planning models, differences of this magnitude may lead to different harvest timing decisions.

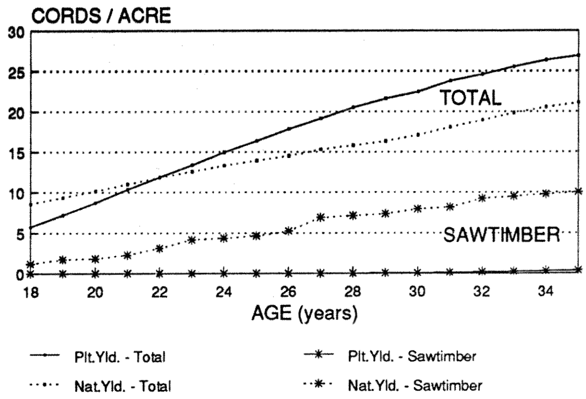

Figure 2. Yield Model Differences, Direct Seeded Pine Strata 11-15 Years of Age

Stratification

The main purpose of stratification is to identify homogeneous planning units with respect to their response to alternative management and harvesting regimes. Also, it is desirable to have strata which can be tied to individual tactical and operational planning units on the ground. Moreover, the method of strata identification should permit post-inventory stratification if inventory results show it to be desirable. In opposition to these goals, the cost of obtaining reasonable samping errors for each stratum will be high if the number of strata are higher than necessary.

Several classes of stand attributes from the Recon Inventory information were chosen as candidates to form SLI Strata:

STAND TYPE	ATTRIBUTES
PINE PLANTATIONS	LOBLOLLY; SLASH; SAND PINE SEEDED; PLANTED CUTOVER; OLD FIELD 3 SITE INDEX CLASSES 3 TREES/ACRE CLASSES 8 5-YEAR AGE CLASSES
NATURAL PINE / PINE HARDWOOD	LOBLOLLY/SHORTLEAF; LONGLEAF 3 SITE INDEX CLASSES 3 BASAL AREA CLASSES 3 AGE CLASSES
NATURAL HARDWOOD	UPLAND; COVE; BOTTOMLAND 4 PHYSIOGRAPHIC TYPES 3 BASAL AREA CLASSES 3 AGE CLASSES

The total possible number of strata formed using these attributes is 1026. This large number would prohibit obtaining accurate estimates of initial strata conditions at a reasonable cost. Fortunately, many attribute combinations do not exist in the field. For example, in the 1990 SLI target population, there were stands with only 115 different attribute combinations.

To reduce the number of strata further, a decision was made to lump attribute combinations having less than 400 acres with their "closest neighbor", if a neighbor could be found of the same stand and vegetation type. The rule used to identify the closest neighbor was to group stands with different density classes together prior to grouping stands with different site index classes. Likewise, stands with different site index classes were placed together prior to mixing age classes. This grouping procedure reduced the number of inventory strata in the 1990 SLI from 115 to 51 (**Table 1**).

Table 1. Reconnaisance Inventory Field Strata and SLI Strata

STAND TYPE	RECON STRATA		SLI YIELD STRATA		
	No. Str.	Min. Acres	No. Str.	Min. Acres	Max. Acre
PLANTED PINE	46	10	24	486	11,149
SEEDED PINE	7	6	4	633	4,164
NATURAL PINE	19	14	9	383	2,432
COVE/UPLAND HDWD.	25	3	6	639	1,254
BOTTOMLAND HDWD.	18	9	8	604	5,710

Sampling Design

Economic theory tells us we should continue to gather information until the increasing marginal cost of additional information is equal to the declining marginal benefit. Sampling theory provides us with various sampling designs for gathering this information in the most efficient manner for differing circumstances and target populations. Both disciplines provide useful starting points and working guidelines for practical application.

In a strategic planning model, the marginal value of inventory information about a stratum is the difference in the value of the objective function caused by a different set of decisions resulting from this information. The focus is on the decisions based on the model and their effect on the objective function. Since most inventories are carried out under budget constraints, the marginal cost of additional information about a stratum is composed of the direct sampling cost plus the opportunity cost of not taking additional samples from the stratum with the next highest marginal value of information.

Several design implications follow from the marginal cost and benefit rule. First, the theoretically correct marginal value of additional information can only be known by jointly considering the sensitivity of model results and the decision making process. Both are likely to be unknowns which to a large extent remain unknowable, at least in terms that can be placed in sampling design formulae. Secondly, information is likely to be more valuable for strata in which changes in initial stand conditions make a difference in decisions to be made prior to the next inventory cycle. Lastly, measured stand attributes will be more valuable if they are likely to affect both decisions and objective function values.

A challenge in developing a sampling design for the Strata Level Inventory was assigning a common measure of value or importance to the initial stand condition information about each stratum. Our desire was to assign an importance criterion consistent with the economic principles outlined above. In addition, it was necessary to relate this criterion to the wide variety of initial stand conditions and yield models used for the various strata. Currently, we have chosen expected present net value (PNV) of a stratum as the importance criterion. We will be better able to judge this choice as sensitivity analysis and decisions are made using the Timberlands Planning Model.

For merchantable strata, PNV was calculated by multiplying the Recon inventory volume estimates for each species and product class times the respective stumpage prices. Therefore, this technique assigns higher importance to information gathered about strata with greater acreages, higher volumes /acre, and higher value per unit volume. For example, strata with high total volumes of pine sawtimber were assigned a higher importance value than strata with the same total volume of hardwood pulpwood.

For strata past a standard harvest age, PNV was set equal to current value. For "merchantable" strata below the standard harvest age (e.g. 17 year-old pine), the expected future product volumes and values were discounted to the present. In both cases the expected variance in PNV was calculated as a function of the estimated variances in volumes by species and product class. 1989 SLI volume variances were used to estimate expected variances for designing the 1990 SLI.

The process was more indirect for younger strata in which there is little or no merchantable volume. For these strata, the expected PNV was calculated using the appropriate yield model and Recon Inventory estimates of site index and initial stocking. The expected variance in PNV was calculated in a two step process. The first step was to calculate how much the PNV changes with changes in stocking. This is illustrated in **Figure 3** for six pre-merchantable plantation strata with differing site index values and initial ages. In the second step the expected variance in stocking was calculated based on information from the 1989 SLI. The assumption made in both steps is that the site index estimate from the Recon inventory is correct with a variance of zero. While this assumption is clearly incorrect, there is little information we can gather in these young stands that would provide a better estimate of site index.

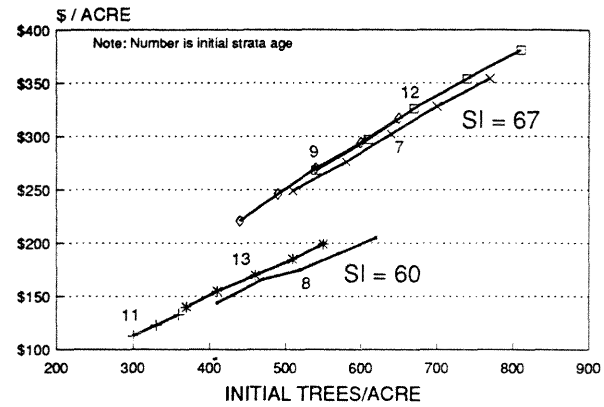

Figure 3. Present Net Value Index for Six Pre-merchantable Pine Strata

Assigning a common importance criterion to each stratum permits specifying a sampling design to minimize the cost of achieving a given sampling error of that criterion for all strata combined. We chose a stratified, random, cluster sampling design. (Freese 1962) In cluster sampling, a group ("cluster") of points is taken at each randomly located cluster location. The efficiency of cluster sampling is derived primarily from recognizing that travel costs to reach different sample points are high relative to the actual time spent measuring the points. Also, the variances between clusters and within clusters can be influenced by choosing different cluster sizes and shapes.

Information about relative costs and variances is used to determine the optimal (least cost) number of points to assign to each cluster. An important feature of the design is that the optimal number of points per cluster in a particular stratum is independent of the optimal (minimize overall sampling error at least cost) number of clusters to place in a stratum. The formula for optimal allocation of points to clusters is: (Freese 1962)

(1) $m = [\mathrm{Sqrt}(Vx_s)] / [\mathrm{Sqrt}\{Vx_p - (Vx_s / M)\} / \mathrm{Sqrt}\{C1 / C2\}]$

where:

m = optimal number of points per cluster

Vx_s = variance between points within clusters

Vx_p = variance between clusters

M = total possible number of points per cluster

C_p = sampling cost per cluster

C_s = sampling cost per point

The optimal number of clusters to place in each stratum is based on considering the relative costs and variances of sampling each stratum. The formula for this is the same as that associated with optimal allocation of any type of stratified random sampling: (Shaeffer et.al. 1986)

$$(2)\quad n_i = n*[N_i*Sqrt(Vx_i)/Sqrt(C_i] \;/\; [\text{Sum over } i\ \{[N_i*Sqrt(Vx_i)/Sqrt(C_i]\}]$$

where:

n_i = number of clusters to allocate to strata i

n = total number of clusters required

Vx_i = variance of strata i

C_i = sampling cost per cluster for strata i

N_i = total number of possible clusters in strata i

In addition to achieving an overall sampling error at minimum cost, we had two other concerns: (1) staying within our budget guidelines, and (2) having a minimum allowable error achieved in certain strata. The first concern relates to our use of summer interns for the SLI field work. Once intern budgets have been made, only a given amount of crew days is available to accomplish an SLI.

The second concern relates directly to the issues discussed earlier about the marginal value and cost of information for each yield projection and planning stratum. We have no quantitative method to determine the theoretically correct allowable error for a stratum. Therefore, minimum allowable errors for each stratum are usually assigned subjectively. To the extent that minimum allowable errors are assigned to each stratum separately, the optimal allocation described in **Equation (2)** is ignored. Therefore, we generally refrain from assigning a minimum allowable error to a stratum unless the second SLI objective of comparing the SLI values with the Recon values requires it.

A spreadsheet program was used to simulate the total inventory budget required to meet an overall allowable error target as well as minimum allowable error targets for each stratum where applicable. Sensitivity analysis can be used to determine the marginal cost of reducing the overall allowable error or the allowable error of a single stratum. A linear program formulation is also a feasible solution technique to this problem. It has the advantage of giving shadow price information for all strata with each solution.

RESULTS

Points per Cluster

In the 1990 SLI the optimal number of points per cluster ranged from two in natural pine strata to five in pre-merchantable pine plantations. These differences reflect the relatively low point sampling costs in pre-merchantable plantations. Sampling costs per point in merchantable strata are about three time greater than in pre-merchantable strata.

Clusters per Stratum

Figure 4 shows the percent distribution and number of clusters allocated in the 1989 SLI to strata of different types. The cluster allocation is compared to the distribution of acreages and values. In 1989 few strata were assigned minimum allowable errors. Therefore, the clusters were allocated based on the optimal allocation of Equation (2) and the budget constraint. It is apparent that relative to their acreage and overall value, few clusters are taken from pre-merchantable pine plantations. This is largely because of the relatively small change in PNV with a change in stocking. (See Figure 3.) This results in small expected variances in PNV using stocking as the only piece of information relating to PNV which can be gathered from these strata. The implication is that there is little information available from pre-merchantable stands that will make a difference in strategic planning decisions. Therefore, sampling intensity should be low.

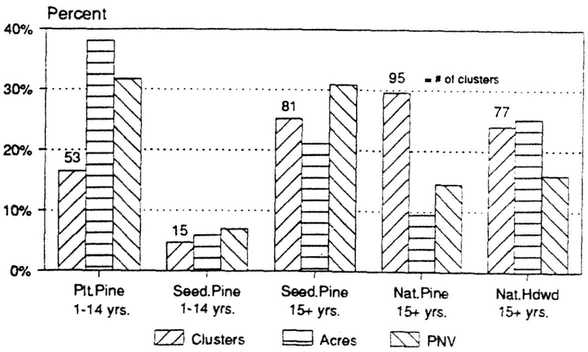

Figure 4. 1989 Strata Level Inventory Cluster Allocation by Strata Type

At the other extreme the percentage of clusters allocated to natural pine strata is three times the percentage of acres and more than two times the percentage of PNV. This is due to the relatively high variances in volume per acre and the higher values per unit volume than in other merchantable strata. Both cause higher expected variances in the total value per acre for natural pine strata. The relatively smaller number of clusters allocated to natural hardwood strata is caused by lower values per unit volume.

Figure 5 shows the cluster allocation results for the 1990 SLI. In this inventory more minimum allowable error assignments were made to individual strata, particularly the pre-merchantable strata. As expected, this resulted in significantly more clusters being assigned to pre-merchantable strata, enabling more precise comparisons between SLI and Recon Inventory data.

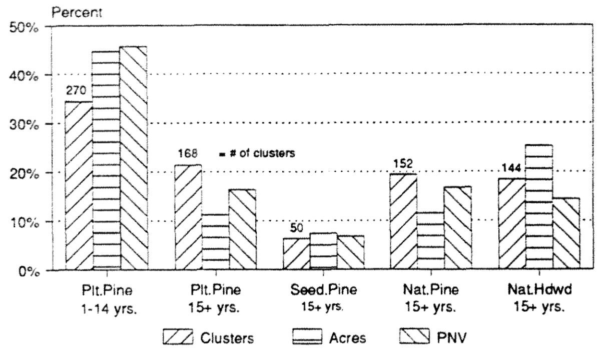

Figure 5. 1990 Strata Level Inventory Cluster Allocation by Strata Type

Efficiency of Strata Designtions

The efficiency of the SLI sample design is in large part determined by the accuracy of the Recon Inventory data used to identify homogeneous SLI strata. For the most part the Reconnaisance Inventory attribute values for each stratum were not significantly different from the values obtained in the Strata Level Inventory. The exceptions were the attributes related to stocking: trees/acre in plantations and basal area in natural stands.

For all strata combined there was no significant difference between the Recon and SLI estimates of trees per acre. However, there were significant differences for many individual strata. This can be attributed to the variation in stocking which exists within individual stands of a stratum and the difficulty of obtaining an accurate estimate of the average stand stocking using the Recon Inventory field procedures.

Recon Inventory estimates of total basal area per acre were significantly less than SLI estimates for all strata combined and for most stratum individually. However, the differences were due to underestimates of hardwood rather than pine basal area. We have observed the same tendency to underestimate hardwood basal area in tract level cruising.

One measure of the efficiency of strata designations is the extent to which the yield paths of strata differ. **Table 2** shows the percentage of 1990 SLI strata in each yield projection category whose maximum total mean annual increments differ by more than 0.05, 0.10, and 0.20 cords/acre/year. For example, forty percent of the natural pine strata differed from their closest neighbor by at least 0.05 cords per acre per year. Only twenty percent differed by more than 0.2 cord per acre per year. By this criteria strata differentiation was most efficient with the older pine plantation strata and least efficient with the hardwood strata.

Table 2. Post-inventory evaluation of 1990 SLI stratification efficiency.

Strata Category	Percent of Strata with MAI Difference from Nearest Neighbor Greater than:		
	0.05 (cords/acre/year)	0.1	0.2
Planted Pine 1-14 yr.	50%	31%	25%
Planted Pine 15+ yr.	67%	50%	33%
Seeded Pine 15+ yr.	50%	50%	50%
Natural Pine 15+ yr.	40%	30%	20%
Natural Hardwood	35%	30%	15%

The poor results with the hardwood strata are in part due to the inaccurate Recon Inventory basal area estimates. Another contributing factor appears to be the lack of correlation between the physiographic type attribute and total yield. This suggests that using that using the current yield model strata level inventories should place less emphasis on physiographic type as a stratification attribute.

CONCLUSIONS

The purpose of a strategic planning model is to give broad direction for decision-making. Inventory information is but one component of the information needed to implement a strategic model. However, inventory costs represent a relatively large portion of the total planning costs. Careful attention to inventory objectives, design, and implementation can help minimize inventory costs and maximize the value of information for strategic planning decisions.

Traditional sampling theory provides various sampling techniques and designs for minimizing inventory costs to achieve specific objectives. Additional research is needed to determine the marginal value of information for different planning strata based on their expected importance in strategic decisions arising from the planning model.

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TRANSACTION EVIDENCE APPRAISAL EQUATIONS: TESTS, DEVELOPMENTS, AND PROBLEMS[1/]

Michael J. Niccolucci and Ervin G. Schuster[2/]

Abstract.--At the 1985 Systems Analysis Symposium, James Merzenich discussed the multiple linear regression approach to transaction evidence appraisal then being developed by the Northern Region of the USDA Forest Service. This paper updates that work by incorporating and discussing the concepts of confusion of purpose, appraised value, accuracy comparisons, reflecting competition, transforming variables, interpreting coefficients, market changes, forest-specific equations, and sale design application.

Keywords: Stumpage appraisal, competition, transformations, responsiveness, interpreting coefficients.

INTRODUCTION

Studies dating to the 1960s documented the use and usefulness of transaction evidence prediction equations for appraisal of timber stumpage (Anderson 1961; Jackson and McQuillan 1979; Merzenich et al. 1982). During the 1985 Systems Analysis Symposium, Merzenich (1985) reported on the experience of applying experimental transaction evidence appraisal (TEA) equations to timber sales in the Northern Region of the USDA Forest Service. In November 1987 the Northern Region of the Forest Service formally replaced the residual value (RV) appraisal process with TEA equations.

Briefly, the equation approach to TEA is based on the multiple linear regression model, which we define in matrix notation:

$$Y = X\beta + \varepsilon,$$

where Y is an nx1 vector of observations, X is an nxp matrix of known constants to be used as explanatory variables, β is a px1 vector of unknown parameters to be estimated, and ε is an nx1 vector of random errors such that $E(ee')=\sigma^2 I_n$. The response variable Y is typically some measure of stumpage value, such as "high bid." The explanatory variables typically represent sale characteristics, such as yarding method and haul distance. Data typically come from records of actual timber sale transactions.

The last 3 years have provided the opportunity to implement the TEA system, identify problems, develop solutions, and again test the system. A great deal has been learned, and the purpose of this paper is to share this knowledge by building on and updating Merzenich's pervious work. Specifically, this paper addresses nine major TEA-related topics: (1) confusion of purpose, (2) appraised value, (3) accuracy comparisons, (4) reflecting competition, (5) transforming variables, (6) interpreting coefficients, (7) market changes, (8) forest-specific equations, and (9) sale design application.

CONFUSION OF PURPOSE

Development, implementation, and acceptance of TEA equations in the Northern Region has been characterized by relentless comparisons between TEA and RV. Some were legitimate, bonafide comparisons; others, however, reflected confusion more than comprehension (Schuster 1989). Principal among these confusions was the purpose of the appraisal and how that purpose related to the "operator of average efficiency" or to the importance of "bid premium."

Even today there remains considerable confusion as to the purpose of stumpage appraisal. Is it to predict fair market value, high bid (winning bid), or is it to establish a minimum acceptable price to start the timber auction (the advertised

1/ Presented at the 1991 Symposium on Systems Analysis in Forest Resources, Charleston, SC, March 3-7, 1991.

2/ Economist and Research Forester, respectively, Intermountain Research Station, Forest Service, U.S. Department of Agriculture, P.O. Box 8089, Missoula, MT 59807.

value, in Forest Service appraisal terminology. Proponents of TEA tend to argue that predicting the high bid is the purpose; proponents of RV tend to argue that Forest Service appraisals establish the minimum acceptable price.

Adding to the confusion, the Forest Service historically relied on the RV appraisal method based on costs, returns, and profit and risk margins which reflect average operator efficiency (USDA Forest Service 1977). Weiner (1982) traced the concept of the "average operator" to the first published timber appraisal manual in 1914, which discouraged reference to either the most or least efficient operator. Yet TEA systems are typically based on the winning or high bid, widely believed to apply to the most efficient operator, not the operator of average efficiency. Because the two appraisal processes have totally different orientations, the appraised values produced by the two processes are not, strictly speaking, comparable.

Nevertheless, the systems are commonly compared. In most cases, "bid premium"--the difference between the appraised value and high bid--is the standard used to compare appraisal systems. Some argue that bid premium, in effect, represents error, the amount the appraisal system missed the mark. (This seems perfectly reasonable if predicting high bid were the objective.) Others argue that in a competitive auction environment, the bid premium is simply a measure of the success of the auction rather than an indicator of an appraisal problem (Teeguarden 1987). (This seems reasonable if the objective was to start an auction with initial reference to the average operator.)

Although disagreements on the above points continue, they may matter little. The General Accounting Office has chosen to use bid premiums as a valid accuracy measure when reviewing appraisal systems in the Forest Service (U.S. GAO 1990). Moreover, the GAO recommended and Congress concurred that RV would generally be phased out within the Forest Service by October 1992. Specifically, current Forest Service appropriations state that cost collection will be discontinued as of October 1992, except in Region 10 and the Black Hills area of Region 2.

APPRAISED VALUE

The appraised value for the operator of average efficiency estimated by the RV appraisal process serves as a floor below which the timber offering is not sold. The competitive auction process, then, determined the market value of the timber. The TEA process is also used to establish the appraised value. But unlike RV with its operator of average efficiency orientation, TEA equations are based on the winning bid, the amount the most efficient operator would pay for timber. Setting the TEA appraised value equal to the predicted high bid would restrict 50 percent of all potential buyers from bidding for any particular sale (Buongiorno and Young 1984). Perhaps half of the timber offerings would go unsold. Clearly a process is needed to identify an appraised value and allow the competitive auction process to establish the market value of the timber[3/]

One of the approaches advanced to deal with this problem defines the appraised value (AV) as the predicted high bid (PHB) minus the standard error (se) times a t-statistic corresponding to a specified probability level:

$$AV = PHB - (se)*(t\text{-statistic})$$

The quantity subtracted from the high bid is called the "statistical adjustment factor." The AV is simply the lower bound of a two-tailed confidence interval for PHB. For example, at one standard error the population parameter (the true high bid value) would consist of a minimum value determined so in repeated sets of samples, each the same size, approximately 84 percent of all such minimum values calculated would be expected to contain the population parameter. (The confidence interval is based on the standard error of the estimate and a t-value only, without adjustment for sample size or individual variables (see Draper and Smith 1981, p. 210).)

To illustrate an application of the statistical adjustment factor, consider a timber sale from the Idaho Panhandle National Forest. The predicted high bid for this sale is $105.46 per M bd. ft. The statistical adjustment factor is 36.05 (based on one standard error and a t-value of 1.00 for an $\alpha = 0.17$ and $n = 748$). The appraised value is $69.41 (= 105.46 - 36.05). In this case, the actual high bid was $79.67.

Currently only the Northern Region uses a statistically-based adjustment to generate appraised values from TEA. Other Regions simply make a percentage adjustment to their predicted high bid. The Northern Region is receiving pressure to use the simple percentage approach for the sake of consistency and to reduce bid premiums. If reduction of the bid premium is a motivating factor, the confidence interval can be modified by adjusting the alpha level to accomplish that goal.

ACCURACY COMPARISONS

In the process of building alternative TEA equations or simply evaluating one appraisal method relative to another, analysts often want to make comparisons on the basis of accuracy in predicting high bid. At first blush this seems to be a simple task. On closer inspection, one

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[3/] Technically, the Forest Service establishes an "advertised rate"--a rate below which it will not sell the timber offering. The advertised rate is equal to the greater of: (1) the appraised value, or (2) the "base rate"--an amount of money sufficient to regenerate the stand and provide a minimal return to the U.S. Treasury (USDA Forest Service 1977).

encounters the problems of (1) comparability in predicted high bid, and (2) selecting the correct measure of accuracy. Schuster and Niccolucci (1990) encountered these problems when comparing the accuracy of six appraisal methods: one based on RV and the other five based on two TEA approaches.

The first problem encountered was that RV and any TEA-based method estimate different quantities. As discussed earlier, RV is intended to identify the stumpage value of the operator of average efficiency. Because TEA methods estimate high bid, the RV appraised value is not comparable to the winning high bid of the sale (Teeguarden 1987). In order to make the two appraisals comparable, either RV would have to be adjusted to predict high bid, or TEA would have to be adjusted to reflect the average operator. Because five of the six approaches studied were TEA-based, RV appraised values were more easily adjusted to predict high bid by adding an equation-based estimate of bid premium. The six appraisal methods studied were: [residual value plus bid premium (RV+BP)], four based on the equation approach to TEA [the mean, multiple regression model (MRA), multiple regression models using the number of bidders as an independent variable (MRA+B), and system of equations (SE)], and one based on the adjustment approach to TEA [adjusting averages (AA)].

The second problem encountered was selection of an appropriate measure of accuracy. Recognizing that choice of accuracy measure could affect comparisons, Schuster and Niccolucci (1990) compared the appraisal methods on the basis of four measures of accuracy. The first measure considered was the average deviation (AD). As a measure of accuracy, AD is seriously flawed because huge positive errors can offset huge negative errors so that the overall result equals zero error. Despite the flaw, AD was included because it is easily understood and widely used. The second measure of accuracy used was the average absolute deviation (AAD), calculated by averaging the absolute difference between the observed and predicted high bid. The average squared deviation (ASD) was the third accuracy measure, calculated by averaging the squared difference between the observed and predicted high bid. The final measure was the percent (%+-) of the estimated high bids within $10 (+ or -) of the actual high bid.

Utilizing information from more than 300 timber sales from National Forests in the Intermountain Region, Schuster and Niccolucci (1990) estimated high bids and measured the accuracy of these estimates. Study results summarizing the rank order of each appraisal method in terms of accuracy are shown in Table 1. After noting differences in appraisal accuracy as determined by the accuracy measure, they conclude that "the best way for other organizations in other locations to assess ... appraisal methods is by determining the objective of the appraisal, identifying test criteria, conducting comparison tests, and analyzing which performs best."

Table 1.--Ranking of Appraisal Methods by Accuracy Measures

Appraisal method	AD	AAD	ASD	%+-
RV+BP	1	1	1	1
MRA+B	5	2	2	2
MRA	6	2	2	3
SE	3	4	4	4
AA	2	5	6	5
MEAN	4	6	5	6

REFLECTING COMPETITION

Accounting for the number of bidders on a timber sale (as did Buongiorno and Young 1984) is important because the degree of competition for timber has a substantial effect on high bids (Haynes 1980). Oppositely, excluding the number of bidders from a TEA equation affects prediction accuracy and model specification (Schuster and Niccolucci 1990). But unlike other explanatory variables used in TEA equations, the actual number of bidders is not known until after the timber auction has started. This problem is known as "errors in variables" (Pindyck and Rubinfeld 1981). A common, but incorrect, solution uses the actual number of bidders as an explanatory variable and then uses an estimate of the number of bidders when implementing the equation. An approach was needed that correctly reflected the fact that the actual number of bidders is only known after the stumpage auction.

Problems associated with the number of bidders can be solved by treating it as an instrumental variable, and using two-stage least squares estimation (Pindyck and Rubinfeld 1981). The first step involves developing a "number of bidders" equation. For example, it could be hypothesized that the number of bidders is a function of sale and market characteristics. Sale and market characteristics include volume per acre, percent volume skyline yarded, uncut volume under contract and selling price, lumber tally. Once the first equation is developed, it is used to predict the number of bidders (the instrumental variable) for sales in the TEA database. Despite the fact that the actual number of bidders is known for each sale, the predicted number of bidders is used as an independent variable in the TEA equation. The success of this approach depends on the quality of the instrumental variable produced.

Schuster and Niccolucci (1990) used this approach and two random samples of timber sales from National Forests in the Intermountain Region of the Forest Service. The first sample provided model-building data, and the second sample provided model-testing data. The "number of bidders" equation explained approximately 32 percent of the variation in the number of bidders. The TEA equation using the number of bidders instrumental variable explained 47.1 percent of the variation in high bid. The TEA equation, without this variable, accounted for 46.6 percent of the variation in high bid.

The similarity in R^2 may be related to the area tested. The Intermountain Appraisal Zone of Region 4 is characterized as noncompetitive, with just under two bids per sale. On the other hand, the Southwest Idaho Appraisal Zone is competitive, with an average of three bids per sale. Thus, the aggregation of appraisal zones may mask the success of the number of bidders model.

TRANSFORMING VARIABLES

In the process of developing TEA equations, the analyst needs to evaluate resulting equations for the correct mathematical form. The mathematical form needs to be empirically derived because the exact form is not known.

In most cases, theory does not prescribe the precise mathematical form of a relationship. For example, economic theory specifies that demand curves are downward sloping and to the right; but it does not state if the demand curve will be linear, nonlinear, or what degree of nonlinearity (Koutsoyiannis 1977). This is also true for TEA equations. For example, high bid theoretically increases as tree size increases, indicating that the general slope of the line is positive; but the specific shape (logarithmic or polynomial) is not stated. The analyst must rely on actual data to guide the mathematical formulation.

In most cases, examination of scatterplots and residual plots provide information about the best mathematical form of the explanatory variables in the TEA equation. But plots are of limited value because: (1) they consider only one variable at a time, ignoring any underlying relationship that may exist among several explanatory variables; and (2) plots are very difficult to interpret when there are a large number of observations. Box and Tidwell (Weisberg 1980) have developed an approach for determining the appropriate power transformations.

The Box-Tidwell approach iteratively determines the power transformation needed for each explanatory variable. The overall objective is to choose the power transformations which minimize the residual sum of squares. The process begins by assuming the power transformation is equal to one. Then, by fitting an augmented linear model, an improved estimate of the power function is obtained. This process is repeated until a desired level of convergence is reached.

Schuster and Niccolucci (1990) applied the Box-Tidwell approach to TEA equations in the Intermountain Region of the USDA Forest Service. Of the approximately 10 statistically significant independent variables in the multiple regression equation developed, only the lumber price and diameter variables required transformations. The iterative Box-Tidwell procedure indicated that the squared power of the lumber price and cubed power of diameter were appropriate transformations. The residual sum of squares was minimized with the remaining variables in their linear form.

Transformations also affect interpretation of coefficients. The nonlinearity of lumber price and diameter leads to marginal interpretation of lumber price and diameter which are not simply a constant for all prices and diameter. This issue is receiving more attention in recent appraisal literature (Weirick and Ingram 1990; Brotman 1990).

INTERPRETING COEFFICIENTS

Transaction evidence appraisal equations were first developed in the Northern Region with the exclusive objective to estimate or predict high bid. After initial development, however, managers in the Northern Region began to interpret the predictive model regression coefficients and draw managerial conclusions.

A common practice is to interpret a regression coefficient as representing the change in the high bid value caused by a one-unit increase in the corresponding explanatory variable, all other explanatory variables held constant. This is equivalent to taking a partial derivative of an equation with respect to a specific explanatory variable and interpreting it. There are several problems associated with this procedure: (1) a cause-and-effect relationship is not inherent in regression analysis using observational data; and (2) interpretation of the regression coefficients must take into account other explanatory variables in and not in the model. Because TEA equations use observational data, the lack of a conclusive cause-and-effect relationship will always be a problem; but accounting for other explanatory variables can be accomplished with analysis for collinearity and mathematical form. Collinearity exists when explanatory variables are correlated. Although estimates of regression coefficients remain statistically unbiased (Koutsoyiannis 1977), coefficients are often nonsignificant and/or very erratic. More important, individual coefficients may be totally erroneous!

We have found two major types of misinterpretations. The first involves inferring coefficients to variables not in the final model. For example, assume the total haul distance from sale to the appraisal point is found nonsignificant and excluded from the predictive model. An incorrect interpretation from this model is that total haul miles does not affect high bid; in other words, the regression coefficient is zero. The second problem involves interpreting coefficients for variables in the final model. Suppose both average log diameter and average log volume were included in the final model (as totally improbable as that seems). Clearly the coefficient on one depends on the presence of the other. To interpret the coefficient on one as if it were independent of the other is a serious mistake. The problems associated with interpreting regression coefficients can be overcome quickly: simply stop interpretation. Short of that, we recommend that all TEA equations be subjected to thorough examination with modern regression diagnostic techniques (Belsley and others 1980). At a minimum, an analysis of collinearity among regression variables should always be conducted. The collinearity analysis will not prevent misinterpretation, but it will make those possibilities more obvious.

MARKET CHANGES

In past TEA equation research, the length of the database period was not uniform (see Buongiorno and Young 1984; Merzenich 1985; Schuster and Niccolucci 1990), nor was there concern over database length. The principal factors influencing database length were: (1) having a database large enough (and hence long enough in duration) to estimate quality equations--high R^2s and low standard errors; and (2) having a database long enough to distinguish true structural changes from random occurrences. Combined, these factors generally suggest the longer the database the better. Performance of resulting TEA equations was satisfactory until stumpage markets became volatile. The long-length database that once provided stability to TEA equations inhibited flexibility and adaptation to changing market conditions. Divergence between predicted high bids and actual high bids began to increase. Recently, the General Accounting Office criticized the Northern Region for its large bid premiums (U.S. GAO 1990). Given this criticism, there was a need to know how to restructure TEA databases so that resulting equations better reflect and react to changing market conditions.

Two approaches were evaluated. The first approach simply modified the database length to make it as short as possible and still consist of ample information to produce an equation which reflects the true structural components of the stumpage market. This approach is easily understood and implemented. The approach, however, does not work well for areas offering a limited number of timber sales. In those areas, it may require many years to obtain enough sale data to estimate a TEA equation. In this case, the equation cannot be responsive to current market conditions because it necessarily consists of a large proportion of "old market information."

The second approach is referred to as weighted regression (see Draper and Smith 1981; Thomopoulos 1980). In our work, the "age" of the timber sale is used to develop the weights. Once weights are developed, they are introduced into the ordinary least squares regression process to obtain coefficient estimates. For example, the most recent timber sales (market information) are considered more important and, hence, are given larger weights. The weighting approach produces a TEA appraisal equation which reflects the most recent market information. A common weighting scheme used in this analysis uses the reciprocal transformation (1/age). For example, in a 2-year database consisting of quarterly data, timber sales in the most recent quarter are assigned a weight equal to one (age = 1) and timber sales in the oldest quarter are assigned a weight equal to 0.125 (age = 8). The most recent quarter is considered to be eight times more important than the oldest quarter.

We tested effects of database length and weights. Two and three-year databases consisting of timber sales from the Northern Region of the USDA Forest Service sold between April 1987 and March 1990 provided the model-building data. (The model-building data period consisted of rapidly increasing nominal high bids.) The subsequent 6-month period (April to September 1990) provided the model-testing data and was used to validate prediction accuracy. Four weighting schemes were developed. The first simply weighted all sales equally, regardless of their age. The three remaining weighting schemes used the weighting function defined earlier (1/age) and simply altered the database into semiannual, quarterly, or monthly configurations. The different database configurations provide a spectrum of weighting options without having to define different weighting functions. The average predicted high bids compared to the average actual high bids were used as the indicator of prediction quality. The actual and predicted high bids for the model-testing data are presented in Table 2.

Table 2.--Actual and predicted high bid values

		Weight			
Database length	Actual	Equal	Semiannual	Quarterly	Monthly
			$ per M bd. ft.		
2-year		130.75	141.94	143.62	148.34
3-year		130.14	141.18	146.70	152.93
	166.70				

The results indicate that the predicted high bid values produced by the monthly configured weighted regression models more closely related to the actual high bid of $166.70 per M bd. ft. In comparison, the equally weighted regression models, on the average, underpredicted by $36 per M bd. ft. The general indication is that weighting schemes placing more emphasis on the most recent timber sales produce predicted high bid values which are more closely related to the actual high bid. Two and three database lengths did not provide much improvement. This suggests that changing the database length did not provide any additional prediction accuracy.

FOREST-SPECIFIC EQUATIONS

Early on, TEA equations were developed for and pertained to the aggregrate of all National Forests in the Northern Region. But there has always been pressure to reflect each Forest's uniqueness with its own TEA equation. There is nothing conceptually wrong with forest-specific equations. Some Forests, however, have too few sales on which to build a TEA equation. Moreover, because TEA equations are updated every 6 months (equations are reestimated to reflect new timber sales in the database), developing an equation for each National Forest would be very time consuming, cause interpretation difficulties, and frustrate comparisons between forests. The first response was to group National Forests into appraisal zones ("westside" and "eastside" for the Northern Region), and estimate separate equations for the entire zone. This was statistically acceptable and an improvement, but the equations were still judged too aggregated. A technique was needed which permits the simultaneous estimation of forest-specific TEA equations.

The indicator variable (dummy variable) approach was adopted (Pindyck and Rubinfeld 1981). This approach uses all data in the estimation process and, hence, produces statistically more powerful results. The technique is based on developing variables (indicators) which represent individual National Forests. Rules for creating indicator variables require there be one less indicator than the number of categories being identified; the category not identified by an indicator is actually identified by the absence of indicators for the other categories. For example, because the westside appraisal zone of the Northern Region consists of seven National Forests, six indicator variables are needed. The indicator for a given Forest takes on the value of one (1) when the timber sale occurs in that Forest, zero (0) otherwise. For example, if the timber sale occurs on the Lolo National Forest, the indicator variable representing that Forest is set to one and all other indicator variables are set to zero.

The approach can be illustrated by a bivariate model with two forests. A bivariate TEA equation with one indicator variable (representing the two forests) is,

$$\text{HIGH BID} = B_0 + B_1{*}\text{SPLT} + B_2{*}\text{LOLO} + e_i$$

where LOLO is the indicator variable name. If the timber sale to be appraised occurs on the Lolo National Forest (LOLO = 1), then the model is,

$$\text{HIGH BID} = (B_0 + B_2) + B_1{*}\text{SPLT} + e_i.$$

If the timber sale to be appraised occurs on the other forest, then the model is,

$$\text{HIGH BID} = B_0 + B_1{*}\text{SPLT} + e_i.$$

Figure 1 shows that an indicator variable adds to the constant term in the TEA equation. This

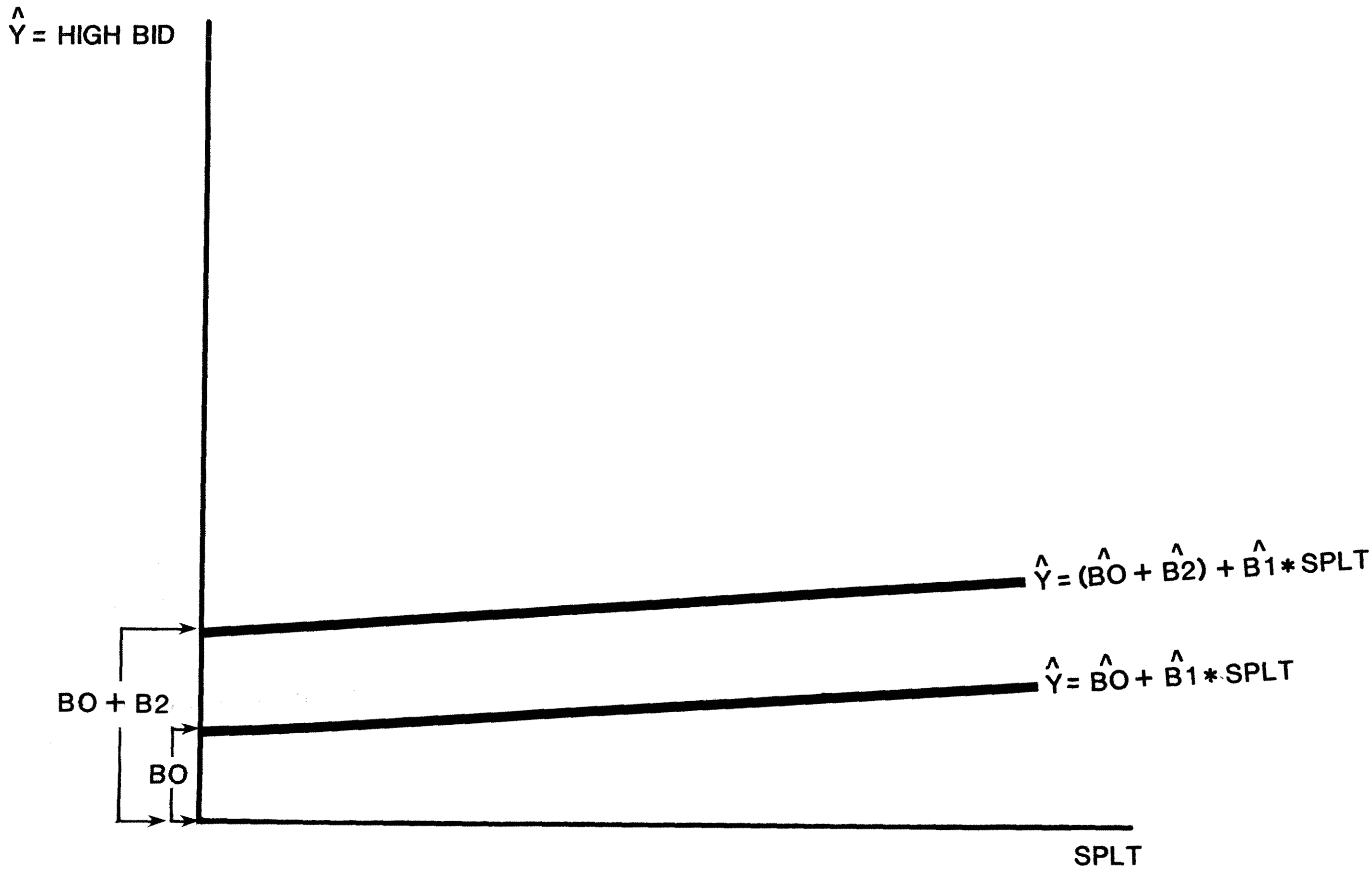

Figure 1.--Bivariate regression equation with indicator variable.

results in an upward or downward shift in the regression line, depending on the sign of the indicator variable coefficient.

Interaction terms can also be introduced, thereby allowing the slope coefficient (B_1) to vary by forest. Interaction terms are simply the indicator variable multiplied by all other variables in the model. The model which includes the interaction term is,

$$HIGH\ BID = B_0 + B_1*SPLT + B_2*LOLO + B_3*(SPLT*LOLO) + e_i.$$

The regression slope coefficient and intercept for the LOLO is ($B_1 + B_3$) and ($B_0 + B_2$), respectively. The regression slope coefficient and intercept for the other forest is simply B_1 and B_0, respectively. A word of caution is necessary at this point: as the number of independent variable increases, the number of possible interaction terms also increases. It is best to limit the interaction terms based on *a priori* considerations. To avoid collinearity, it is advisable to transform all independent variables to deviations from the mean (Neter and others 1990).

SALE DESIGN APPLICATION

Not surprisingly, TEA equations appear to some as a tempting tool for use in timber sale planning and design. In fact, TEA equations have been incorporated into timber sale planning software to estimate cutting unit high bid values used to derive financial feasibility or desirability measures (see USDA Forest Service 1990).

But problems arise when the TEA equation is used to predict the high bid for individual cutting units in the proposed sale. The problem arises because the TEA equation is being applied to a situation that is mismatched relative to the data on which it was based. Recall that TEA equations are developed from sale-level measurements. Using TEA equations at the cutting unit level extrapolates the equation well beyond the range of its original data. This extrapolation produces a coefficient bias which is reflected in the predicted values.

The problem is particularly acute for sale-level variables which are not meaningful if quantified at the cutting unit level. Consider the variable "total volume harvested." Sale-level data used in the process of equation building may range, for example, from 750 to 10,000 M bd. ft. The resulting coefficient has no meaning when applied to a cutting unit with a 200 M bd. ft. harvest level. This problem can be overcome by deriving a sale-level measurement for this variable, based on data for the cutting unit. For example, suppose the sale in question has 50 cutting units. In this case, enter 10,000 M bd. ft. for the total volume harvested, which effectively assumes all 50 cutting units are harvested at 200 M bd. ft., the harvest level for the cutting unit in question.

DISCUSSION

The decade of the 1980s witnessed the initiation and maturation of TEA equations for stumpage appraisal in the Northern Region. During the first half of the decade, the atmosphere was quite experimental and tentative. Folks knew little about TEA equations, both in terms of how to build them and how they would function. By the end of the decade, the technology of TEA equations had been developed to a high level of sophistication. But in addition to the wide range of statistical improvements made to TEA equations came an increased awareness of the limitations of TEA equations, both in term of technical issues such as intrepretation of coefficients and in terms of professional acceptance, both in and out of the Forest Service. Given our sense of the future, we think the 1990s will probably be characterized by a sharper focus on the problems of better understanding and increasing the acceptance of TEA equations as an appraisal technique.

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ECONOMIC ANALYSIS OF STATE PARK RECREATION USING THE IMPLAN MODEL[1]

Charles H. Strauss and Bruce E. Lord[2]

Abstract.--The economic effects resulting from the use and operation of Pennsylvania's state park system were analyzed with an input-output model of the state's economy. Direct expenditures by park users and park operations were estimated at $263 million for the 1987 study year. Secondary effects, stemming from inter-industry trade and recreation-related employment, provided an additional $299 million in total sales. Employment attributed to direct and secondary effects amounted to 10,880 full-time jobs.

Keywords: Economic effects, input/output, public recreation.

INTRODUCTION

The current attention placed upon travel and tourism as a source of economic development parallels the increasing importance of service industries within the U. S. economy. Our nation's dependence on educational, financial, health-care, housing, and recreational services was underscored during the 1986-1989 period, when over half of the gross national product was attributed to the consumption of these services (U.S. Bureau of Economic Analysis 1989).

Documenting the total value of recreation-related expenditures is a difficult assignment. Existing measures of output from such sectors as lodging and food services do not differentiate recreation- from business-related trade. Similar problems arise when attempting to measure recreation-related expenditures within the transportation, retail, and manufacturing sectors.

Improved estimates of recreational expenditures have been obtained from studies addressing the actual consumption patterns of particular user groups (Mittleider and Leitch 1984, Donnelly and Nelson 1986). These investigations have typically involved direct survey methods to identify the expenditure and demographic characteristics of various user groups. As a further extension of this work, recreational expenditures have been entered into regional input-output models to determine the subsequent value of inter-industry trade generated by the initial expenditures and the added household consumption originating from recreation-supported employment (Alward and Lofting 1985, Fritschen 1989).

In an effort to measure the financial effects of state park recreation within Pennsylvania's economy, a cooperative research effort was initiated between the Pennsylvania Department of Environmental Resources and Penn State's School of Forest Resources. Two basic objectives were involved: (1) to determine the expenditure and demographic characteristics of state park users and (2) to evaluate the total economic effects of park-related expenditures within the state's economy. An earlier paper presented the details of the survey methodology and the expenditure profiles of state park users (Strauss and Lord 1990). The following paper focuses on the demographics of park users and the total economic effects of park-related expenditures within the state.

THE STATE PARK SETTING

Pennsylvania's state park system includes 114 parks and is distributed uniformly throughout the Commonwealth. The size and distribution are credited to the early history of state park development, coupled with a general state mandate to provide increased public access to recreational areas (Forrey 1984). Over the past three decades, a combination of state and federal funds was used

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[2]Professor, Forest Economics and Research Assistant, respectively, School of Forest Resources, The Pennsylvania State University, University Park, PA, 16802.

to more than double the size of the state park system.

Operational costs have also increased, with $36 million required in 1987 to operate and maintain the system. Renovation of many of the older parks, coupled with the first cycle of major maintenance in the relatively newer parks has placed an increased cost burden on the overall system.

State parks also serve an economic purpose within their immediate regions through the employ of local resources and the generation of expenditures by park users. This particular attribute of state parks is poorly defined and has received little attention in the past. In an effort to correct this oversight and to identify the financial role of state parks within Pennsylvania's economy, the following project was established with Penn State's School of Forest Resources.

PROCEDURES

The initial stage of research was directed to obtaining information on the expenditures and demographics of park users. A controlled sampling design was used in conducting over 7000 visitor interviews at 30 state parks during the 1985, 1986, and 1987 summer seasons. Park audiences were stratified on the basis of six major activities: camping, picnicking, swimming, fishing, boating, and hiking. Typically, these activities attract over 80 percent of annual park attendance on a statewide basis. Details on the study procedures and expenditures patterns of various activity groups were previously reported (Strauss and Lord 1990). The second stage of work, initiated in 1989, analyzed the economic effects of park-related expenditures within Pennsylvania for the 1987 study year.

The economic effect of park user and agency expenditures was analyzed with a computerized, input-output model of the state's economy. The Pennsylvania model was generated from the Impact Analysis for Planning (IMPLAN) System, organized by the USDA Forest Service for the national economy (USDA Forest Service 1985). The Pennsylvania IMPLAN model identified the network of trade relationships between business, government, and household sectors. More than 500 individual sectors are described in terms of production, employment, and the related exchange of goods and services between the sectors. IMPLAN also enumerates the economic functions necessary for balancing production, consumption, and the import and export of goods and services during a given period. On the downside, the model is dependent on 1982 data, with many of the state's production and trade relationships based on national averages for the same period.

In using the IMPLAN model, user and state expenditures were deflated to 1982-equivalent values and entered as direct payments to the primary sectors receiving this money. Since the park system largely serves a resident population and with Pennsylvania representing a major-sized geographic region, the analysis of economic impacts, or effects, was not limited to the inflow of nonresident expenditures. Rather, the analysis used all in-state expenditures from the total park audience and the agency itself to estimate the secondary effects of the direct expenditures.

Operation of the model identified the subsequent cycles of secondary effects resulting from these payments. Secondary effects included the indirect business trade from sectors providing inputs to the primary sectors and the subsequent chain of inter-industry trade generated by this process. Additional secondary effects were identified in terms of the consumer expenditures induced by the salaries and wages earned from the direct and indirect business activities. All secondary effects were inflated back to 1987-equivalent values.

RESULTS

Demographics of State Parks Users.

State park users were characteristically young, family-oriented people with moderate-level incomes. Their average age was 32 years. Fifty-five percent were male and 45 percent female, with nearly 60 percent of the park usage identified with family groups. Average annual family income approached $28,000.

Age distributions indicated that nearly one-fourth of the park users were under 15 years old (Figure 1). Another 9 percent were

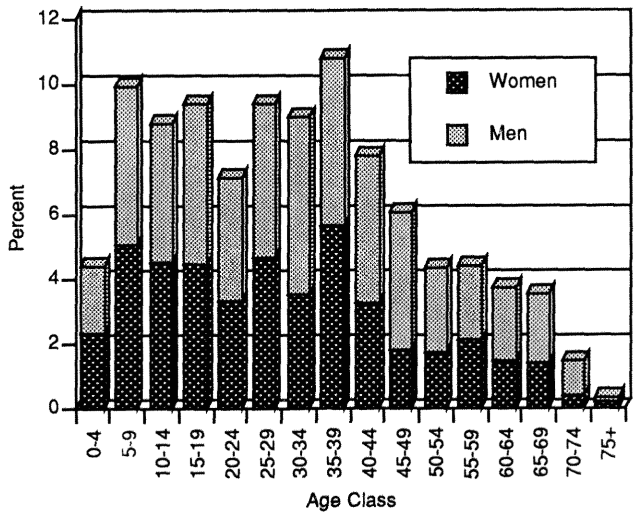

Figure 1. Distribution of State Park Users by Age and Gender.

teenagers in the 15- to-19-year class. Persons 20 to 39 years of age represented over one-third of the total audience. Middle-aged persons, 40 to 59 years of age, represented 22 percent of park usage, with persons over 60 years involved in 9 percent of the usage.

Park usage was greatest among low-to moderate-income families, with 65 percent of the attendance identified with individuals having annual family incomes under $30,000 (Figure 2). Twenty-six percent of the park users were in the family-income brackets of $30,000 to $50,000 per year.

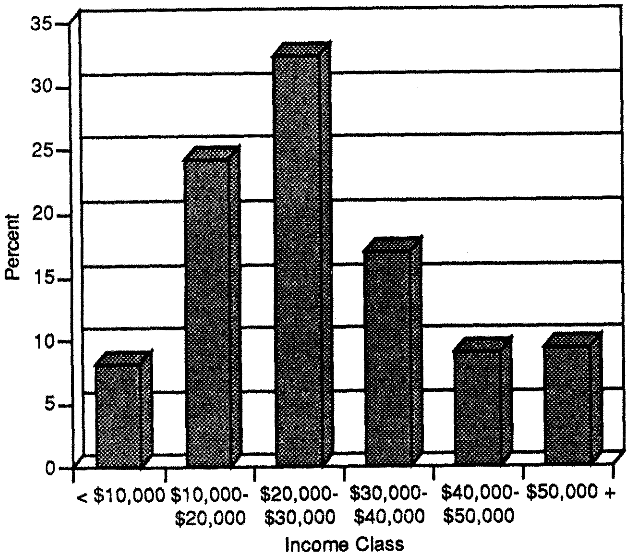

Figure 2. Distribution of Respondents by Family Income.

Forty percent of those interviewed had post-high school educations, with another 56 percent having high school or technical school degrees. Paralleling these results, 35 percent of the respondents were employed in blue collar occupations, with nearly the same percentage employed in white collar jobs. Fifteen percent of those interviewed were retired.

Day-use activities provided the major recreational focus at state parks during 1987. In total, day-use activities accounted for 95 percent of annual attendance, with picnicking, swimming, and hiking representing the more popular recreational pursuits (Strauss and Lord 1990).

Most park users lived near the parks where they were interviewed. One-fourth of the users were within a 20-minute drive of the park and over three-quarters were within 40 minutes of the park. Twenty percent of the audience traveled over an hour to reach their park destinations.

User Expenditures

Activity costs included the specific charges for activity-related items and the prorated costs of equipment and such general expenses as food, lodging, and travel. Equipment costs represented the major recreational items purchased over the past year and used at a state park location. These expenditures were proportioned specific to state park usage and averaged among all park users. General recreational expenses were also prorated in terms of the time spent in state parks and in particular activities. Costs were identified on an activity day basis, representing an individual's cost of pursuing a given activity over some portion of a day's visit.

The six activities fell into two cost ranges (Figure 3). Swimming, hiking, picnicking, and fishing were in a moderate cost range, averaging $5 to $9 per activity day. Over 85 percent of these expenditures were directed to general and activity-related items, with less than 15 percent involved in equipment. Camping and boating were more expensive, averaging $20 and $26, respectively, per activity day. Most of this increase was for equipment costs.

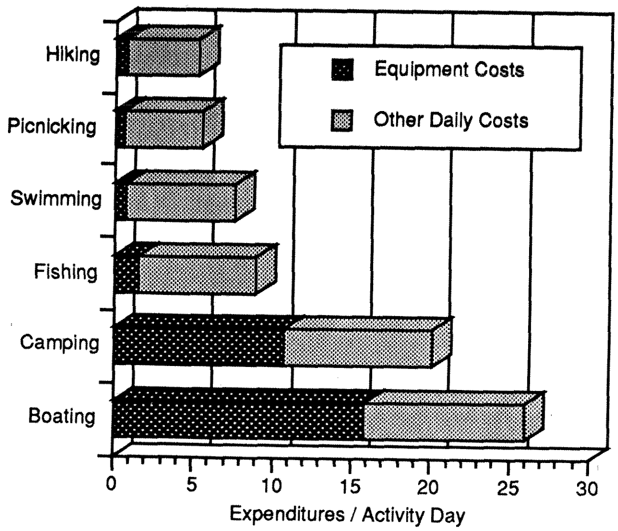

Figure 3. Expenditures per Activity Day by Activity.

Total Expenditures

Total user expenditures were developed by multiplying the average activity costs by respective annual attendances and summing over all parks and all activities. Expenditures for non-surveyed activities were estimated from auxiliary studies. Total user expenditures for the 1987 calendar year were estimated at $250 million.

Food and food-related services were the largest cost item, amounting to 32 percent of total user expenditures. Equipment purchases nearly matched food costs, for another 32 percent of the total. Transportation costs, measured on the basis of fuel purchases and minor vehicle repairs, accounted for 14 percent of the total. Activity-related items, involving expendable recreational supplies and fuel for boating and fishing, constituted another 9 percent of the total. Lodging and incidental trip costs were the final 13 percent of expenditures.

The cost of operating, maintaining, and developing state parks during 1987 was obtained from Department of Environmental Resources records. Total expenditures from all sources amounted to $36 million, with 95 percent used in the operation and maintenance of existing park facilities and the remainder directed to the construction of new facilities. On the basis of key inputs, 65 percent of the expenditures went to the employ of state personnel, 19 percent to contract services, and 16 percent for park supplies and utilities.

Economic Effects to Pennsylvania

The economic effect of state park recreation within Pennsylvania, as determined from IMPLAN model analysis, was $562 million in total sales. This included in-state expenditures of $263 million from park users and park operations and secondary demands of $299 million from inter-industry trade and recreation-based employment (Table 1). In-state expenditures by park users were $241 million, and for park operations, $22 million.

Principal sectors receiving the $263 million in direct expenditures were manufacturing (41 percent), service industries (27 percent), and wholesale and retail trades (21 percent) (Table 1). Most of the manufacturing sales was tied to recreational equipment and apparel, food products, and transportation fuels. Service industries benefited from the trade realized in food services, lodging, and associated recreational services (e.g. photo processing). The wholesale and retail sector participated in the direct expenditures process on the basis of retail food and recreational product sales.

As a result of the direct expenditures, secondary effects were generated through inter-industry trade and employment-based demands in the amount of $299 million. The major sectors participating in these secondary effects were manufacturing (25 percent of secondary sales); finance, insurance, and real estate (24 percent); and service industries (24 percent) (Table 1). Manufacturing again played a prominent role on the basis of the goods sold to other production sectors and to the household sector. Finance, insurance, and real estate participated in the secondary process on the basis of banking services and real estate sales to the household and business sectors. Secondary demands within the service sector included health care, food services, and other domestic services.

The $562 million in total sales showed a value added to production of $262 million (Table 1). Value added represented the amount of total sales directed to wages and salaries, interest payments, taxes, depreciation, and profit. Sectors with a high ratio of value

Table 1. Economic Effects of Recreation in Pennsylvania State Parks.

Industrial Sectors	Direct Sales	Secondary Sales	Total Sales	Value Added	Employee Income	Employment
	($1,000's)					(jobs)
Agriculture, Forestry and Fisheries	2,455	13,195	15,650	4,428	1,450	223
Mining	7	505	512	294	102	3
Construction	1,947	10,956	12,902	5,844	5,263	175
Manufacturing	107,966	75,274	183,240	47,575	38,547	1,693
Transportation, Communications, and Utilities	6,854	28,960	35,814	13,572	8,095	256
Wholesale and Retail Trade	54,177	19,785	73,962	52,903	33,740	3,634
Finance, Insurance, and Real Estate	3,869	72,898	76,767	54,779	11,229	487
Services	71,858	71,787	143,645	74,734	50,233	3,220
Government Enterprises	13,774	5,106	18,880	8,049	5,466	282
Special Industries	22	292	314	314	314	25
Total	262,929	298,758	561,686	262,492	154,439	9,998

added to total sales were typically labor-intensive and service-oriented industries. These included wholesale and retail trades, the finance, insurance and real estate group, and the service industries.

Two social measures of this economic process were the employment income and the number of jobs originating from total sales. Nearly 27 percent of total sales was directed to employment income, amounting to $154 million (Table 1). In turn, almost 10,000 jobs were credited to this recreation-based demand. Sectors having the highest levels of employee income and jobs were the service industries, manufacturing, and wholesale and retail trades. Further employment was also credited to the Bureau of State Parks in terms of 640 full-time positions and 950 seasonal jobs, representing an annual equivalent of nearly 880 positions within the agency.

DISCUSSION

Although outdoor recreation is often characterized as supporting a cyclical and largely service-oriented industry, the IMPLAN analysis of park-related expenditures showed a broader economic involvement with a composite of industrial sectors. Nearly 41 percent of the direct expenditures went to the manufacturing sector, with 27 percent channeled to the service industries sector and another 21 percent to wholesale and retail trades. Secondary economic effects of these direct expenditures showed a further involvement with the manufacturing, financial, and service sectors.

Overall, the state park system created a wide array of economic effects on a sector-by-sector basis and, in all probability, represented an economic process not confined to any particular season. Results from this study suggest that the business process may require a substantial lead time in preparing for this recreational market and may also create certain lagged effects in terms of secondary expenditures. For example, although 76 percent of the direct expenditures were identified with the "summer recreational season", nearly 30 percent of this amount was for equipment purchased over the previous year. In addition, food products, recreational equipment, and apparel would require a certain lead time in their manufacture and distribution. Finally, the secondary effects realized by other supporting industries and from induced consumer demands would involve a continuing span of time.

SUMMARY

Implications to Park Management

State park users are largely a family-oriented audience, having moderate-level incomes, and living within close proximity of state parks. Most of their recreational expenditures were tied to food and food services, recreational equipment, and transportation. In turn, these monies were channeled into the manufacturing industries, the service sector and the wholesale and retail trades. All told, expenditures tied to the use and operation of state parks resulted in total economic effects of $562 million within the state. Total industrial employment attributed to park expenditures represented 10,000 industrial jobs and an additional 880 positions within the Bureau of State Parks.

These economic results can be largely credited to the state-wide system of 114 parks, with the operation and maintenance of the system representing a certain catalyst to the overall process. During 1987, the $36 million in park operations led to a fifteen-fold increase in economic activity throughout the state.

Pennsylvania's park system is an established recreational entity that provides three basic types of benefits to our society. First, they meet the recreational needs of the public in terms of a diverse set of activities and park locations. Second, they represent ecological reserves that contribute to the maintenance of a healthy environment. Third, they support a substantial volume of economic activity. The challenge presented to park management is sustaining this unique set of natural resources for future generations while continuing to meet the public need for recreational opportunities. As an ancillary feature of this system, the public's pursuit of outdoor recreation will continue to contribute to our state's economy.

ACKNOWLEDGEMENT

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ECOLOGICAL ECONOMICS: CAN WE APPLY ITS ETHOS TO FOREST RESEARCH AND PRACTICE? [1/]

Dennis P. Bradley and Bernard J. Lewis [2/]

Abstract.--Ecology and economics, through a synthesis based on their common ground, may better contribute to solving major social and environmental problems. Major changes in world-views may also be required. The implications of an Ecological Economics for a more realistic and responsible forest science are also discussed.

Keywords: Aesthetics, chaos, ideology, morals, rationality, reductionism, thermodynamics

INTRODUCTION

As forest resource professionals we are expected to determine how forests actually work, and upon developing this knowledge, to interpret what it means for society. These responsibilities are indeed great, and our ability to at least approach the truth in these matters is what defines our status as professionals. For upon the information we provide rest immense and compelling expectations for the sustainable flow of materials, services, and amenities. At the same time, these expectations are often couched in ideologies based on such essential notions as human development, growth, or progress. This paper questions both the material and ideological expectations upon which forestry and other natural resource disciplines rest, and suggests how our concepts of development, as currently envisioned by the West, may have to be redefined. In addition, we suggest the possibility of integrating concepts from ecology and economics in ways that may place the profession of forestry and its role in society on more solid ground.

At the 19th IUFRO World Congress in Montreal, a new Project Group entitled Ecological Economics was formed as part of a reorganized Division 6: Social, Economic, Information and Policy Sciences. But what is ecological economics and why should foresters be interested? While ecological economics may not yet be a discipline--more a framework--it is based on very old ideas (Martinez-Alier 1987) and may provide an ethos or moral spirit for a forest science urgently in need of more realistic approaches to balancing human needs with forest ecosystem capabilities. As illustrated by its new international society and journal, ecological economics is a movement to develop an interdisciplinary science that recognizes the deep and inseparable connection between healthy ecosystem functioning and society's attempts to meet its continuing needs. Its primary stimulus is a growing sense that local, regional, and global environments are under great, even catastrophic stress as a result of steadily increasing urban, agricultural, and industrial activity. It is precisely these activities--the linkages between economic activity and ecological impact--that forms the common ground which ecological economics seeks to elaborate. Such a linkage could have important implications for forestry.

Ecological economics suggests that the current modern ideal--capitalist as well as socialist--of unrestrained economic growth, reflected in the pursuit of ever greater per capita consumption of goods and services, is in actuality impossible to attain. For although food and many other materials are indispensable, many question whether the intensity and scale of modern technology--primarily employed by Western societies in their own regions and others, largely for their own benefit, and often for trivial purposes--is actually dissipating the very ecosystems and resources upon which all of us must depend. A growing number of economists, ecologists and others believe that many of these difficulties, and the ideologies that led to them, can be traced in part to a long standing isolation between these key disciplines, as well as an inappropriate reductionist perspective, particularly by economics. Paraphrasing Georgescu-Roegen (1971), reality is a seamless whole which we necessarily but arbitrarily reduce--that is, cut into

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[2/] Forest economist, Forest Service, USDA, North Central Forest Experiment Station, St. Paul, MN 55108 and Research Associate, College of Natural Resources, University of Minnesota, St. Paul, MN 55108.

pieces--for convenient study. Ecology and economics are two such pieces. The results of their reduction have been impressive in many respects, but unless we eventually put the pieces back together and reexamine our model of the whole, we deceive ourselves about the depth of our understanding. We will argue that our present environmental and social difficulties in part reflect an excessive reduction by ecology and economics and that to be truly useful, each must be integrated in some fashion with each other and with other ways of thinking (Proops 1989).

In the following sections we briefly consider the manifestations of these problems in ecology and economics. We then turn to some fundamental changes occurring in our understanding of the natural and social worlds; and to how they may be taken into account within the framework of an integrated ecological economics. Finally, the implications of such a synthesis for the practice of forestry are discussed.

WHAT IS ECOLOGY MISSING?

Ecological economics holds that ecology is not as relevant or useful as it might be. Primarily due to the reduction just described and the desire to comprehend ecosystem functioning uncontaminated by human activity, ecology has emphasized exotic and unspoiled ecosystems far from urban areas. And although this focus has helped define the global enormity of human activity, the ecological problems related to this activity in cities, factories, farms and forests have been largely ignored. Partly as a consequence, the world's poor often view environmental issues as irrelevant disputes among wealthy elites. More seriously, it may have contributed to the false impression held by many that it is the wilder, more remote areas which most require protection. Despite the compelling ecological problems of urban areas, their industrial surroundings, or the agricultural areas upon which they depend, ecology's focus on the exotic combined with the appealing ideology of unlimited growth has helped to obscure the obvious: ecosystems are more than just rare plants and animals; people are increasingly the dominant force in most ecosystems; and various socio-economic processes--particularly their pathologies such as persistent poverty and crime--are ecological phenomena no doubt as important as old-growth forests and wolf packs. Problems such as acid rain, ozone depletion, tropical deforestation, climate change, and so on, with their large scale and synergistic properties, must be understood in terms of a global ecosystem in which humans play a central role. In short, ecology's focus on the maintenance of the earth as a life support system requires that it include humans both as ecological actors and as a central force in shaping the future of the biosphere.

WHAT IS ECONOMICS MISSING?

It is also a key theme of ecological economics that neoclassical or mainstream economics, in spite of its achievements, has contributed to the social and environmental problems noted above. Mainstream economics now embodies a reductionist approach to important biophysical and social phenomena. And although any theory by definition involves a reduction or simplification of what it describes, we believe that the natural and social costs of this reduction have become too great.

Economics envisions a world of individuals, each motivated only by self-interest, who exchange items which they own or control for items of others. These exchanges define the social system as far as economics is concerned. Individuals also draw upon Nature for resources that may be used in various ways to create wealth. The more skilled one is at converting resources into exchangeable products, the greater one's potential to accumulate wealth. For economics, therefore, all value associated with the natural world is exchange value, whether such an exchange is real or simply contemplated.

But what else happens when part of Nature is brought within the economic system for human use? When a tree is harvested it becomes part of a process that ultimately results in the production of an exchangeable good. But this very act of harvesting also involves biophysical transformations of Nature. It is precisely these processes about which a language of social exchange has great difficulty in speaking. As a result, economics does not adequately account for the biophysical foundations of production--i.e., the physical and thermodynamic transformations underlying economic activity. In the language of ecology, "Production is the set of...activities which feed on low entropy and materials. Physical and biological principles suggest...a strong interdependence between material, energy, and information flows and the machines and agents which...utilize these flows" (Christensen 1989).

And just as the language of economics fails to account for the biophysical effects of resource extraction on energy and material flows, neither does it accurately reflect these flows within the production process itself. For economics views inputs as "marginally productive", assuming that each input contributes independently to the process of production and ignoring the fact that many inputs are complementary--production is enhanced as various inputs work with one another. Forests exhibit many examples of input complementarity as well as a closely related fact--joint production.

We have also noted that economics, by design, reduces social life to a single relation--that of exchange. In so doing, the social world is itemized in the same way as Nature, only in this case the items are individuals concerned solely with their own welfare. This is expressed in two basic premises that define their motivations. First, they act only out of self-interest--a desire to maximize utility. Second, their overall wants are insatiable. This economic behavior reflects a reasoning process that identifies items for possible consumption, estimates their value, and assesses the risks involved in acquiring them. Rationality, therefore, is exclusively instrumental and strategic in nature. Value is determined through exchange and quantified in terms of price.

Economics does not deny that other values exist; instead it subsumes all such values under the heading of "preferences" which are simply presumed to exist. And while preferences undoubtedly drive exchanges, how they arise, and the values (other than exchange value) they embody, are seldom examined. Or if these are, it is only after they have been translated into the language of exchange--for example, "willingness to pay." In this way, the substantive content of preferences--i.e., their specific focus, their moral or aesthetic justifications, their physical and ecological implications--and our ability to discuss such matters directly, is eliminated.

This twofold reduction of nature and culture that occurs in the language of mainstream economics is succinctly described by White (1990), upon whom we draw heavily: "...exchange takes place under natural and cultural conditions that are absolutely essential to it, but about which economics has no way of talking except by itemization, quantification, and conversion into the material of actual or [possible] exchange.... The enormous matrix of productive human life and meaningful activity that lies outside the practices of exchange, like the matrix of the natural world, is simply excluded from the exchange mentality; or if it is included, it is on terms that destroy its meaning."

But according to the way economics defines rationality, there must be <u>some</u> ends explicitly designated for economic activity, since means without ends are irrational. And as economics cannot discuss political or moral values (they are noneconomic), it must draw these ends from within its own language. This it has done by adopting self-justifying, intrinsic goals such as "economic growth." Thus the language of economics is not, as it claims to be, value-free. It supplies its own values through its very use of a certain kind of language. Further, there is strong pressure to inflate those values which it has adopted--in this case, the value of economic growth. And given an economic picture of individuals with unlimited wants acting to maximize their utility, it is natural to view the aggregate manifestation of such behavior in terms of "the more economic growth, the better." In effect, there is strong pressure to expand the value of economic growth to that of "unlimited economic growth."

There is another problem, however. It is difficult--particularly in the social sciences where many key terms are taken from everyday language--to think habitually of human action in terms such as "self-interest" or "rich" without tending to generalize their everyday--as opposed to their technical use. This tendency is further strengthened by an emphasis on an individualism and self-centeredness fostered by capitalism. When combined with the natural inclination of experts to view the economic language of exchange as the most useful--perhaps even the right--way to picture human action, there is a powerful impetus for the rest of us to follow suit. Increasingly, this has led to many viewing government primarily as an interference with the efficient functioning of a free market economy. This attitude impoverishes our thinking about government as a forum in which we--as citizens--can act creatively and collectively to shape our future, and is a recipe for societal disaster. The notion of the market as eminently "fair" and "free" because no one is restrained from entering or leaving often reduces crucial questions of distribution to irrelevancies, when compared to the concrete differences in living standards of the actors involved. The value of human freedom--with its enormous responsibilities and potentials for creativity--is reduced to a mere absence of constraint.

In summary, the reduction of the natural and social worlds by mainstream economics is clearly shown in its discussions of value. By itemizing Nature for the purpose of exchange, and by ignoring the biophysical foundations of production, neoclassical theory has no language to consider the biophysical consequences of economic activity--whether these effects result from extracting resources, the complementarity of inputs in production, or the wastes generated in production. And by subsuming the content of political and moral values within the rubric of "preferences", while supplying the value of economic growth from within itself, economics provides an appealing portrait of reality easily susceptible to universalization in a culture such as ours. In the process, economic discourse trivializes most of the important questions in social and political life, including the intrinsic value of healthy functioning ecosystems, now and in the future. As a result, it short circuits its ability to address effectively the large scale environmental problems we face today.

WHERE IS THEIR COMMON GROUND?

Economics and ecology have a common ground--individuals and nations acting in economic contexts alter their ecological and social environment in significant and unpredictable ways. Their common problem and the aim of ecological economics is highlighting the <u>identity</u> of the <u>economic transformations</u> of matter and energy--undertaken with economic motives and described in economic terms--with their simultaneous status as <u>biophysical transformations</u> --similarly described in ecological terms. But while these economic and ecological transformations and their physical consequences may be identical, human motivations are far different from those of other living things. For humans--with their abilities to reason, grasp consequence, and at least imagine the power to control their destiny--add a new dimension to the problems of survival not experienced by other species. Humans are driven not only (and perhaps not even primarily) by the necessary requirements for survival, but also by immense cultural and technological forces and the expectations they set in motion. Resolving our economic and ecological dilemmas will require that we come to grips with these motivations and look to sources of inspiration beyond science for their justification and meaning.

The two global sub-themes of the 19th IUFRO World Congress--first, forest decline from air pollution and global warming, and second, tropical deforestation--are welcome evidence that foresters all over the world now recognize these linkages. Of course, there are many ironies, but our asking why we didn't see these links sooner is not due to idle curiosity. Our myopic but understandable expectation for unlimited growth and the activities it has led to, is a direct reflection of a metaphysics--and the world-view it implies--upon which the West's present technological emphasis rests. This world-view is no longer adequate for grounding the complex relationships between man and Nature.

METAPHYSICS, IDEOLOGIES, AND WORLD-VIEWS

Metaphysics refers to those necessarily speculative and axiomatic foundations--plausible but not provable--upon which we all must build our views of the world. Bunge (1977) describes metaphysics as concerned with asking the question --What is the world made of and how does it work--and dealing with such notions as substance, form, things, possibility, change, space, and time. World-views are the practical manifestations of our metaphysical systems. There are many possibilities. The ancient Greeks, for example, perceived their world as permeated by tempermental gods and human destiny as driven largely by fate--a radically different view than the "objective" world of modern science. However, our present day world-views are not totally objective either, but are deeply influenced by such anthropocentric notions as "destiny" and "progress."

Ideology refers to those parts of our world-views which seem to explain our particular place or status in society, but actually function to justify, often unconsciously and self-deceptively, an existing power structure and social arrangement. Power--especially its arbitrary concentration and use; often for purposes of economic exploitation and domination--is the subject of ideology. We have already discussed the possibility that ideological influences penetrate current scientific and economic practice. World-views often mix ideology and metaphysics to arbitrarily justify the status quo as "natural" and therefore immune to change--thereby silencing dissent. E.F. Schumacher (1973) gives a good example of the power of current economic ideology: "Call a thing immoral or ugly, soul-destroying or a degradation of man, a peril to the peace of the world, or to the well-being of future generations; as long as you have not shown it to be uneconomic you have not really questioned its right to exist, grow, and prosper."

If our metaphysical beliefs and their resulting world-views are misinformed, incomplete, and/or contaminated by a self-deceiving ideology--as recent science and other sources described below are beginning to suggest--their ongoing criticism may permit us to better ground our efforts in reality, even as it changes under our feet.

What is the nature of these new findings about how the world works and what does it say about current world-views? The dominant perspective that still guides most of our day-to-day activities in the West is based on a metaphysics of mechanism traceable at least to Francis Bacon and Rene Descartes in the 17th century. They believed that the universe was a deterministic machine whose past and future states could be mathematically predicted. Such a mechanism had perfect order, was timeless and unchanging--planetary motion was considered the perfect example.

More recent scientific and philosophical opinion, incorporating ideas from Hegel and others suggests that the concrete phenomena affecting us and affected by us are not mechanisms but processes. Unlike mechanisms, processes are characterized by constant and largely irreversible change. Unlike mechanisms, processes are open-ended and in a constant flux of becoming something new--the stunning surprise, the truly unexpected novelty-by-combination. Unlike mechanisms, no one can say what processes are becoming or where they are heading (Georgescu-Roegen 1971). Their new properties over time can therefore be described as emergent (Prigogine and Stengers 1984). And unlike even our most complicated machines, process unpredictability is not simply a matter of complex probabilities beyond the power of current computers, but of possibilities that cannot even be imagined before the fact.

Ambiguity is a more appropriate term than uncertainty for describing this central feature of change inherent in all processes--natural as well as social. One of its implications is that neither ecosystems nor societies can be reduced to mere collections of humans or other living and nonliving things. We must attempt to understand the interactions between cultures and the technologies they develop, and the biosphere they inhabit. As Schumacher, urging caution, so aptly put it, "We always get more than we bargained for." This means that our real and awesome power to change the future by individual action, culture, and technology must be evaluated with much greater care than ever before. Our power to change is evident. Our power to direct this change over the long-term--to steer these processes toward ends and at rates we choose--is highly unlikely. While our much vaunted technology is always a source of these changes--and frequently a source of change none of us would choose before the fact--it is doubtful that we will ever have the control over processes that we have imagined about mechanisms.

Science can, however, tell us with somewhat more certainty, the much smaller number of paths not to explore--paths declared dead-ends by those few fundamental laws of physics that are primarily laws of impossibility. In contrast, possibilities --those yet-to-be, often emergent and therefore surprising properties of things and systems of things undergoing constant change--while surely conforming to these laws, are nevertheless fundamentally unknowable before the fact, and therefore unlimited in a different sense. For example, recent discoveries epitomized by two notions of chaos--the realization that huge events may be triggered by the almost infinitesimal; and the apparent structure and order sometimes underlying seemingly random complexity in virtually every field from particle physics to social change--suggest that the complexity we observe around us is due not only to the multiplicity of interactions, but also to entirely unsuspected possibilities for change and creation, with their roots in thermodynamics. Gleick (1987) gave it the appropriate sense of awe and mystery it deserves: "Certainly these evolving islands of order [or disorder] must obey the Second Law (of thermodynamics). The important laws, the creative laws, [however] lie elsewhere." Yet current ideologies about the possibilities for unlimited technical sophistication and unlimited economic growth are precisely the kinds of paths that the laws of physics, particularly thermodynamics, suggest we cannot follow.

WHAT WOULD ECOLOGICAL ECONOMICS DO FOR FORESTRY?

Ecological economics would highlight the connections between economic activity and ecological functioning in light of the newer world-view described above--these connections include static and dynamic concepts of both stocks and flows. This is familiar ground to foresters whose first scientific task was to track the linkages between harvest levels and future growing stocks. Ecological economics would extend these procedures to other components of nature such as soils, water, and other biota. For it is upon these interrelated stocks and flows that the biosphere and humans must sustain themselves. Isard (1971) and more recently Hannon (1989) suggest how to extend input-output analyses to consider the interactions between ecologic and economic processes--those transformations of ecological stocks and flows into economic capital and income.

Ecological economics would give special attention to thermodynamics in economic and ecosystem function. Energy, either its direct use by plants and animals to transform and transport substances, or its indirect influence through biosphere climate, is the driving force for all acivity. Recent global climate change is only the most obvious manifestation of the tremendous scale of human energy use and of our continuing failure to grasp the significance of thermodynamics in developing and implementing technical change. The seemingly universal hope to find a cheap non-polluting source of energy--like the search for perpetual motion--is still with us. But even if that miracle occured, we would still face the problem discussed above. We have no energy shortage, but a world already reeling--socially and ecologically--from too much energy. Indeed, giving each of us even more energy to use as we see fit can only make the ecolgical and social difficulties worse. Odum (1983) illustrates the central importance of the material and thermodynamic transformations underlying ecological and economic activity--traditional estimates of forest productivity which have not considered embodied energy and materials from all sources, may be exaggerated.

Ecological economics may highlight the limitations of prices to reflect resource scarcity, at the same time providing the basis for criticising the seemingly unlimited faith of some optimists in the potential of technology to develop new forms of resources. Rather, resource scarcity may now be seen to reflect disruptions in energy and material flows in natural systems--disruptions caused by the inability of these systems over the long-term to produce as much as we have been accustomed to extracting, or their inability to absorb many of the "unnatural" wastes resulting from economic activities. Such a view may allow pricing systems to be reconstructed in ways that explicitly account for the "multiplier effects"--both positive and negative--of economic production on scarce raw materials, subtle environmental services, or waste sinks defined in biophysical terms. This may best be done, as Christensen argues, by extending the range of price calculations to reproduction prices--not only for commodities, but also for the biophysical costs of the energy and materials extracted from natural systems. Materials, for example "...would be priced in terms of the costs of recycling or in terms of the costs of substitutes...current prices would be recalculated to reflect the reproduction values of critical environmental resources and services."

As highlighted earlier while discussing the reduction of value by mainstream economics to only value in exchange, ecological economics would also suggest that we explore a wider range of values--the criteria by which we would judge ecosystem, individual, and societal health. While traditional economic definitions of market value are useful in many instances, we must consider the symbolic, psychological, and perhaps even (yes, let us admit it) spiritual values of ecosystems in transition as we seek a sustainable society. Questions of the moral status of species and ecosystems; of our possible obligations to preserve biodiversity; and of the procedures through which justifications for our actions are advanced and debated are not peripheral concerns but an integral part of our membership in the scientific and forestry community (Lewis 1990). In short, an ecological economics must entail a reflective attitude on the part of its practitioners--hopefully to include foresters--that exhibits a more sophisticated use of moral and aesthetic reasoning. These two modes of reflection have themselves been unjustifiably downgraded to something less than rational via the extreme emphasis on science and the presumably objective world-views of modern society. A systemic but also a moral and aesthetic view of society is required--current problems are witness to the shortcomings of a purely technological and market approach.

A case in point involves a recent effort in Africa to exclude native peoples from national parks set up to protect endangered wildlife. Yet, who but these indigenous people may be better equipped socially and culturally to effect their joint survival, which is, after all, the real problem? The parallel of their dilemma with our own controversy about old-growth harvests and spotted owl habitat in the Pacific-Northwest is striking. To what extent is Western economic and technological ideology the primary source of the cultural change that make national parks necessary? And in a world of interconnection, to what extent can such a strategy ever be successful --any more for these africans, than for us?

WHAT'S IN IT FOR FORESTERS?

While many applied disciplines would benefit from the insights of an ecological economics, forestry seems particularly well situated.

* First, there is both a need and opportunity to apply the concepts of ecological economics to forestry. Most forestry agencies and firms already claim the moral high ground with sustainable management as the centerpiece of their policy--if not yet actual practice. An ecological economics, with its goal of developing a more refined understanding of the interconnections between economic activity and ecosystem dynamics, may provide just the evaluative perspective forestry seeks. Fortunately, many forests are still in a relatively natural condition when compared to agricultural or urban areas. These lands still feature species and characteristics that might yet be saved from extinction or obliteration from the well meaning but probably over-simplified abstractions characterizing much current forest practice.

* Second, forests must continue to play a pivotal role in economic development, however much our expectations and definitions of this concept change. An ecological economics may allow foresters to find new frameworks within which to accommodate subtle environmental services, nonmarket values, as well as those traditional (and we must emphasize, necessary) commodities they have always sought.

* Third, our still primitive but growing understanding of the role of forests in all facets of global health, gives new credibility to the intuitive and poetic concerns of environmentalists from all cultures and eras. Although debates surrounding forest practices have always displayed both ecological and economic dimensions, these dimensions have served merely as cornerstones upon which alternative and usually antagonistic courses of action have been advanced with little apparent chance for a happy resolution. An ecological economics may provide the common ground and language upon which we may construct more realistic and equitable policies.

* Fourth, as foresters elaborate the connections between economic activity and forest ecosystem function, the widespread appeal of forests will be a great advantage in teaching ourselves and others just how complex and ultimately fragile the world really is.

SUMMARY

There is an open conflict between world-views regarding the interactions of ecological and economic activity that may lead to positive change. The currently dominant world-view is founded on long-standing notions of mechanism and often ideological expectations for the eventual control of the natural and social world. In profound contrast, a more recent world-view emphasizes process, emergent properties, ambiguity, and substantially less confidence in our ability to steer these complex social and natural processes over the long-term.

A key part of the difficulties can be traced we argue, to a twofold reduction by mainstream economics which attempts to translate all aspects of human relations and all human values into the language of economics and the activity of exchange. We argue that while we must begin our science by breaking big things into parts for study, we must eventually reintegrate the elements to see how they work together. This synthesis will require many disciplines--however crude the result, and however much it falls short of our inflated expectations. We must consider the notions of change and surprise in a new light, and reevaluate our expectations for control. That we cause change is clear--that we can control the direction and intensity of these changes over the long-term is extremely unlikely.

These refinements to our science, though profound, would not diminish its crucial role in improving our understanding of the multi-dimensional practice of forestry. They do, however, suggest a more humble expectation of what science can accomplish, of the need for a more refined and explicit study of the links between economic activity and ecosystem functioning, and of what we can and cannot predict about the ecological and social consequences of human action. In so doing, we must recognize that, while current expectations have revolved around a technological tactic of deciding which path to take, we might have to balanced it with the less satisfying but safer tactic of determining which paths to avoid. All such efforts must, in turn, be conducted in light of the crucial questions of how humans can strike a balance between equity and efficiency in attempting to meet urgent needs now while preserving possibilities for the unknowable exigencies that unborn generations will surely face.

Foresters have always been aware of the interaction between ecosystems and society. And like other scientists trained in the middle of the 20th century, they have naturally embraced the world-view presented to them regarding the accepted tenets of scientific practice. But the social and ecological problems of the 21st century are of a different sort. If foresters, economists, ecologists, and others are able to make what appear to be necessary albiet difficult changes in their world-views, and as a result, clarify the connections between economic activity and ecosystem functioning, their efforts could have sweeping and largely positive impacts on the structure and direction of society.

While science, technology, ecology, and economics will continue to make valuable contributions to human development, they cannot offset the fact that these are only possible, indeed meaningful, in a world that still has the potential to sustain human life with all its possibilities. What many have forgotten is that without a sustainable forestry and agriculture, embedded in a bioshpere that we did not create and that we cannot steer, none of these other things will count for much. We have suggested here that ecological economics may provide a framework for making explicit connections between economic activity and ecosystem functioning and thereby contribute in some way to solving many of the problems cited above. In responding to these challenges--especially to doubts about the ability of science to deliver on all its promises--ideologues may claim that the "gloom and doomers" are at it again, but they have it backwards. Only by recognizing the unlimited moral and aesthetic possibilities of humans--for good or ill--can we sustain the hope of ever learning how to live and advance within the real limits of Mother Earth.

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GENERALIZED HARVEST SCHEDULING IN FORPLAN VERSION 2: AN UPDATE[1/]

Michael Bevers and Brian M. Kent[2/]

Abstract.—A generalized approach to constructing harvest scheduling variables in FORPLAN Version 2 was described and developed as a test system by Johnson and Stuart. A number of corrections and extensions have recently been developed and made available in Release 14. These enhancements include flexible use of both Model 1 and Model 2 decision variables, flexibility in regeneration class assignments, and capabilities for modeling probabilistic outcomes by proportional acreage transfers through the matrix acreage contraint rows.

Keywords: Linear programming, Model 2, decision tree.

INTRODUCTION

Johnson and Scheurman (1977) defined two classes of harvest scheduling decision variables, Model I and Model II. The principal difference between these variables in linear program (LP) matrix formulations is that with Model I all rotations within the planning horizon for a particular combination of harvest scheduling options under a land management prescription are combined into a single decision variable. Under Model II each rotation is given a unique decision variable which must then transfer assigned acres to another set of decision variables for the next rotation through use of additional acreage constraint rows.

FORPLAN Version 1 analysts have been able to choose between Model I and Model II timber harvest scheduling formulations for many years now (Kent et al. 1985, Johnson 1986, Johnson and Crim 1986, Kelly et al. 1986). Since 1985 a few FORPLAN Version 2 analysts have been testing similar but much enhanced capabilities, now referred to as Model 1 and Model 2, initially developed by Johnson and Stuart[3/] (Johnson et al. 1986, Johnson and Stuart 1987). These enhancements were designed to address risk and uncertainty problems in forest planning, such as those described by Routledge (1980), Knapp et al. (1984) and others. Additional design criteria were identified to increase LP analytical flexibility in a manner that is explicitly and simply portrayed in a FORPLAN data set, and to offer opportunities for reducing model sizes. Similar formulations, described as Models A, B, and C, appear to have been developed by Garcia[4/] in New Zealand with the FOLPI LP modeling system (Garcia 1984). Recently, a number of corrections and extensions to the matrix formulation and system implementation were made and released on the Fort Collins National Computer Center Unisys 1100/90 mainframe as FORPLAN Version 2, Release 14, by the Land Management Planning Systems Section in Fort Collins, Colorado (Gilbert et al. 1991). From an LP model formulation point of view, the enhancements include flexible use of both Model 1 and Model 2 decision variables, flexibility in transfer (regeneration) class assignments, and capabilities for modeling multiple probabilistic outcomes by embedding decision trees within the LP matrix.

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2/Research Forester and Project Leader, respectively, Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Fort Collins, CO.

3/Johnson, K. Norman; Stuart, Thomas W. 1984. Representing multiple outcomes in timber management planning. Draft copy. Land Management Planning Systems Section, Forest Service, U.S. Department of Agriculture, Fort Collins, CO.

4/Garcia, Oscar. 1990. LP and related approaches in forest planning. Presented at the IFORS'90 12th Triennial Conference of the International Federation of Operations Research Societies, Athens, Greece, June 25-29, 1990.

MIXED DECISION VARIABLES

Previously, FORPLAN Version 1 provided users a choice of either a Model I formulation or a Model II formulation while FORPLAN Version 2 offerred only a Model I formulation. With the new Model 1 and Model 2 decision variables in Version 2, users may assign formulation choices to prescription sets in a thematic or relational manner. This allows analysts to employ Model 2 formulations to reduce out-period model size by selectively collapsing regeneration classes for future rotations without having to incur the extra LP acreage constraints for all prescription sets.

Perhaps of even greater importance, users may now elect to have classes of acres or prescriptions transfer between Model 1 and Model 2 formulations. This capability is particularly useful for controlling transfers near the end of the planning horizon when the LP might ordinarily opt in the last period to bring into solution decision variables incommensurate with earlier management options. An example would be the transfer of acres in the last decade to a decision variable representing a shorter rotation in order to garner a smaller average inventory coefficient, making it easier to satisfy an ending inventory constraint. This could be undesirable if one argues that the contribution to average inventory for the acres in question should correspond to the harvest regime under which the acres were managed during the previous decades rather than to some other possibility.

TRANSFER CLASSES

A major enhancement of the Model 2 formulation is the development of transfer classes as a generalization of earlier Model II regeneration classes. By incorporating transfer age into the definition of acreage control classes users have the ability to invoke transfers at ages other than zero to place acres on a different growth trajectory and make them available to different prescription groups. Transfers at age zero continue to function as regeneration classes. As an additional part of the new transfer class capability, acres are no longer locked into a particular transfer or regeneration class throughout the planning horizon unless the user so chooses.

MULTIPLE OUTCOMES

To complement the new transfer class capability and provide for full use of decision trees in FORPLAN LP's, acreage transfers are now proportional and can occur at nearly any time the user wishes. Proportional acreage transfers allow the analyst to split acres between more than one transfer class to model expected probabilistic outcomes. These transfers can occur at the end of a rotation for Model 2 decision variables, when all the acres must be transferred, or they can occur during a rotation for either Model 1 or Model 2 decision variables for up to the full acreage as a method for modeling mortality or other shifts in portions of a prescription group. To model mortality, the acreage would be transferred to one or more new regeneration classes with a beginning age of zero. To model changes such as shifts in growth rates or species composition the acres would be transferred to one or more new transfer classes where the beginning age is not reset to zero.

CONCLUSION

With the generalized harvest scheduling capabilities of Model 1 and Model 2 decision variables and transfer classes, Release 14 of FORPLAN Version 2 offers very flexible alternatives for modeling probabilistic outcomes for forest planning. Furthermore, these enhancements are easily invoked and readily changed in the FORPLAN data set and explicitly portrayed in printouts making it a simple matter to revise any probabilistic estimates for further analysis. An additional benefit is the creation of better opportunities for model size reduction by collapsing to fewer regeneration classes under Model 2, thus dropping the number of groupings of acres and prescriptions that must be represented by rows and columns in the LP matrix.

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THE UTILITY OF FORPLAN FOR USDA FOREST SERVICE PLANNING: THE PERSPECTIVE OF AGENCY PERSONNEL[1/]

Brian M. Kent, A. Allen Dyer, and Linda A. Joyce[2/]

Abstract.--Perceptions on the part of USDA Forest Service personnel as to the utility of quantitative tools used in resource planning are a function of a number of factors, including discipline, education and experience, personal attitudes and administrative responsibility. In 1989-1990, the Forest Service and the Conservation Foundation conducted a critique of the agency's Land Management Planning Processes. Four questionnaires were sent to agency employees, two to analysts, one to planners and one to resource specialists. This paper will summarize the results obtained from these questionnaires. Particular attention will be given to comparing and contrasting the respondents' attitudes towards the use of the FORPLAN system and the problems arising from this use.

Keywords: land management planning, multiple resource management, national forest management act.

INTRODUCTION

The USDA Forest Service has been involved, throughout the 1980's, with the development of multiple use land management plans on each national forest as mandated by the National Forest Act of 1976 (NFMA) and it's set of attendant regulations (Federal Register 1982). Largely because of the nature both of the NFMA and it's regulations, the roles of analysis and information have been important to the forest planning exercise. For example, in December 1979, the Associate Chief of the Forest Service designated the Forest Planning Model (FORPLAN), a linear programming based system as "the required primary analysis tool" for national forest planning. Over the ensuing 10 years, while FORPLAN has evolved through two versions as a result of lessons learned (Kent, et al., 1991), it has always played a central role in the development of forest plans.

The agency has recently completed an in-depth critique of all aspects of forest planning (Larsen et al., 1990), and one major component relates to the analytical tools and information used in planning (Hoekstra et al., 1990). Not surprisingly, much of what was addressed in this component of the critique relates to FORPLAN. Even prior to the critique, FORPLAN has been the focus of comment on analytical tools used in the first round of land management planning on national forests. It has been the focus of numerous papers (Iverson and Alston, 1986; Bare and Field, 1987; Kent et al., 1991) and has been the subject of review in two symposia (Bailey, 1986; Hoekstra et al., 1987). Some characterized the system, especially the first version, as being nothing more than a elaborate timber harvest scheduling model (Iverson and Alston, 1986). It also has been described as so complex that even the people who develop applications with it cannot understand its results (Kent et al., 1991).

As we began work on the critique, we planned to draw on the extensive body of conclusions drawn from prior evaluations of FORPLAN as well as on our own experiences. However, we also recognized that much of the earlier work was two to five years old and that, with the exception of some forest and regional analysts, many of the agency

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1/ Presented at the Symposium on Systems Analysis in Forest Resources, Charleston, SC., March 3-6, 1991.

2/ Project Leader, Rocky Mountain Forest and Range Experiment Station, 240 W. Prospect, Fort Collins, CO. 80523; Department Head, Dept. Forest and Wood Sciences, Colorado State University, Fort Collins, CO. 80523; Range Scientist, Rocky Mountain Forest and Range Experiment Station, 240 W. Prospect, Fort Collins, CO. 80523.

personnel who worked with the FORPLAN system or its results had never had the opportunity to provide input to these previous efforts. In order to rectify this, three groups (planners, analysts, and resource specialists) involved in forest planning were surveyed. In this paper, we describe issues pertaining to planning analysis surfaced by agency personnel from each of these three groups.

METHODOLOGY

Four questionnaires were developed, one for planners, two for analysts and one for resource specialists. For analysts, one questionnaire focused on education and training while the other was general, touching on all aspects of planning analysis. Due to limitations of time and resources, the questionnaires were developed independently, thus they do not represent a coordinated package. Consequently, it is important to note that the results reported here reflect the population of respondents since the survey procedures preclude characterization on the total populations. However, we believe that the number in individuals is large enough to suggest generalizations.

Thirty two planners responded to the planner questionnaire, fifty six analysts responded to at least one of two questionnaires administered to analysts, and twenty nine people responded to the resource specialist questionnaire. Table 1 describes the skills mix of each group based on their education backgrounds. The large number of individuals with backgrounds in forestry, the high proportion of analysts with advanced degrees stressing operations research techniques, and the relatively low representation of some disciplines among respondents to the resource specialist questionnaire are characteristics that are immediately noticed in this data. As will be shown later, these characteristics influence the results we obtain.

The data from these surveys was aggregated together to allow description of similarities and differences in perception about the utility of FORPLAN and its role in national forest land management planning. Bringing information from the three groups together into a single data set involved substantial review of the questionnaires. Responses to open ended questions produced much of the characterization used in this paper. In summarizing these responses, we have described each respondent in terms of the role they played in the planning process, their education-skills mix, and their characterization of FORPLAN. The issues used to categorize their assessments of FORPLAN are listed in Table 2 under the "Concern" column. In compiling the information in Table 2, we counted the number of times that individuals indicated "yes" to the statement in the column title "Concern". Non-responses are not indicated.

To develop the list of concerns shown in Table 2, we developed an initial list based on previous evaluations of forest planning/FORPLAN and on our own experiences. We then modified this initial list to reflect issues actually identified in the responses we reviewed. Thus, items in our final list in Table 2 reflect issues raised by at least one respondent.

Because different questionnaires were administered to each of the three groups, response by each group to these issues varies. For example, resource specialists responded more in the categories related to adequacy of data than planners because there were specific questions in the resource specialist survey on data. In contrast, responses on data that we used from the planner survey were taken from an open ended question on problems with the planning process and analysis. To see this, note that 12 resource specialists (Table 2) provided input on the issue of biodiversity in planning analysis because it was identified specifically in the resource specialist questionnaire. On the other hand, no planners and only two analysts addressed biodiversity as it was not mentioned specifically in any of the three remaining questionnaires. This again suggests caution should be used in generalizing these results to the total populations of planners, analysts, and resource specialists.

DISCUSSION

<u>The Perspective Analysts, Planners, and Resource Specialists Brought to the Planning Process</u>:

Before attempting to characterize similarities and differences in the evaluation of FORPLAN by these groups, it is useful to speculate on the perspective each brought to the evaluation process. Planners undoubtedly viewed the analysis as a means to explore alternatives and support decisions developed for and presented in the plan and EIS. They probably viewed it as primarily a strategic process with strong tactical implications. Analysts viewed the process somewhat differently, depending on their background and perhaps experience. Some viewed the process as a combined strategic-tactical planning analysis. For these individuals, not only were strategic land allocations decisions to be identified within the FORPLAN analysis; but specific tactical projects were to be identified as well. In fact these analysts would undoubtedly argue that strategic land allocation decisions are directly affected by tactical project decisions. Others, in contrast, viewed the analysis as simply a way to test various alternatives suggested by the management team.

In at least one area, however, analysts and planners were in general agreement. Another questionnaire utilized to gather data for the critique addressed the issue of what decisions or questions were to be answered in forest planning (Hoekstra et al. 1990). Twenty eight of the 40 analysts and planners who responded to this questionnaire agreed that the following seven questions should be answered (requirements to do this have recently been incorporated into Forest Service policy through forest plan appeal decisions):

Table 1.—Skills and educational backgrounds of respondents to the analysts, planner and resource specialist surveys.

Skill	Analysts	Planners	Resource Specialists	Total
Ag Economics	1	0	0	1
Business	1	0	0	1
Economics	2	0	1	3
Engineering	4	1	0	5
Forest Admin.	2	2	0	4
Forest Biometry	2	0	0	2
Forest Econ.	5	1	2	8
Forest Planning	3	0	5	8
Forest Technician	0	0	1	1
Forest/Range	0	1	0	1
Forestry	7	13	7	27
Forestry - Operations Research	13	0	0	13
Geology	0	0	2	2
Landscape Architecture	0	4	4	8
Range Economics	1	0	0	1
Recreation	1	0	0	1
Resource Economics	0	1	0	1
Resource Planning	4	2	1	7
Soils - Watershed	1	2	0	3
Transportation	2	0	0	2
Unknown	3	3	1	7
Watershed	2	2	0	4
Watershed Planning	1	0	0	1
Wildlife	0	0	4	4
Total	56	32	29	117

1. Forest multiple-use goals and objectives
2. Forest-wide management requirements
3. Establishment of management areas and management area direction
4. Establishment of allowable timber sale quantity and designation of land suitable for timber production
5. Nonwilderness allocations or wilderness recommendations
6. Establishment of monitoring and evaluation requirements
7. Project and activity-level decisions identified in the record of decision for the forest plan and adequately disclosed for National Environmental Policy Act (NEPA) purposes in the environmental impact statement of the plan.

Hoekstra et al. (1990), say they found that "At least 12 respondents ... indicated that they were unable to satisfactorily address at least one of the seven requirements." They go on to say, "Most respondents agreed that the first six ... were the most important ...(most felt that item 7, site specific decisions, should be the exception rather than the rule in forest plans)." These remarks highlight the tension between strategic and tactical planning that existed throughout the first planning cycle. It is important to note that this issue was not addressed with an explicit agency policy until very late in the cycle. This makes it difficult to interpret the responses of planners and analysts on the relative importance of identifying site-specific projects in the plan.

Resource specialists brought a much different set of perspectives to forest planning and analysis. Perhaps the most important difference is one of scale — they tended to focus on sub-forest problems rather than on forest-wide analyses. Consequently, they wanted to quantify management responses at a finer scale than FORPLAN would allow because of model size and data quality limitations. Examples of such limitations include numbers of analysis areas that could be represented in a FORPLAN generated linear program and the numbers of yield tables that could be generated and included in FORPLAN data sets (especially in Version 1).

Resource specialists viewed their role in planning primarily as one of providing information to individuals constructing FORPLAN models. They encountered several sources of frustration in this role. Many had little experience with the FORPLAN analysis structure, and found it very difficult to respond to information needs. They were often unable to "fit" their models or model results within the FORPLAN construct. Also, the development of this information required a spectrum of analyses ranging from inventory summaries to modeling. These activities were not high on some specialists' priority lists as such tasks took them away from their normally assigned duties. Resource fields other than forestry, have tended to focus more on qualitative as opposed to quantitative training. Specialists' skills reflectd their training and the lack of quantitative backgrounds increased frustrations for some when they had to deal with quantifying resource responses. Finally, some resource specialists were also frustrated with the lack of inventory data and their inability, because of constraints like time and money, to provide what they perceived was really needed to answer analysts' data requests.

Evaluation of FORPLAN by Planners, Analysts, and Resource Specialists:

In this section, we turn our attention to characterizing the similarities and differences in the perspectives of the utility of FORPLAN by the three groups. This will be based primarily on the information contained in the responses to the four questionnaires but will also reflect findings from previous FORPLAN evaluations as well as our experiences with forest planning over the last decade. This discussion focuses on the issues we deem most important, with each issue being comprised of one or more of the concerns listed in Table 2.

The Role and Uses of FORPLAN in the Planning Process

First we consider problems that were identified relating to the role of FORPLAN analysis and the way in which these analyses were used. Individuals with broad planning or administration backgrounds (planning, economics, forest administration, forest planning, forestry-operations research, landscape architecture, and watershed planning) were much more concerned about this issue. In other words, the background of individuals (Table 1) seems to be of more significance in shaping (or perhaps creating) opinion on this issue than is the group they currently belong to (Table 2). Thus, the position of respondents to the planner and resource specialist questionnaires with backgrounds in these areas appears to be similar to that of analysts. On the other hand, the position of the remaining respondents is unclear based on our data.

Among those with planning or administration backgrounds, almost 40% identified communication by analysts of results of FORPLAN to managers (Forest Supervisors and District Rangers) or communication from managers to analysts about their expectations from FORPLAN as problems. It is likely that these problems stem in part from the fact that many managers had a poor understanding of FORPLAN and how to use it. Analysts, on the other hand, may not have always understood managers' needs and hence may have been ineffective in communicating the information managers needed to understand how they analysis process worked and how it should be used.

As an aside, we suspect, based on our own experience that communication problems were more extensive, involving all three groups as well as managers. This most likely stemmed from the focus and perception (as discussed above for the three groups) of the individuals involved. As already mentioned, resource specialists focused on a smaller stand or allotment scale than did the others. Analysts focused on attempts to quantify the forest and model the implications of management. Managers were concerned about overall or strategic management directions for the forest. Planners' concerns tended to overlap those of analysts and managers. With such disparate views, problems in communication were inevitable.

Respondents with planning/administration backgrounds also expressed concerns about the timber focus of FORPLAN. While greatest concern was expressed concerning Version 1, there was a general perception that, regardless of the version of FORPLAN used, timber received more than a fair share of the attention. Analysts, and to a lesser degree, planners did recognize that these problems were not solely due to limitations in Version 2 FORPLAN. One important cause is that, historically, timber management activities have been central to much of what the agency does on the ground. Additional causes included the way in which FORPLAN was used as well as the fact that, poor though it may be, the timber related data available is of better quality and far more extensive than that available on other resources. It is also likely that resource specialists were concerned about timber focus issues, however their questionnaire did not address this subject and no specific responses were made.

A high proportion of analysts and planners (over 20% in both cases) indicated that the inherent complexity of FORPLAN caused problems. This is undoubtedly related to the difficulty in communicating with managers, the public, and the

Table 2.--Characterizations of FORPLAN by planners, analysts, and resource specialists

Concern	Planner	Analyst	Resource Specialists
There was a problem with the way FORPLAN was used in the process. FORPLAN is appropriate for strategic not strategic-tactical planning analysis.	2	20	0
There were problems in communicating between analysts and managers.	8	16	0
FORPLAN's role in planning is as a support tool.	0	7	0
FORPLAN is a timber focused model that is limited in its ability to address other resource issues.	0	13	0
FORPLAN results had little influence on the plan.	0	5	0
The influence of FORPLAN results on the plan was moderate to strong.	0	33	0
Use FORPLAN in the next round of planning.	0	38	3
FORPLAN should be used for sensitivity analysis, benchmarks, and developing alternatives.	0	18	0
FORPLAN is most appropriate for sensitivity analysis.	19	0	0
FORPLAN should be used to develop benchmark alternatives.	13	0	0
The quality of data was generally bad.	7	9	24
The problems of dealing with spatial interrelationships limited the utility of FORPLAN.	10	41	10
There were serious problems in the wildlife analysis.	0	5	14
There were problems doing good range analysis.	0	0	2
FORPLAN was not adequate for analysis of unevenaged management.	0	5	3
It was impossible to analyze minerals within FORPLAN.	1	38	0
There were problems in completing visual analysis given the FORPLAN focus of planning.	0	5	13
There were problems with recreation analysis.	4	0	16
It was difficult to incorporate biodiversity into the analysis.	0	2	12
FORPLAN hindered integrating resources.	4	3	8
FORPLAN was useful in integrating resources.	0	28	1
The complexity of FORPLAN caused problems in the planning process.	6	14	0
Analysis was constrained by available time.	0	12	8

rest of the interdisciplinary planning team. Again, it is almost certain that resource specialists shared this concern, but it was not addressed in their questionnaires. The fact that few people other than the analysts had extensive training in FORPLAN probably contributed to communication difficulties. It is hard to accept the results of a process you cannot understand.

Some analysts indicated that results of FORPLAN analysis were modified either to meet the expectations of the public or to match results with those desired by managers. Related to this is the frustration of some analysts stemming from the fact that the results of FORPLAN analysis did not have more direct impact on plans. Putting these frustrations aside, Table 2 indicates a belief by almost 60% of the analysts that the results of FORPLAN had a moderate to strong impact on the plan.

The Appropriate Role of FORPLAN and Forest Planning

None of the questionnaires contained questions that asked respondents to characterize the appropriate role of FORPLAN and the purpose of the planning process as strategic, tactical, or some combination. The position of respondents to the planner and resource specialist questionnaires is unclear on this point. However, we believe analysts' responses strongly suggest that some viewed the process as one in which the results had both strategic and tactical components. As it turns out, this is in direct conflict with the agency's position that the results of the planning process were to be strategic. However, as noted above, this position did not become explicit until very late in the planning cycle. This delay probably accounts for much of the confusion that prevailed throughout the agency's planning staffs on this issue. Perhaps the delay can be explained in part by the fact that the first round of forest planning was a learning experience for all involved. In particular, much was learned both about ways to best utilize FORPLAN as a analysis support tool and, through the appeal process, about the decisions/questions forest planning should address.

When asked what specific components of the planning analysis should be addressed by FORPLAN, analysts were more likely to indicate that the model should be used to develop alternatives and benchmarks and to conduct sensitivity analysis. Planners were more likely to indicate that the model was most appropriate for sensitivity analysis. It is hard to say whether this difference stems from the difference in the questionnaires or a difference in perspective on the planning process.

Even with the high level of concern about the role of FORPLAN and the problems in handling the full range of resource relationships, almost all analysts felt that it should be used in the next round of planning. Planners and resource specialists were not asked this question, and planners did not offer comments on the topic in responding to open ended questions. Interestingly enough, however, a few resource specialists, who had worked with Version 1 and subsequently been exposed to Version 2, felt that the later version was a big improvement and would be suitable for use in the next round.

Data as a Limiting Factor

A consistent theme of concern about data was expressed by many respondents. Some allude to poor data in general, but most point to specific resource elements that caused them difficulty. Because of the structure of the questions, respondents to the resource specialists questionnaire identify these problems more clearly than either the analysts or planners. Visual resources, wildlife, recreation, and biodiversity are most frequently cited as sources of severe data and analysis difficulties. Not only did resource specialists identify basic data as a problem, but they usually had to address these resources outside of FORPLAN. In some cases, this was necessary because FORPLAN simply didn't allow consideration of a resource (see below). However, in other cases, there simply were no data or estimated production functions available for analyzing a given resource either in or out of FORPLAN.

Respondents to the resource specialist questionnaire were largely people with formal training in forestry or some related forestry area such as economics, biometry, or landscape architecture (20 of 29 respondents). There were 4 people with training in wildlife. This distribution leaves many resource areas (recreation, water, range, oil and gas, and wilderness) unrepresented. It is at least possible that some of the problems with data stem from the lack of resource specialists with appropriate discipline training. What is not clear, however, is how much this distribution of disciplines is due to the way in which respondents were selected on forests. There is some reason to believe that, in many cases, the resource specialist questionnaire was passed along to someone who had been heavily involved in planning (analysts, planner, timber specialist, etc.) rather than to a resource specialist.

Resources That Did Not Fit the FORPLAN Structure

In general, analysts and resource specialists expressed more concern over this issue than did planners, in part because of the differing nature of the questionnaires. Since there were no questions directed to planners about the analysis of specific resources, references to problems in this area only appeared in responses to open ended questions.

Analysts were asked about the minerals resource and most indicated that analysis of minerals within FORPLAN was impossible. An expected, but still disturbing, observation made by some analysts and resource specialists was that FORPLAN did not allow efficient analysis of unevenaged silvicultural systems. At best it seems to have been an exercise in forcing unevenage concepts into evenaged management prescription formats. Some analysts also indicated that problems with conducting wildlife analysis and visuals analysis in FORPLAN were encountered. This is one manifestation of concerns over difficulties in representative spatial relationships in FORPLAN, a major problem area in the opinion of many respondents from all three groups.

Resource specialists were given ample opportunity in their survey, to express concerns about analysis of specific resources. Many specialists felt there were general problems with all aspects of water, insects and disease, wildlife analysis and with some aspects of recreation analysis. Some of these related to spatial concerns such as cumulative effects of management practices on water quantity and quality, and visual management issues. They also felt there were specific problems relating to more traditional resources such as timber (old growth) and range (carrying capacity estimation). Concerns were also expressed that it was difficult to represent biodiversity in FORPLAN.

Resource Integration in a Planning Process Focused on FORPLAN

This issue was not directly surfaced by any planners and only by one resource specialist, again probably because they were not specifically asked to address it. However, it seems likely that resource integration was an underlying concern, at least for resource specialists. Analysts were asked to address this issue and fifty percent indicated that FORPLAN was useful in integrating resources. A few analysts indicated that FORPLAN hindered the interdisciplinary team's efforts to develop integrated resource management plans. Overall, most of the responses indicate that analysts are firmly behind FORPLAN as a tool that can help develop integrated resource plans. Over two thirds of the analysts indicated that they believed FORPLAN should be used in future planning analysis.

Time Limits on Planning Analyses

Analysts were the only group specifically asked to address this concern and they indicated that lack of time and or resources necessary to complete the planning analysis limited the effectiveness of the planning process. There is little doubt that this contributed to the frustration that many analysts had with the planning process. Other survey results suggest that managers, on the other hand, felt that analysis was too time consuming and that issues could not be addressed in a timely manner. This problem stemmed in part from the fact that in many cases, the analyst was expected to do more than just build and solve FORPLAN models. They were often responsible for activities like data gathering, solving other peoples' computer problems and perhaps even managing supervisor's office computer resources. Some resource specialists also felt that time was too limiting, usually because of other duties they were assigned.

CONCLUSIONS/IMPLICATIONS FOR FUTURE PLANNING

It is clear from the foregoing that our results were influenced both by the nature of the four questionnaires and by the ways in which the samples of respondents were drawn. It is also clear that three important factors influenced respondents' perspectives and hence their responses. These are; background, education and training; the nature of the current assignment; and the level of involvement in the forest planning exercise. It should be noted that overall, the concerns and problems identified in these responses are not very different from those surfaced in earlier critiques by both agency and non-agency people.

There are several suggestions for future forest planning that we feel can be made based on our analysis of these responses. There must be a broader base of ownership in planning than just analysts and planners. Analysis must be conducted that provides managers with information that facilitates their decisionmaking. It must be recognized that tools like FORPLAN are decision support systems whose role is to provide information to managers, not to make decisions or to serve as screens or barriers between what is taking place on national forests and interested publics.

Resource specialists also must have more ownership in what is going on in planning. One important way to do this is to increase their faith in planning analysis by developing better estimates of resource production functions and the resource data that are utilized in systems like FORPLAN. Another area needing attention is that of developing improved analysis approaches that will address major problem areas such as incorporating spatial considerations in these analyses and addressing risk and uncertainty. Finally, it is important to improve the analysts' tool kit by developing linkages between FORPLAN and other systems such as GIS and relational data bases. Clearly, efforts by research and development groups both in and out of the agency will be needed if these advances are to be made.

Some problems surfaced by respondents suggest that a less prescriptive approach for doing analysis be adopted in the future. Current NFMA regulations call for zero-based planning for each revision. A "need to change" driven incremental approach that addresses only the problems that have arisen since the last round would be quicker to do and should be simpler and easier to understand for all involved. Such an approach should take less time and hence alleviate such concerns on the part of managers and analysts. Monitoring, which was largely ignored in the first planning cycle, needs to be more carefully conducted in the future and could provide the basis for defining a "need to change" by identifying problems that need attention.

While there are many problems with what has gone on in the first round of planning, much has been accomplished and many lessons have been learned. It is important that the agency capitalize on this and keep what has been developed that is good about planning analysis tools and approaches.

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IMPLICATIONS OF SHORTER TIME HORIZONS ON FOREST PLANNING ANALYSES[1/]

Larry A. Leefers and Daniel B. Jones[2/]

Abstract.--Many analysts have proposed the use of shorter time horizons as a means for reducing forestwide FORPLAN model size. Using a microcomputer-based harvest scheduling model, this paper presents results and implications for models based on 5-decade, 10-decade and 15-decade time horizons.

Keywords: Harvest scheduling, linear programming, FORPLAN, modeling, forest management.

INTRODUCTION

USDA Forest Service (Forest Service) personnel and others use large linear programming models (e.g., FORPLAN) for analyzing harvest schedules and multiple-resource tradeoffs. Often, these models rely on a 15-decade planning or time horizon. Several authors have discussed the role of time in Forest Service analyses and the need for more sensitivity analysis (Barber 1986, Greer 1986). The purpose of this paper is to use several simple harvest scheduling models for examining linear programming results based on different time horizons and different forest age-class structures.

METHODS

For all analyses, a simple harvest scheduling problem is used to provide the analytical structure for comparing model results. The general linear programming model used can be described as follows:

Maximize Present Net Value
subject to:
- Acreage Constraints
- Area Control Constraints
- First-decade Harvest Constraint
- Nondeclining Timber Yields
- Long-term Sustained Yield Constraint
- Nonnegativity constraints

Sensitivity analyses are performed using 5-decade, 10-decade and 15-decade time horizons. In addition, four age-class structures are examined. To maintain consistency with Forest Service FORPLAN applications, present net values in the objective function are calculated from midpoints of decades using a 4-percent discount rate. Moreover, the time horizon for a given model formulation is used to truncate benefits and costs (Johnson et al. 1986). For example, a 5-decade model includes benefits and costs through year 50 only.

Only timber costs and returns are included in this case study. Timber yields, costs and returns data are from the Michigan Department of Natural Resources' Escanaba River State Forest (ERSF). These data are based on management for the aspen timber types (*Populus tremuloides* and *Populus grandidentata*). Rotation lengths of 40 through 80 years are available for existing stands, whereas rotations of 40 through 60 years are available for regenerated stands. Based on inventory data, yields are 14, 18, 20, 22 and 22 cords per acre for 40-, 50-, 60-, 70- and 80-year rotations using clearcutting, respectively. Revenue per cord is $7.57 in constant 1986 dollars. Four costs are included: periodic costs of $2.50 per acre per decade, first-time harvest cost of $1.50 per acre, sale preparation and harvest administration costs of $46.00 per acre, and regeneration costs of $16.15 per acre.

Four forest structures used as acreage constraints in analyses are presented in table 1. ERSF aspen acreage is presented in column 2 of table 1 with three other hypothetical distributions included for sensitivity analyses. Area control constraints were identical for all forest structures and time horizons. Specifically, a minimum of 1000 acres in each of the five oldest age classes cannot be harvested, and at least 8,000 acres total in those classes cannot be harvested. These constraints simulate acreage allocations currently being considered on the ERSF. Similarly, first-decade harvest volume ceiling of 417,721 cords approximates desired aspen harvest targets.

All linear programming formulations are Model 1 harvest scheduling problems (Johnson and Scheurman 1977). Alternative schedules are structured using FORSOM (FORest Simulation-Optimization Model, Leefers and Robinson 1990), a spreadsheet model, and are solved using LINDO-based software (Savage 1991).

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[2/]Associate Professor of Forestry, Michigan State University, East Lansing, MI 48824; and Operations Research Analyst, U.S. Department of Agriculture Forest Service, Eastern Region, Milwaukee, WI 53203.

Table 1.--Forest structures used in analyses

Current age class	Actual forest	Even distribution	Young-aged distribution	Old-aged distribution
	Forest structure			
		Acres		
0-9	22,150	10,000	15,000	5,000
10-19	20,096	10,000	15,000	5,000
20-29	8,785	10,000	15,000	5,000
30-39	5,958	10,000	15,000	5,000
40-49	6,447	10,000	5,000	15,000
50-59	17,498	10,000	5,000	15,000
60-69	22,689	10,000	5,000	15,000
70-79	12,063	10,000	5,000	15,000

RESULTS AND DISCUSSION

Analysis results are presented in two sections, one for the actual ERSF age-class structure and one for hypothetical age-class structures. In both sections, results are presented in terms of time horizons, objective function values, harvest volumes and selected first-decade harvest activities. The first two types of results are commonly reported. The latter type is presented because forest planning "...means evaluating immediate decisions with an assessment of the long-term consequences, not making long-term decisions (Barber 1986)."

ERSF Age-Class Structure

Results for the harvest scheduling problem with ERSF data are presented in table 2. Though the 15-decade model uses the longest time horizon, it has the lowest present net value. This reflects lower initial harvests. Over the first 5 decades, the highest harvest levels are projected in the 5-decade model. For it, first-decade harvests are constrained by the harvest ceiling, but then volumes immediately increase to the long-term sustained yield of 48.7 thousand cords per year. In essence, it harvests as much volume as feasible since volumes in decades 6 and later have no value. Thus, it is comparable to a maximum timber volume solution in many regards.

Acreage projected for first-decade harvest is identical in both the 5- and 10-decade models. Following those harvests, as expected, 40-year rotations are prescribed for the 5-decade model whereas a combination of 40- and 60-year rotations are prescribed for the 10-decade model. The 15-decade model prescribes the most economically efficient 50-year rotation for approximately 97 percent of the area regenerated in the first decade. Both 5- and 10-decade models allocate 1,000 acres of the oldest age class (i.e., 70-79 years old) to a nonharvest prescription; the 15-decade model allocate 1,815 acres.

Three conclusions can be reached by examining these results. First, the truncated objective function for 5-decade models may bias solutions to favor relatively higher harvesting than those with longer time horizons. This can be addressed by revising objective function values to account for an infinite time horizon (Leefers and Robinson 1990). Second, multiple optimal solutions are possible because prescriptions with identical 5-decade costs and returns are available. For example, a 60-year existing stand rotation followed by a 50- or 60-year regenerated stand rotation will be identical during the first 5 decades. Reducing options eliminates this problem. Finally, the 15-decade model in the case study underperforms the other models in terms of economics and harvesting. This may be due to the ERSF's age-class structure which is somewhat

Table 2.--Selected linear programming outputs and activities for aspen types using truncated objective functions for 5-, 10-, and 15-decade time horizons, Escanaba River State Forest

Time horizon[a]	Present net value[b]	First decade harvest volume	Last decade harvest volume[c]	First decade harvest area
Decades	Million dollars	Thousands of cords/year		Acres/year
15	3.78	38.5	38.5	1,749
10	3.94	41.8	43.5	1,899
5	3.84	41.8	48.7	1,898

[a] Truncation decade for objective function and number of nondeclining yield constraints.
[b] Objective function.
[c] Harvest volume in the last decade of the time horizon.

Table 3.--Selected linear programming outputs and activities for aspen types using non-truncated objective functions for 5-, 10-, and 15-decade time horizons, Escanaba River State Forest

Time horizon[a/]	Present net value[b/]	First decade harvest volume	Last decade harvest volume[c/]	First decade harvest area
Decades	Million dollars	Thousands of cords/year		Acres/year
15	3.79	38.5	38.5	1,749
10	3.99	41.8	43.5	1,899
5	4.08	41.8	48.7	1,899
5[d/]	4.08	41.8	44.0	1,899

[a/] Number of nondeclining yield constraints.
[b/] Objective function.
[c/] Harvest volume in last decade of the time horizon.
[d/] Regenerated stand prescriptions limited to most efficient rotation length, 50 years.

overmature (i.e., 45 percent is in the three oldest age classes). To examine the relationship of age-class structure to the time horizon, results of several additional analyses are presented in the next section.

The first three rows of data presented in table 3 are almost identical to data in table 2. The only difference in model formulation is the use of a perpetual series of rotations to calculate the present net value of regenerated stands. As a result, the coefficients in the objective function for all three models are identical, thus overcoming any bias due to different truncation points. Present net values are higher due to the infinite time horizon relative to table 2, but outputs and activities are very similar.

As noted previously, model solutions for longer time horizons place more reliance on economically efficient prescriptions. Therefore, a final ERSF model formulation restricts the time horizon to 5 decades and regenerated prescriptions to the efficient 50-year regenerated stand rotation. Results are presented in the last row of table 3. These results are quite similar to those from the 10-decade model. Thus, active management prescriptions are reduced by two-thirds and the time horizon is halved while short- and long-term results are relatively stable. Moreover, the problem of multiple-optimal solutions is overcome.

Hypothetical Age-class Structures

Three hypothetical 80 thousand acre forests are used to explore the relationship between length of time horizon and forest age-class structure. Two changes are made for these models: (1) adjusted present net values, noted in the preceding section, are included, and (2) the first-decade harvest ceiling is reduced by one-third to 27,848 cords. The latter adjustment is somewhat arbitrary, but is similar in magnitude to the acreage reduction. Selected outputs are presented in table 4.

Table 4.--Selected linear programming outputs for aspen types for 5-, 10-, and 15-decade time horizons, three hypothetical forest structures

Age distribution[a/]	Time horizon[b/]	Present net value[c/]	First decade harvest volume	Last decade harvest volume[d/]
		Million dollars	Thousands of cords/year	
Even	15	2.56	25.7	25.7
	10	2.70	27.8	29.4
	5	2.84	27.8	32.7
Young-aged	15	2.30	25.9	25.9
	10	2.33	26.8	26.8
	5	2.34	26.8	27.0
Old-aged	15	1.85	19.8	19.8
	10	2.80	27.8	30.0
	5	2.97	27.8	32.8

[a/] See table 1.
[b/] Number of nondeclining yield constraints.
[c/] Objective function.
[d/] Harvest volume in the last decade of the time horizon.

For all three forests, the 15-decade models underperform their 5- and 10-decade counterparts. The nondeclining timber yield constraints act as dampers on long-term harvest levels. The effect is most pronounced, as expected, in the "old-aged" forest. Here, excessive timber volumes are available in the short-term, but cannot be sustained. As a result, more acres received nonharvest prescriptions.

Projected harvest volumes are similar for the even- and old-aged forests when 10- or 5-decade time horizons are modeled. The young-aged forest did not have enough volume available to reach the first-decade harvest ceiling. At best, only modest increases in harvest volumes are projected over the planning horizons. However, in all cases, last-decade harvest volumes are below the long-term sustained yield. Thus, opportunities for expanded harvests exist, but not within the longer sets of nondeclining timber yield constraints. The least constrained models are reasonably consistent in short-term harvesting activities, regardless of initial forest structure. Hence, five-decade models may be satisfactory for many forest planning analyses, given the dynamic nature of periodic plan revision.

IMPLICATIONS

Analyses in this case study are subject to a number of qualifications. The models, however, are intentionally simple so that subtle differences in results are not obfuscated by complex model formulation. The thrust of this paper is to explore whether models can be simplified by reducing the analytical time horizon. Clearly, they can be, but with certain implications.

The existence of an objective function "truncation bias" in 5-decade models is evident and can be overcome easily in this spreadsheet modeling framework. Addressing this problem in the FORPLAN environment will require more ingenuity to insure that values will not be altered as time horizons are reduced. The truncation can also lead to multiple optimal solutions which can be handled through elimination of redundant prescriptions.

Overall, long-term model outputs are fairly sensitive to nondeclining timber yield constraints, especially for the 15-decade models. Additional prescription choices may alleviate this problem to a certain extent. However, the effect on short-term outputs may be negligible. Long-term models are designed to "guarantee" sustainability over very long planning horizons. Short-term models, on the other hand, go after surplus old-aged timber that long-term models cannot. Thus, certain analysis requirements may be met with shorter term models though sustainability may be in question. Clearly, more research is necessary to address this question.

It is likely that highly constrained forestwide FORPLAN models will not be very sensitive to shortened analytical time horizons. Forests with relatively more old-aged timber may be the exception. Given the time for and cost of constructing and solving FORPLAN models, it would be useful to develop a series of case studies examining the implications of shorter time horizons on short- and long-term outputs and activities. Since each forest is unique, rules-of-thumb rather than rules could then be developed to assist in selection of appropriate time horizons.

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evaluating the seriousness of a risk. These factors include, among others, catastrophic potential, familiarity, voluntariness, and dread.

Where homes, lives, or treasured ecosystems (e.g., Yellowstone) are at risk, the relevance of these findings is obvious. No matter how appealing economists and planners may find the C+NVC paradigm (or the underlying principles of marginal analysis, monetary valuation, and identification of potential Pareto improvements) we must be careful to avoid building decision-support systems that fail to reflect critical social and cultural considerations (Davis, 1965).

In light of these problems, it is hardly surprising that the overwhelming majority of CDF decision-makers could be characterized as suspicious of a C+NVC-based planning model, or indeed of any planning model designed to provide a "single solution" or "optimal budget". Their suspicion can not be dismissed as simply an aversion to limits on managerial discretion or a misplaced reliance on "experience". The same decision-makers have proven to be willing and able to accept a planning model that is consistent with the marginal decision-making process characteristic of their past efforts to rationalize investment and deployment decisions for firefighting resources, i.e., a model in which the focus is upon the effectiveness of identifiable firefighting resources in a familiar geographic context.

FPPS

FPPS consists of four Pascal programs (Figure 1): FBDMOD (calculates fire behavior using the NFDRS), MERGE (associates fire behavior estimates with historical fire records), FPPSTATS (calculates distributional characteristics of fire load), and CFES-IAM (simulates initial attack), and CFESDB (a Paradox database application for managing and querying CFES-IAM simulation inputs and results).

CFES-IAM simulation results are presented in four kinds of output screens or printouts, and are also saved to a datafile for input to CFESDB. Simulation results for particular representative fire locations are shown in "Event List" screens (Figure 2). These results are aggregated for reporting at the level of fire management analysis zones (FMAZs) (Figure 3). Utilization of individual firefighting resources is displayed in "Expected Annual Missions" screens (Figure 4). Finally, success in containing fires within simulation time and size limits is displayed in an "Initial Attack Success" screen (Figure 5).

EVALUATION OF FPPS DEVELOPMENT AND IMPLEMENTATION

That the FPPS analysis system has been as successful as it has thus far can in large part be traced to the dedication of the outstanding, dedicated individuals serving on the agency staff. Certainly, it is rare for an effort of this scope to be mounted with so little staff support. Only three agency staff, one of them an administrator, have been assigned to expedite this analysis, and all are charged with a host of other duties. The human resources constraint is binding, has greatly slowed the development and implementation of FPPS, and has been largely responsible for some costly mistakes. There has been no budget for a full-time staff programmer, forcing reliance upon a succession of undergraduate and graduate university students working on summer contracts, or on a part time basis. Though some were enrolled in computer science programs, these students were often new to programming, and learned many of their skills on-the-job, through trial and error. None had any background in wildfire protection or modeling, so it was unrealistic to expect them possess a level of understanding (of the data for which they were writing processing programs) that would permit them to assess the reasonableness of the output from their computer programs. Lack of programming experience and frequent redeployment of the planning staff on other agency analyses and the turnover rate contributed to an inadequate understanding of exactly what goes on in the FPPS programs, undermining their ability to detect programming bugs early on. An overarching emphasis on ease-of-use and data entry error-trapping motivated by the lack of computer experience among field personnel resulted in programs that were full of flash, but hardly bug-free.

The planning staff's lack of experience in designing, developing and maintaining computerized databases, and the field employees' lack of computer experience were other serious obstacles to successful implementation. Because of this inexperience, the planning staff was inclined to automate the data processing to the maximum extent possible. Towards this end, they contracted with the authors through the University of California to hire a student to develop RBase applications; however, the relatively primitive capabilities available in RBase at that time rendered that effort a failure. When this became clear, UC researchers wrote Pascal code to achieve a suitable degree of automation outside of RBase, and the databases became mere repositories. These programs were turned over to the CDF student programmers for interface development and maintenance.

Even more problematic has been the task of maintaining data integrity throughout the analysis process. The fire history databases have always contained records that appeared unlikely, but could not easily be verified. While most key-punch errors could be corrected, multiple reports of the same fire incident were quite difficult to determine, and the common practice of entering a final fire size of 0 for both small fires (less than .1 acre) and for non-fire incidents (like emergency medical responses) added to the confusion. Because of the distributed implementation, there is limited quality control over the CFES-IAM input data

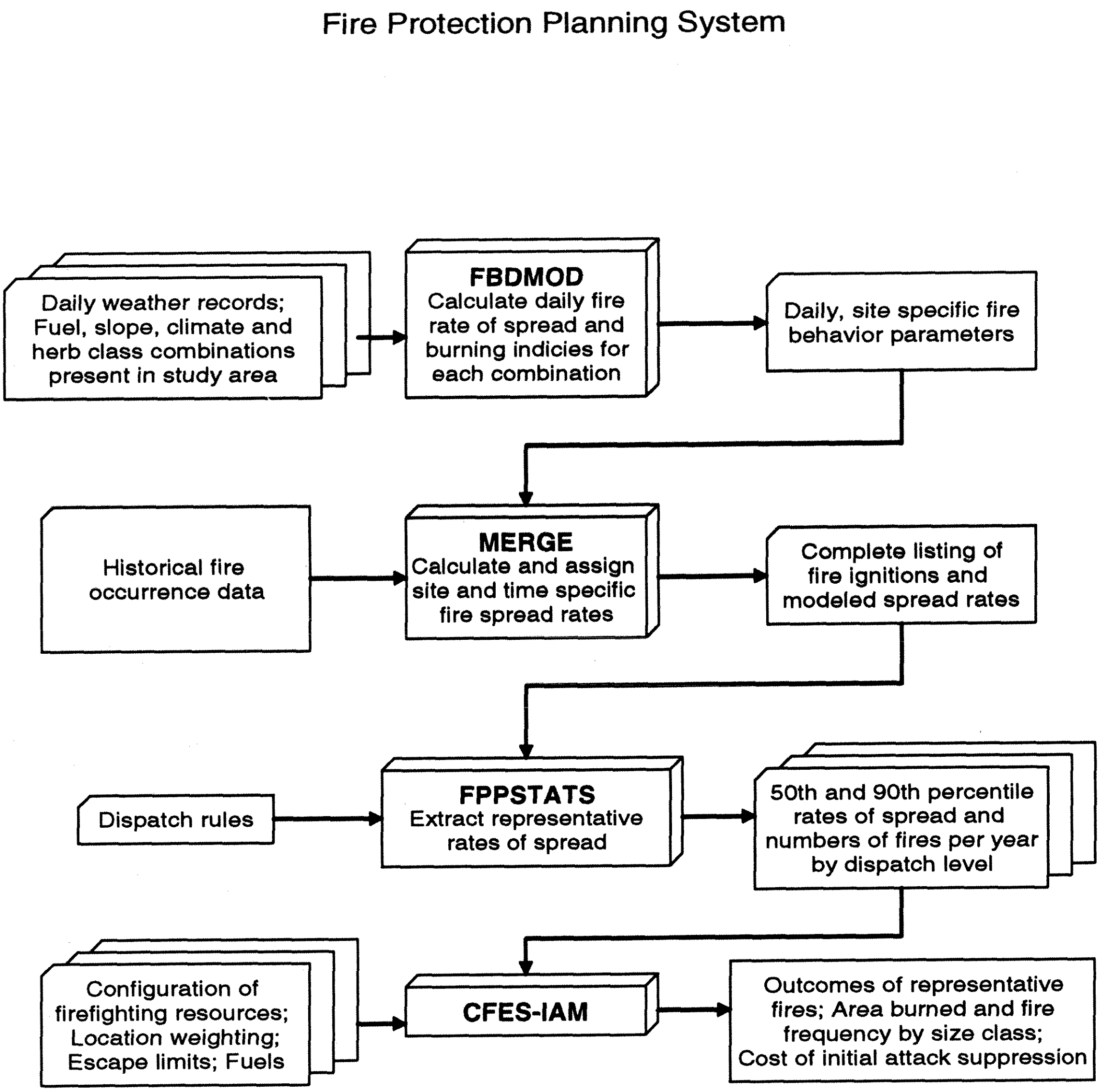

Figure 1.--Data flow diagram for the Fire Protection Planning System. Micro-computer programs are indicated in bold face type.

File: SNCAM.CF1

CFES-IAM OUTPUT SCREEN # 101

EVENT LIST FOR RFL # 1

FDL/ ROS %ile	ROS CH/HR	PERIM. IN-CREASE RATE CH/HR	TIME TO CONTAIN-MENT MINUTES	ACREAGE FINAL OR ON ARR. OF LAST RESOURCE	# OF RES. USED/ AVAIL.	UNCON-TAINED PERIM ON ARR. OF LAST RES.	AGGREG. PRODUC. ON ARRIVAL OF LAST RES.	NUMBER OF FIRES PER YEAR	SUPPRESS. COSTS $
L/50	0.0	0.0	0	0.00	0/34			0.0	0.00
L/90	0.0	0.0	0	0.00	0/34			0.0	0.00
M/50	30.4	73.6	11	1.45	2/37			4.3	0.00
M/90	110.7	268.1	ESL @ 81	877.72	24/37			1.1	UNKNOWN
H/50	56.7	137.3	53	100.93	17/40			2.1	0.00
H/90	137.2	332.3	ESL @ 92	1739.30	34/40			0.5	UNKNOWN

Figure 2.--Event List output screen from the California Fire Economics Simulator.

File: SNCAM.CF1

CFES-IAM OUTPUT SCREEN # 113

EXPECTED ANNUAL ACREAGE BURNED IN CONTAINED FIRES FOR ALL RFLS

FDL	0-0.25	0.25-3.0	3.0-50	50-100	100-300	AVERAGE FIRE SIZE	TOTAL ACRES
L	0.00	0.00	0.00	0.00	0.00	0.00	0.00
M	0.00	19.37	325.44	0.00	0.00	6.37	344.80
H	0.00	0.00	63.21	520.16	1255.63	71.28	1839.00
TOTAL	0.00	19.37	388.64	520.16	1255.63	27.33	2183.80

EXPECTED ANNUAL NUMBER OF FIRES BY SIZE CLASS

FDL	0-0.25	0.25-3.0	3.0-50	50-100	100-300	ESL	TOTAL FIRES
L	0.00	0.00	0.00	0.00	0.00	0.00	0.00
M	0.00	21.21	22.07	0.00	0.00	10.82	54.10
H	0.00	0.00	1.44	9.08	10.11	5.16	25.80
TOTAL	0.00	21.21	23.52	9.08	10.11	15.98	79.90

Figure 3.--Expected Annual Fire Statistics output screen from the California Fire Economics Simulator.

File: SNCAM.CF1

CFES-IAM OUTPUT SCREEN # 114

EXPECTED ANNUAL MISSIONS

ID CODE	LOW FDL	MEDIUM FDL	HIGH FDL	TOTAL	MISSION COSTS
LNUB2576	0.00	3.68	5.93	9.61	$ 0
LNUB2563	0.00	3.68	5.93	9.61	$ 0
LNUB3864	0.00	3.68	7.59	11.26	$ 0
SCUB6176	0.00	9.41	11.04	20.46	$ 0
SCUB6169	0.00	9.41	11.04	20.46	$ 0
SCUB4184	0.00	35.92	21.88	57.80	$ 0
SCUB4161	0.00	35.92	21.88	57.80	$ 0
CZUB1175	0.00	9.63	10.17	19.79	$ 0
SNUB2174	0.00	1.08	0.52	1.60	$ 0
SCUB3183	0.00	17.53	12.59	30.12	$ 0
SCUB3179	0.00	17.53	12.59	30.12	$ 0
SCUB3281	0.00	9.74	10.11	19.85	$ 0
SCUB2275	0.00	19.26	12.07	31.33	$ 0
SCUB1165	0.00	19.26	13.52	32.78	$ 0
SCUB1178	0.00	19.26	13.52	32.78	$ 0

Figure 4.--Expected Annual Missions output screen from the California Fire Economics Simulator.

File: SNCAM.CF1

CFES-IAM OUTPUT SCREEN # 120

INITIAL ATTACK SUCCESS

PERCENTAGE OF FIRES CONTAINED WITHIN SIMULATION SIZE AND TIME LIMITS

RFL	LOW FDL	MEDIUM FDL	HIGH FDL	TOTAL	SUPPRESSION COST FOR CONTAINED FIRES
1	100.0	100.0	80.0	93.5	0
2	100.0	100.0	80.0	93.5	0
3	100.0	100.0	80.0	93.5	0
4	100.0	100.0	80.0	93.5	0
5	100.0	100.0	80.0	93.5	0
6	100.0	100.0	100.0	100.0	0
7	100.0	100.0	80.0	93.5	0
8	100.0	80.0	80.0	80.0	0
9	100.0	100.0	80.0	93.5	0
10	100.0	100.0	100.0	100.0	0
11	100.0	100.0	100.0	100.0	0
TOTAL	100.0	98.6	89.6	95.7	0

Figure 5.--Initial Attack Success output screen from the California Fire Economics Simulator.

files or simulation nomenclature. When simulation outputs are loaded into a master database (CFESDB) in Sacramento, they usually contain some errors (due to faulty inputs) that go undetected for several months. Within the CDF, there still appears to be some hope, however unrealistic, that an application can be written to automate all queries to CFESDB. The nature of the queries is so varied that an intensive instruction of Sacramento planning staff in the art of ad hoc database query, probably via a standardized protocol like QBE or SQL, appears to offer the best chance of fututre success. Though the planning staff strongly desires field level self-sufficiency in answering "what-if" questions, the current state of relational databases and the background and time constraints of field personnel make this an unlikely prospect in the near term.

Partly because agency administrators in Sacramento had little, if any, experience working with analytic models generally, let alone, computer simulation models, confusion about the capabilities of FPPS and the range of analyses that could be conducted using it was not uncommon. After the existence of FPPS became generally know throughout the CDF organization, (thanks to a high profile rollout at all levels of the agency), CDF brass began to turn to the fire protection planning staff when a crisis arose with a request to find a solution using FPPS. These requests occasionally indicated an incomplete understanding of what FPPS is or how it works. Some requests would have required data not yet collected. Quite possibly, the briefing sessions at which these administrators were introduced to the simulator fired up their imaginations about what kind of analyses would be desirable.

Despite these difficulties, FPPS is enjoying a degree of success at the central and regional levels. Rightly or wrongly, as a result of consistent lobbying and early ad hoc FPPS analyses that proved valuable, most CDF administrators have come to hold FPPS in reasonable esteem. At the ranger unit level, early adopters have used the model to explore all kinds of alternatives, from repositioning a fire station to dropping air tankers from most dispatches, and have usually found that the model confirmed their intuition. At the regional and Sacramento (central) levels of CDF, administrators have run numerous scenarios in preparation for the deepest budget cuts the agency has ever seen. While these FPPS users strongly desire a model that yields cut-and-dried answers to the question of which firefighting resources to idle, they have accepted that they cannot escape the responsibility for such decisions and seem to appreciate having this tool available to enhance their assessment of the options.

As with most simulators deployed in an operational context, a principle benefit has been the enhancement of agency staff's understanding of the system that they guide and plan for. Part of this understanding results from the process of formalizing decision rules to be built into CFES-IAM and its more sophisticated descendent, CFES-IAM version 2. Agency personnel, especially at the higher administrative levels, were often ill equipped to answer the model-builders' questions, so considerable opportunities for expert surveys and "Delphi" knowledge acquisition were exploited. Ancillary benefits of these sessions included a heightened awareness among Sacramento staff of the situations faced in the field and the methods used to address them, and a higher degree of respect by the field personnel for the Sacramento staff, both because of their perception of the utility of FPPS and the self-esteem generated by the "mucky-mucks" seeking their expert opinion.

CONCLUSIONS

In the development of FPPS, we abandoned the C+NVC paradigm and tried to work within the decision-making framework to which the agency was accustomed. Borrowing liberally from NFMAS (and especially its IAA model), we limited the scope of FPPS to a manageable problem (initial attack). We cast the model in terms of the utilization of identifiable firefighting resources (e.g., the Santa Rosa engine) in easily visualized situations (e.g., high population density grasslands along Highway 101). This greatly simplified our task as consultants -- we were able to focus our attention on the part of the problem that was realistically amenable to quantification by a couple of researchers, rather than forced to design a system to reduce a mass of questionable data to a single decision criterion. But most importantly, this strategy produced outputs that enhanced, rather than threatened, the CDF's decision-making process.

To conclude on a philosophical note, if we (the members of the SAF E4 working group) want to keep our egos in check, we need only stop and make an objective appraisal of the degree to which the models we develop have been successfully integrated into our clients' management decision-making. Our track record is abysmal. We assume that everyone in E4 wants their models to be actually <u>used</u> and honestly wants to be responsive to the needs and mission statements of land grant universities and government agencies that fund our work. If this is true, we must all be ready to jettison time-honored economic paradigms that have outlived their usefulness (or that never had anything useful to say). In the case of wildfire protection planning on non-federal wildlands, it is time to allow the C+NVC paradigm to gracefully depart to the nether regions where bi-metalism and mercantilism now reside.

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MODELLING REGENERATION AND PEST CONTROL ALTERNATIVES FOR A FOREST SYSTEM IN THE PRESENCE OF FIRE RISK[1]

Richard H.H. Moll[2]

Abstract.-- This paper describes an optimization model developed to solve for the optimal regeneration harvest and pest protection schedule by age and species taking account of fire risk, which produces a desired wood quantity over time at maximum discounted net profit.

Keywords: Optimal Forest Management, Harvest Scheduling, Stochastic Linear Programming.

INTRODUCTION

In the spirit of existing forest planning models (Boychuk [1988], Reed and Errico[1986]) this paper proposes a simulation-optimization model which integrates the following concepts in a single framework:

(1) species diversity;
(2) catastrophic losses due to fire;
(3) infestation of susceptible species;
(4) natural regeneration and planting;
(5) pest protection; and
(6) conversion of susceptible to non-susceptible.

The fire-pest-regeneration control model was designed to economically evaluate: (1) alternative regimes for protection spraying of susceptible species against insect infestations; and (2) harvesting strategies which include conversion of susceptible species to non-susceptible species by planting; subject to the risk of catastrophic losses due to fire and insect infestations. The model determines the optimal timber regeneration[3] harvest and pest protection schedule during each simulation time period subject to fire risk that produces a desired wood quantity over time at maximum net profit.

This is a problem of applying dynamic optimization procedures to a renewable natural resource system. For an excellent recent review of these optimization techniques used in the analysis of natural resource systems see Williams [1989]. According to his classification the technique proposed in this paper may be characterized as simulation-optimization or simulation-gaming. That is, due to the uncertainty inherent in long term forest management problems, sub-optimal strategies are evaluated via a simulation model for feasibility.

As pointed out by Williams [1989] , " . . *the responsive, evolving nature of these systems requires adaptive management strategies that influence, and are influenced by, the system dynamics.* " Consequently, a feedback control strategy is adopted to take into consideration the stochastic nature of fire and insect infestation damage.

We are concerned with proof of concept and will keep the model structure as simple as possible yet sufficiently rich to be able to examine the required concept. We need to be able to represent the evolution of a forest with several species. We are also concerned with insect infestation therfore it is reasonable to first partition the forest into susceptible and non-susceptible species. For the susceptible species we further subdivide the areas into those infested and those that are not. Furthermore, for the infested stands, we need to account for areas which are protected through spraying programs.

We consider only one type of spraying: to protect the stands for harvest in the subsequent period. Since we are addressing strategic problems associated with a large region it would, in the first instance, be sufficient to treat the losses due to fire and insect infestations deterministically. The regeneration options (i.e natural versus planting) will be associated with the definition of the harvesting variables. For example the definition of these variables will assume either natural regeneration or regeneration by planting .

[1] presented at the Symposium on Systems Analysis in Forest Resources, Charleston, SC, March 3-7, 1991
[2] Senior Research Analyst, Statistics Canada, 20-L R.H. Coats Bldg., Tunney's Pasture, Ottawa, Ontario, K1A 0T6.
[3] natural versus planting

Why solve this problem? Preliminary results from Reed and Errico [1986] suggested that even low rates of fire can result in considerably lower harvest projections than those obtained assuming no catastrophic losses. It is expected that the combined effect of loss due to insect infestations and fire will further reduce the sustainable harvest level. The nature of the harvest trajectory required to approach maximum sustained yield may also change. The immediate implication of these concepts for forest management is that, given the existence of catastrophic losses, current timber supply projections based on forest models which ignore these losses may well be too high.

In order to validate the proposed fire-pest-regeneration forest management model as described in the next section we need to answer the following question: *"How confident are we to use the deterministic policy when faced with obvious uncertainties such as fire and insect infestations ? "* This forest management problem (FMP) can be solved using linear programming. We used GAMS for the implementation of the proposed FMP. A PC version of GAMS has been developed (Brooke, Kendrick and Meeraus [1988]). With GAMS automatic model documentation is achieved by having a language easily read by people and computers. This assures that the model the analyst conceives is in fact being solved by the computer. Also the readability of the GAMS programs means the analyst can explain the model to others with ease and benefit from their comments and suggestions.

ALGEBRAIC DESCRIPTION IN GAMS

In this section we present the mathematical description of the forest management problem in **GAMS**. This suggests a consistent, unambiguous modelling style. First, all entities of the model are identified and grouped by type (e.g. indices, decision variables etc.) Second, the ordering of entities is chosen so that no symbol is referred to until it is defined. Third, the units of all entities are specified, and, fourth, the units are chosen to a scale such that the numerical values to be encountered by the optimizer have relatively small absolute orders of magnitude. Terminology varies amongst modellers. For example, economists use the terms "exogenous variable" and "endogenous variable" for "given data" and "decision variable", respectively. In GAMS, the terminology adopted is as follows: indices are called SETS, given data are called PARAMETERS, decision variables are called VARIABLES, and constraints and the objective function are called EQUATIONS.

We describe the state of the forest by four state variables $x_i(t)$, $y_i(t)$, $z_i(t)$ and $zp_i(t)$ which represent the area of timber at the beginning of time period t in age-class i which is **non-susceptible, susceptible uninfested, susceptible infested unprotected** and **susceptible infested protected** respectively. These variables are related inter-temporally by fire, infestation, harvesting and growth processes which are described algebraically in the area balance equations or graphically in next section.

Sets

Sets are fundamental building blocks and allow a model to be succinctly stated. These describe the level of disaggregation while providing a notation for indexing. The elements in a set are the labels.

i	age-classes {i-20, i-40, i-60, i-80, i-100, i-120, i-140, 1-160, i-180}	
t	time periods	{P-1*P-10}

Scalars

PD	sales price of pulp	($ /m^3)
i	interest rate	
MUP	planting cost	($ /ha)
MUC	cutting cost	($ /ha)
MUS`	spraying cost	($ /ha)
μ	percent vol. reduction unprotected infested	(%)
ß	percent vol. reduction protected	(%)
γ	max inter-period pulp flow proportion	

Parameters

$p_i(t)$	proportion of non-susceptible timber burned in age-class i during period t	
$q_i(t)$	proportion of susceptible uninfested timber in age-class i during period t burned	
$s_i(t)$	proportion of susceptible uninfested in age-class i that becomes infested in period t and remains in age-class i in t+1	
$ru_i(t)$	proportion of susceptible unprotected infested area in age-class i burned during period t	
$rp_i(t)$	proportion of susceptible protected infested area in age-class i burned during period t	
xo_i	area of non-susceptible timber in age-class i at the start of time period P1	(ha)
yo_i	area of susceptible uninfested timber in age-class i at the start of period P1	(ha)
zo_i	area of infested susceptible species in age-class i at the start of period P1 not protected.	(ha)
zpo_i	area of infested susceptible protected timber at the start of period P1.	(ha)
VNS_i	volume of non-susceptible existing and planted forest	(m^3/ha)
VS_i	volume of susceptible existing and planted forest	(m^3/ha)

PositiveVariables

$h_i(t)$	area of non-susceptible timber harvested in age-class i in period t and regenerates naturally as age-class i-20 at the start of period t+1.	(ha/period)
$g_i(t)$	area of uninfested susceptible timber harvested in age-class i in period t and regenerates natural as age-class i-20 at start of period t+1	(ha/period)

$gc_i(t)$ area of uninfested susceptible timber harvested in age-class i in period t and is converted to non-susceptible species as age-class 1 at start of period t+1 by planting. (ha/period)

$f_i(t)$ area of infested susceptible not protected species harvested and naturally regenerates as age-class i-20 a the start of period t. (ha/period)

$fc_i(t)$ area of infested susceptible unprotected timber which is harvested and converted to non-susceptible timber at the start of period t+1. (ha/period)

$pr_i(t)$ area of susceptible infested area protected in time period t. (ha/period)

$fp_i(t)$ area of susceptible infested protected timber in age-class i harvested in period and regenerates naturally as age-class i-20 at the start of period t+1 (ha/period)

$fcp_i(t)$ area of susceptible infested protected timber in age-class i harvested and converted to non-susceptible age-class i-20 at the start of period t+1. (ha/period)

$x_i(t)$ area of non-susceptible timber in age-class i at the start of time period t . (ha)

$y_i(t)$ area of susceptible uninfested timber in age-class i at the start of period t (ha)

$z_i(t)$ area of infested susceptible species in age-class i at the start of period t not protected. (ha)

$zp_i(t)$ area of infested susceptible protected timber at the start of period t (ha)

pulp(t) final shipments of pulp (m^3/period)

Free Variables

phi	total benefit	($)
phip(t)	planting cost	($ /period)
phil(t)	cutting cost	($ /period)
phix(t)	sales revenue	($ /period)
phis(t)	spraying cost	($ /period)

Equations

PBAL(t)	Pulplogs balance	(m^3/period)
ASALES(t)	Sales revenue	($/period)
ACUTC(t)	Cutting cost	($/period)
APLANT(t)	Planting cost	($/period)
ASPRAYC(t)	Spraying cost	($/period)

Area Balance Constraints

BALX1(t)	non-susceptible age-i-20	(ha)
BALX2(i,t)	non-susceptible middle ages	(ha)
BALX3(t)	non-susceptible oldest age	(ha)
BALY1(t)	susceptible uninfested age-i-20	(ha)
BALY2(i,t)	susceptible uninfested middle age	(ha)
BALY3(t)	susceptible uninfested oldest age	(ha)
BALZ(i,t)	susceptible infested unprotected	(ha)
BALZP1(i,t)	susceptible protected i-20 to i-180	(ha)
BALZP2(t)	susceptible protected age i-180	(ha)

Area Cut Restrictions

CUTX(i,t)	non-susceptible	(ha/period)
CUTY(i,t)	susceptible-uninfested	(ha/period)
CUTZ(i,t)	infested-unprotected	(ha/period)
CUTZP(i,t)	infested-protected	(ha/period)
SY1(t)	max declining yield	(m^3/period)
SY2(t)	max increasing yield	(m^3/period)
BENEFIT	Total benefit	($)

CONSTRAINT EQUATIONS

PBAL(t)..

pulp(t) =L=

$$\text{sum}(i, VNS_i[h_i(t)+gc_i(t)+(1-\mu)fc_i(t)+(1-\beta)*fcp_i(t)]$$
$$+VS_i*[g_i(t)+(1-\mu)*f_i(t)+(1-\beta)*fp_i(t)]\ );$$

ASALES(t)..

phix(t) =E= PD*pulp(t);

ACUTC(t)..

phil(t) =E=

$$MUC*\text{sum}(i,[h_i(t)+g_i(t)+gc_i(t)+fc_i(t)+fp_i(t)+fcp_i(t)]);$$

APLANT(t)..

$$phip(t) =E= MUP*\text{sum}(i,[gc_i(t)+fc_i(t)+fcp_i(t)]);$$

ASPRAY(t)..

$$phis(t) =E= MUS*\text{sum}(i, pr_i(t));$$

SY1(t-1)..

$$pulp(t) =G= (1-\gamma)*pulp(t-1)\ ;$$

SY2(t-1)..

$$pulp(t) =L= (1+\gamma)*pulp(t-1)\ ;$$

BALX1(t+1)..

$$x_{"i-20"}(t+1) =E=$$

$$\text{sum}(i, [h_i(t)+p_i(t)\{x_i(t)h_i(t)\}+gc_i(t)+fc_i(t)+fcp_i(t)]);$$

BALX2(i,t+1) $ (ord(i) NE 1)*(ord(i) NE card(i))..

$$x_i(t+1) =E= \{1-p_{i-1}(t)\}\{x_{i-1}(t)-h_{i-1}(t)\};$$

BALX3(i,t+1) $ (ord(i) EQ card(i)) ..

$$x_i(t+1) =E= \{1-p_{i-1}(t)\}\{x_{i-1}(t)-h_{i-1}(t)\}$$
$$+\{1-p_i(t)\}\{x_i(t)-h_i(t)\};$$

BALY1(t) ..

$y_{"i-20"}(t+1)$ =E=

sum(i, [$g_i(t)+f_i(t)+q_i\{y_i(t)-g_i(t)-gc_i(t)\}$

$+ru_i(t)\{z_i(t)-f_i(t)-fc_i(t)-pr_i(t)\}+fp_i(t)$

$+rp_i(t)\{zp_i(t)-fp_i(t)-fcp_i(t)\}$]);

BALY2(i,t) \$ (ord(i) NE 1)*(ord(i) NE card(i))..

$y_i(t+1)$ =E= $\{1-q_{i-1}(t)-s_{i-1}(t)\}\{y_{i-1}(t)-g_{i-1}(t)-gc_{i-1}(t)\}$;

BALY3(t+1) \$ (ord(i) EQ card(i)) ..

$y_i(t+1)$=E=$\{1-q_{i-1}(t)-s_{i-1}(t)\}\{y_{i-1}(t)-g_{i-1}(t)-gc_{i-1}(t)\}$

$+\{1-q_i(t)-s_i(t)\}\{y_i(t)-g_i(t)-gc_i(t)\}$

BALZ(i,t+1)..

$z_i(t+1)$ =E=

$s_i(t)\{y_i(t)-g_i(t)-gc_i(t)\}+\{1-ru_i(t)\}\{z_i(t)-f_i(t)-fc_i(t)-pr_i(t)\}$;

BALZP(i,t+1) \$ (ord(i) NE card(i))..

$zp_i(t+1)$ =E= $pr_i(t)+\{1-rp_{i-1}(t)\}\{zp_{i-1}(t)-fp_{i-1}(t)-fcp_{i-1}(t$

BALZP(t+1) \$ (ord(i) EQ card(i))..

$zp_i(t+1)$ =E=

$pr_i(t)+\{1-rp_{i-1}(t)\}\{zp_{i-1}(t)-fp_{i-1}(t)-fcp_{i-1}(t)\}$

$+\{1-rp_i(t)\}\{zp_i(t)-fp_i(t)-fcp_i(t)\}$;

CUTX(i,t) .. $h_i(t)$ =L= $x_i(t)$;

CUTY(i,t) .. $g_i(t)+gc_i(t)$ =L= $y_i t)$;

CUTZ(i,t) .. $pr_i(t)+f_i(t)+fc_i(t)$ =L= $z_i(t)$;

CUTZP(i,t) .. $fp_i(t)+fcp_i(t)$ =L= $zp_i(t)$;

BENEFIT..

PHI =

sum(t, (1.05)**(-20*(ORD(t)-1))*[phix(t)-phip(t)-phil(t)-phis(t)

MODEL **FPM** /ALL/;

SOLVE **FPM** USING **LP** MAXIMIZING **PHI**;

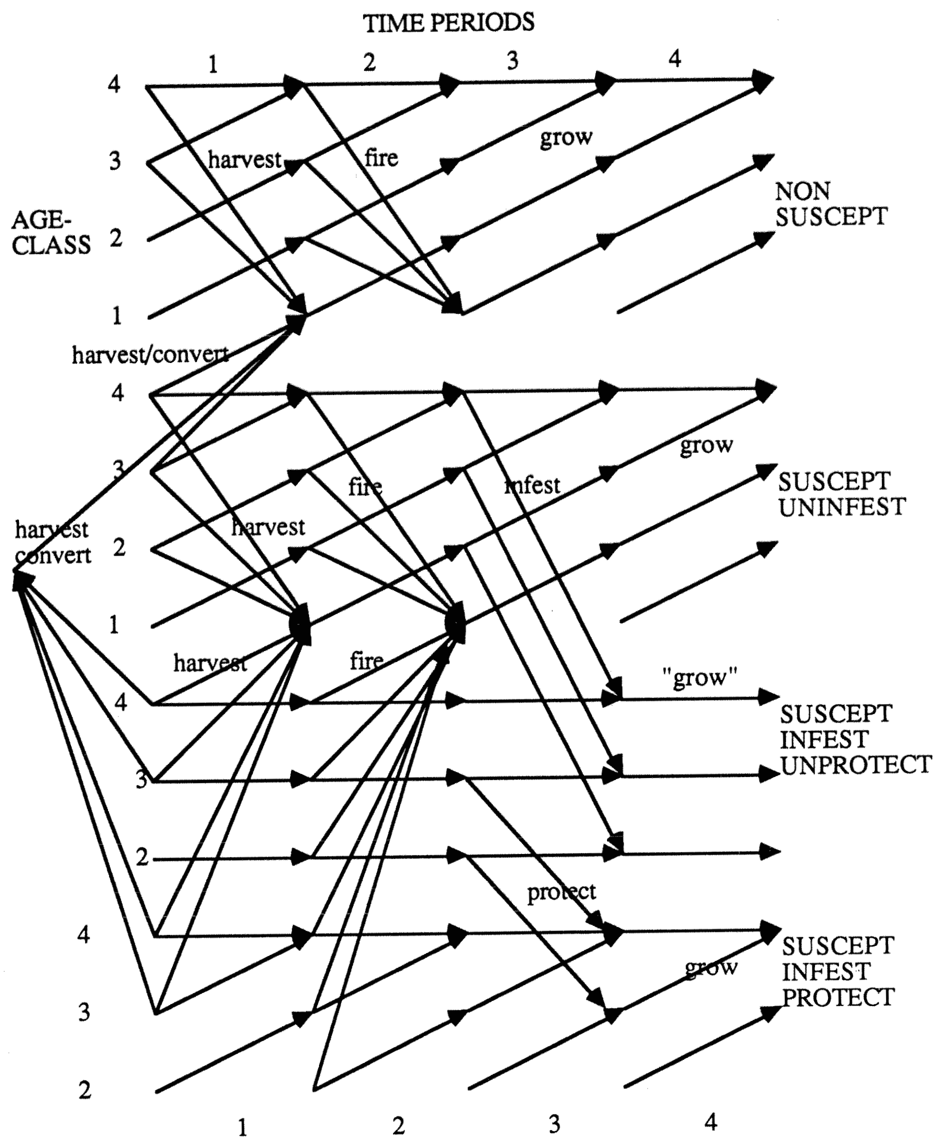

Figure 1: Graphical Representation of the Fire Pest Protection Model

GRAPHICAL REPRESENTATION

The area balance constraints as described by the equations BALX, BALY, BALZ, and BALZP above may be more easily understood by reference to a graphical representation of the problem. We consider in *Figure 1* four sets of nodes corresponding to the state variables $x_i(t)$, $y_i(t)$, $z_i(t)$ and $zp_i(t)$. For each variable a node may be referenced by (i,t) the age-class i and the beginning of the time period t.

The sum of all inflowing arcs is equal to the state variables $x_i(t)$, $y_i(t)$, $z_i(t)$ and $zp_i(t)$. For example if we consider node (4,2) the area of non-susceptible species in age-class 4 at the beginning of time period 2 is $x_4(2)$ and equals the flow from node (4,1) plus the flow from (3,1). At each node there is conservation of flow: i.e. the sum of inflows equals the sum of outflows.

It is easy to identify from *Figure 1* the principal activities which occur at each node. For each variable we may classify activities that occur at the oldest age-class, intermediate age-classes and the first or regeneration class. For the non-susceptible species we notice that for any age-class other than the first, area transitions to the regeneration class at the start of the next period may be a result of harvesting or fire loss. In the susceptible species we may either harvest and regenerate naturally (i.e the same species) or harvest and convert to the non-susceptible species. The susceptible uninfested states may become infested by spruce budworm and so a transition to the state susceptible-infested-unprotected would occur. Also this state may be protected by spraying which would result in a transition from susceptible-infested unprotected to susceptible-infested-protected. Fire loss may occur in all three susceptible states and it is assumed that after fire natural regeneration is established at the beginning of the subsequent period.

MODEL VALIDATION

In this section we develop confidence in the model by testing how well the deterministic policy holds in a simulated stochastic environment as well as providing a sensitivity analysis to examine the model's response to parametric and structural changes. In the first sub-section we attempt to validate the assumptions of using deterministic fire and infestation hazard rates. Due to the long term nature of the problem it is not possible to validate the fire and pest protection model in the real world; we cannot wait a hundred years! However, we propose a "validation procedure" which tests how well the model works in a simulated stochastic environment. In the second sub-section the impact on the "optimal" timber supply of changing the discount rate, annual fire rates and the maximum proportional increase or decrease in the sequential flow constraints is provided in a sensitivity analysis.

Simulation of a Stochastic Solution

Events such as forest fires and insect infestations occur randomly. Therefore, we need to know how well the deterministic policies hold in a simulated stochastic environment. We can then test the performance of the deterministic model in a simulated "real" world. The solution to the simpler deterministic problem may be sufficient to provide an estimate of the long run sustainable yield subject to fixed rather than random losses due to fire and insect infestation. In order to test the validity of the deterministic policy we seek an answer to the question:

Q1. *How confident are we to use the deterministic policy when faced with obvious uncertainties such as fire and infestation losses ?*

A procedure was developed to answer this question by attempting to solve the stochastic control problem. The solution will be a "feedback policy" where the optimal harvest will depend on the current state and possibly on previous states and harvests. Since a solution to the true stochastic problem is difficult to obtain an approximation of the *stochastic control problem* is suggested. This solution may then be compared with the simpler deterministic policy. The closeness of these two policies will provide a measure of confidence for the simpler policy.

The idea is to use the optimal solution to the deterministic problem in a *feedback fashion* to obtain an approximately optimal solution to the stochastic control problem. An iterative simulation-linear programming approach is used to solve the fire and pest protection problem when fire proportions were allowed to be random variables with empirically based distributions.

The *iterative simulation-LP approach* involves:

(1) solving the deterministic problem at each time period based on the current system state and average values for the fire and infestation proportions; and

(2) updating the the system state based on the optimal harvests and protection controls, and then simulating the state transition at the next period with the simulation model (the dynamical area balance equations), using random fire infestation proportions.

The *approximate optimal harvest strategy* obtained in this fashion is compared with the *deterministic solution.* Problems in which parameters are unknown or uncertain rarely have exact solutions.

The iterative *simulation-linear programming procedure* reminds us that the major purpose in using a timber management scheduling model is only to consider the long run impact of management actions in developing a schedule for the immediate period. Decisions concerning the use of limited resources in future periods should be delayed until more information becomes available.

The key to this process is that at any point (period) in time one is solving for the *immediate actions* only. Other actions are considered only to help measure the long-term impacts of the immediate actions. Uncertainty makes it difficult to evaluate the long-term impacts.

Results and Conclusions from the Stochastic Simulation

Application of the iterative "feedback" procedure using randomly generated fire probabilities was efficiently implemented using a SAVE and RESTART feature of GAMS. The deterministic fire pest model using average per period fire and infestation rates was solved (*the deterministic solution*) and saved using the GAMS SAVE command which saves an entire problem setup and values of all defined parameters during execution.

The subsequent solutions LP2 to LP10 are obtained from another GAMS file, the "stochastic LP simulator" by calling upon the saved file which contained *the deterministic solution* using the GAMS RESTART command. The stochastic simulator is providing, for each re-run LP2-LP10, new initial conditions on the states for the originally defined problem.

This enables all the stochastic solutions to be referenced to the same deterministic run. Furthermore, we recall the fire and pest model has a *network flow structure.* One characteristic of network problems is that an initial feasible solution is difficult to obtain. This is evidenced by the large number of iterations required to obtain the initial optimal deterministic solution. However, once a feasible solution is found subsequent solves, as required in the creation of the sample path (i.e. solutions LP2-LP10), were obtained much faster.

An example of a sample path is given in *Figure 2.* For the sample path (st4), each point on the graph (i.e. at each time period) is obtained from one LP solution as explained in the above iterative optimization procedure. We obtained eight sample paths by resetting the seed of the pseudo random number generator for each one.

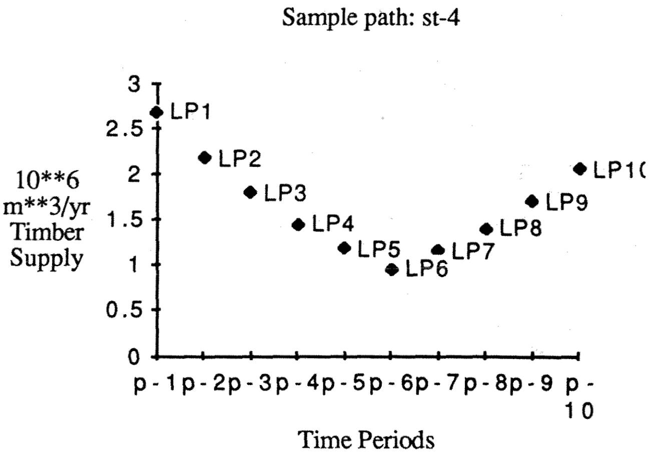

Figure 2: An example of the application of the Deterministic Control using Randomly generated Fire Probabilities; one sample path st4

We compare the approximate solutions to the stochastic control problem with the deterministic policy which assumed fixed fire and infestation rates. In *Figure 3* eight sample paths (labelled st1 to st8) obtained by simulating fire destruction and insect infestation rates for eight independent ten-period time horizons are shown together with an overlay of the deterministic solution obtained using an average period infestation rate of .2 and average period fire rate corresponding to a rate of .005 per annum which is traced by the solid line.

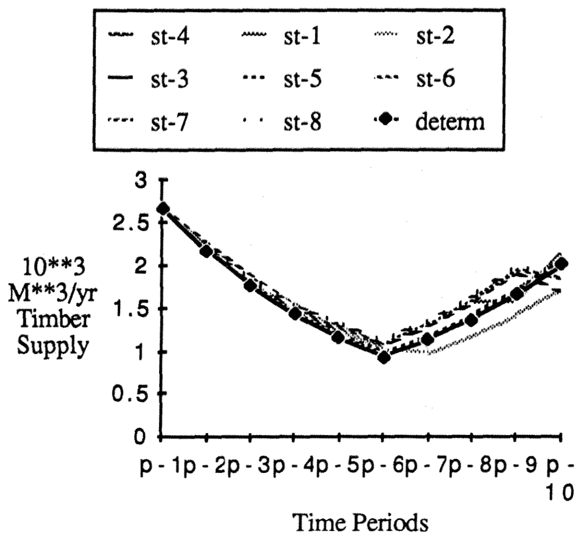

Figure 3: Optimal Feedback application of the Deterministic Control using Randomly generated Fire and Infestation Probabilities; eight sample paths (st1 to st8) plus an overlay chart of the Optimal Harvest solution using .005 average annual fire loss and average period infestation rate of .2 (the Deterministic Solution).

We observe that the deterministic solution follows closely the approximation to the stochastic solutions for the first six periods and then for the last four periods the randomness increases. The timber supply trajectories obtained from this iterative optimization procedure provide a region of confidence for the deterministic solution. This region widens towards the end of the time horizon indicating that we cannot be as sure of the timber supply in the long term when faced with uncertainties such as insect infestations or fire loss.

This increase in the variability of the optimal timber supply obtained from the state updating procedure may be explained by the restrictions imposed on cutting younger stands. During the latter part of the time horizon all the original older stands have been harvested and a large amount of regenerated timber is available for harvest in period 7. Specifically, the initial age-class distribution is uneven and has considerable over mature timber in age-classes i-120 and i-180 with little timber in i-140 and i-160 as can be seen in *Figure 4*.

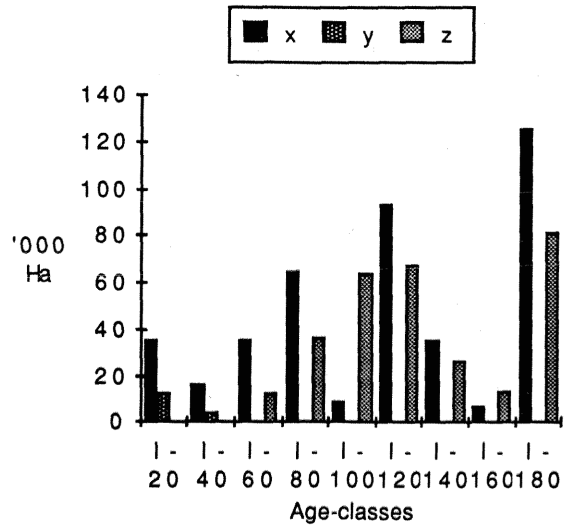

Figure 4: Initial Age-Class Distribution of The Kamloops Timber Supply Area.

Since we restrict cutting to at least age-class i-120 (non-susceptible) and i-100 (susceptible), by period 6 most of the original over-mature stands have been harvested and by period 7 much regenerated timber is available for harvest. The effect of fire in the younger stands appears to increase the variability in the optimal harvest. This is an important problem since, in our ideal model, we restrict the cutting of younger age-classes, yet in reality younger stands are often chosen for harvest for reasons of accessibility. If this suggestion is correct then the variability in the optimal supply would be higher and the problem compounded.

From these results we conclude that, since the optimal solution using average per period fire and infestation rates is sufficiently close to the approximate stochastic solutions obtained using the feedback application of the deterministic control using randomly generated fire and infestation probabilities, the deterministic fire and pest protection model is valid for evaluating policies for the present while taking the long term effects into consideration.

SENSITIVITY ANALYSIS

We have "validated" the stochastic components of the model. We extend this validation by providing answers to the following question in a sensitivity analysis:

Q2. *How sensitive is the optimal timber supply to variations in key model parameters such as discount rate, fire and inter-period flow constraints?*

Discount Rate Sensitivity

We solve the fully articulated fire and pest protection model using average period fire rates corresponding to a fixed per annum probability of .005 and period discount rates corresponding to 0, 1, 2, 3, 4, 5, and 6 percent real interest rates per annum. From Figure 5 we see that the optimal timber supply trajectory is relatively insensitive to changes in the discount rate. However, the total discounted net present value obtained from these solutions is affected as shown in Figure 6.

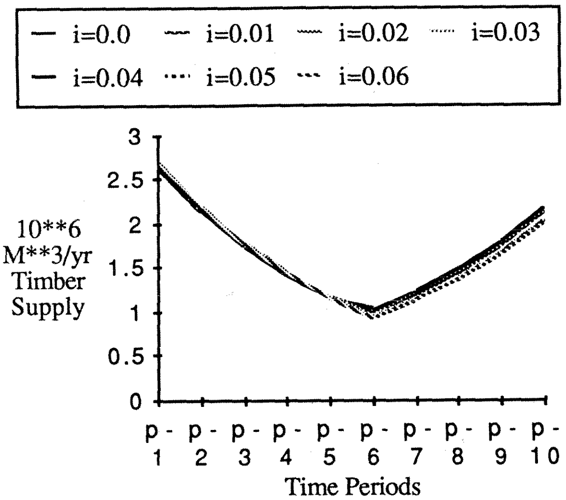

Figure 5: Effect of the Discount Rate on Timber Supply.

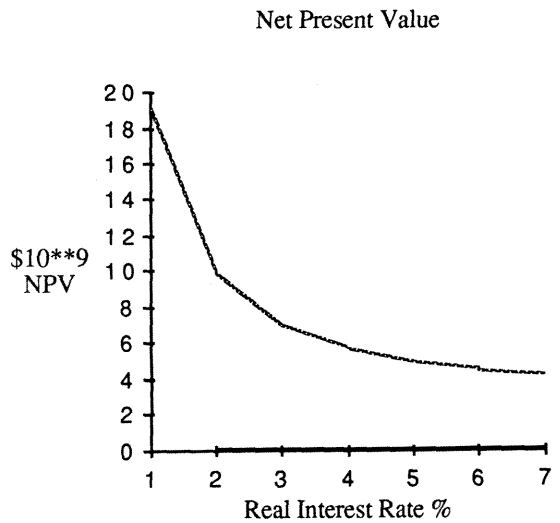

Figure 6: Effect of the Discount Rate on the total NPV.

Fire Rate Sensitivity

We show in *Figure 7* the optimal timber supply subject to changes in the fire rate. The solutions corresponding to annual fire destruction rates of 0, .001, .0025, .005, .0075, .01, and .0125 are compared. The trajectory using a fire destruction rate of .005 is highlighted since we used this rate in the scenario analysis described in chapter eight. Historical data for the Kamloops TSA suggest a mean annual fire rate of approximately 1/10%. We have solved for fire rates which are 2.5, 5, 7.5, 10, and 12.5 times as large. These rates would not necessarily be expected to happen and are used to demonstrate that the model solution is sensitive to changes in the average fire rate. For example a 12.5 times increase in the average annual fire rate from p = .001 to .0125 produces a 30% drop in the optimal harvest level for the first period.

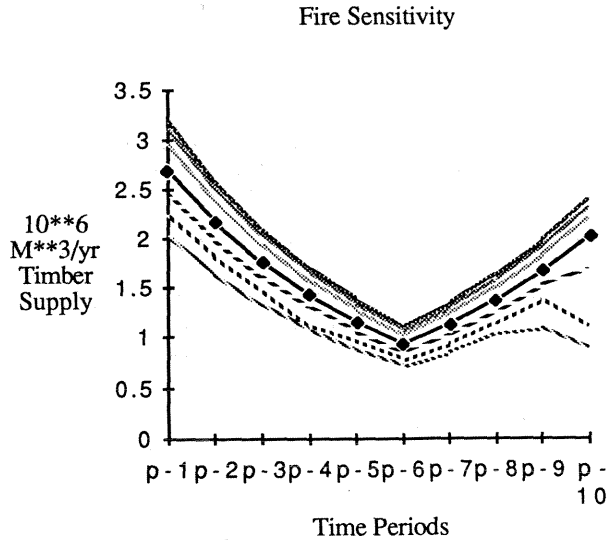

Figure 7:Effect of changing the Fire Rate on Timber Supply.

Sequential Flow Constraint Sensitivity

In *Figure 8* we show the effect on the "optimal" timber supply of changing the maximum proportional inter-period change in sequential pulp flow for a ten year period. We see how important this constraint is in determining the shape of the optimal harvest level. We have overlaid the solution obtained using a non-declining yield constraint. This constraint is equivalent to using a sequential flow constraint with zero maximum proportional decrease inter-period flow (i.e. pulp(t) ≥ pulp(t-1)). This solution provides a sustainable optimal harvest level of $1.53*10^6$ cubic metres per year. By increasing the maximum proportional decrease/increase for a ten-year period from 0 to .14 (i.e. 0% to 14%) the optimal first period supply increases 100%. This demonstrates that the supply is very sensitive to these inter-period flow constraints.

We also observe in *Figure 8* that increasing the maximum proportional decrease/increase in inter-period flow produces a supply characterised by a higher initial harvest which decreases to a minimum after 120 years and then increases towards the end of the planning horizon. We have identified the extreme trajectories for γ = 0, .14 as well as that corresponding to γ = .1 which was used in the stochastic validation.

Flow Constraints
Sensitivity

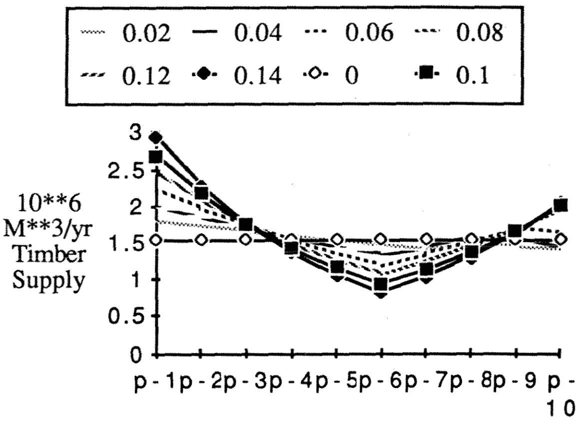

Figure 8: A comparison of the Optimal Timber Supply due to changes in the maximum proportional increase/decrease in sequential pulp flow corresponding to a ten-year period.

We have shown that the harvest flow constraints determine the nature of the "optimal" timber supply trajectory. The choice of these constraints will reflect government objectives as they relate to the forest industry. A non-declining yield, for example, could be used if the objective was to maintain stability in employment for a region.

Conclusions from the Sensitivity Analysis

We have examined how sensitive the fire and pest protection model optimal harvest trajectories are to changes in the discount rate, fire hazard rate and inter-temporal maximum proportional increase and decrease in sequential pulp flow. From this analysis we may conclude that model solutions are highly sensitive to changes in the fire and inter-period flow rates yet relatively insensitive to changes in the discount rate. We further conclude that since the optimal timber supply is so sensitive to changes in inter-temporal flow restrictions it supports the idea that the *forest-level harvest scheduling problem* is largely characterised by the form and magnitude of these constraints.

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LOBLOLLY PINE POPULATION DYNAMICS IN A NATURAL TWO-STORY STAND[1/]

Charles A. Gresham[2/]

Abstract.--A two-story, natural loblolly pine (Pinus taeda L.) stand in South Carolina's lower coastal plain was inventoried in 1976 and in 1987 to determine changes in both overstory and understory population characteristics. Understory mortality was great and overstory growth was slow during the 12-growing season period. A Weibull probability density function could not model the diameter distribution of both the overstory and understory populations together but could model the populations separately.

Keywords: DBH distributions, Weibull pdf, mortality.

INTRODUCTION

Two forestry issues have recently increased the need to understand the structure and function of mature pine stands. Red-cockaded woodpecker (Picoides borealis) den tree requirements necessitate long-rotation pine management and the still-developing "New Perspectives" forestry will probably result in more mature stands on National Forests.

Managing for woodpecker habitat involves not only retaining mature potential den trees, but also regenerating stands to provide future den trees. A two-story stand would support mature den trees while allowing regeneration beneath, thereby minimizing the area solely devoted to red-cockaded woodpecker management.

New perspectives forestry with its emphasis on biodiverstiy and ecosystem level management will probably result in more long rotation management because older ecosystems are thought to be the most diverse. Management of mature and over-mature stands for these objectives requires a knowledge of stand dynamics.

Hobcaw Barony is an ideal area to study processes in mature pine stands since the Barony is dominated by older loblolly and longleaf pine (Pinus palustris) stands with a known stand history. Supporting soil, hydrology and land use data are compiled for the Barony.

For these reasons a study was established to describe changes in the dbh distribution over a 12 growing season interval of a two-story loblolly pine stand. The study also sought to quantify the distributions by fitting a Weibull probability density function to the data. This would allow objective comparison of the distributions by comparing the a, b, and c parameters of the Weibull model.

STUDY AREA

A nine-hectare two-story loblolly pine stand on Hobcaw Barony, just north of Georgetown, SC was chosen for study. At the beginning of the study loblolly pine accounted for 89 percent of the 27.9 m^2 ha^{-1} stand basal area and 65 percent of the stem density (Table 1). The soil was a Leon sand, a sandy, siliceous, thermic areic Haplaquad. The stand was burned many years prior to the study and was not burned during the study.

Increment core analysis of pines throughout the Barony indicated a competition release during the period from 1885 to 1900. This corresponds to the time when the South was reconstructing from the Civil War and the once prosperous lowland rice culture was decreasing. Also during this time, a large pine sawmill was constructed in Georgetown, and old pictures indicate that large pine logs were used in the mill. Thus it could be logically concluded that the competition release seen in growth rings was a result of a diameter limit cut by the landowner to generate income.

The forest destruction of Hurricane Hugo offers an alternative explanation of the release.

1/ Presented at the System Analysis in Forest Resources Symposium, Charleston, SC, March 3-7, 1991.

2/ Associate Professor of Forestry, Department of Forest Resources, Baruch Forest Science Institute of Clemson University, P.O. Box 596, Georgetown, SC 29442.

Larger pine trees on the Francis Marion National Forest broke at mid-bole and died. Only the younger pine trees that were able to flex and bend in the high winds of the hurricane survived. Therefore the 1885-1900 release could have resulted from hurricane destruction of the older trees, releasing the saplings. South Carolina's coastline has a documented history of hurricanes during this time (Purvis and Landers, 1973).

For either or both of the above reasons the overstory of the study stand was released in 1885-1900 and logging records indicate that the stand was thinned in 1959 to 7 to 14 m^2 ha^{-1}. This cut probably allowed the present understory to establish. At the beginning of the study (1976), the overstory was over 100 years old and the understory was about 20 years old.

FIELD METHODS

A biomass and productivity study was installed on Hobcaw Barony. A mature two-story loblolly pine stand and a younger, though mature, longleaf pine stand were chosen to study growth and productivity of tree, shrub and herb strata. The field work for the study included surveying the location of study plots and initial plot inventory. Twenty-five 20m X 20m plots were surveyed in the central section of the stand during February 1976. Plots were arranged in six, four-plot rows without buffer areas between rows. The twenty-fifth plot was above the top row. Plot corners were marked with 3/8 inch painted iron rods and each corner was labeled with an aluminum tag.

All woody stems 3.0cm diameter breast height (dbh) and larger were tallied by plot during March 1976. Plot location, species, dbh to the nearest 1/10 cm and crown width were recorded for each stem. Tree and shrub biomass, litterfall and annual growth sampling was conducted for several years in both stands during the study.

Several years after the productivity study was terminated an opportunity arose to re-inventory the study plots in the two-story loblolly pine stand. A retired consulting forester indicated an interest helping with forestry research and was willing to do the re-inventory field work. This was easily accomplished because the plot corners were permanently marked and the initial inventory was conducted on a plot basis.

Plots were relocated in November, 1987 and re-inventoried as before. Crown widths were not remeasured during the re-inventory.

Southern pine beetle (<u>Dendroctonus frontalis</u>) killed 26 trees in two of the plots just prior to the re-inventory. The spot was discovered in July, 1987 and killed trees were tallied as "alive" during the November re-inventory.

ANALYTICAL METHODS

The 1976 inventory data were edited to delete 43 trees that were destructively sampled for biomass estimation in 1976 and one tree felled in 1977.

Data were summarized into stem counts of 2-centimeter wide dbh classes starting at 3.0 cm; 3-5cm, 5-7cm etc. Dbh distributions were graphically analyzed. Natural log transformations of stem counts facilitated analysis of the overstory population because their counts were quite low compared to the understory population.

A three-parameter Weibull probability density function was chosen to model dbh distributions because the Weibull model has been shown to successfully described pine stand dbh distributions (Bailey and Dell 1973, Bailey 1980, Bailey et al. 1980). The percentile method of Bailey et al. (1980) was used to calculate the a, b, and c parameters. Dbh distributions were calculated separately for 1976 and 1987 populations and plotted with inventory data. Dbh distributions of the understory and overstory populations for both years years were modeled seperately.

RESULTS AND DISCUSSION

<u>Population changes during 12-growing seasons.</u>

Stand stocking changed greatly during the 12-growing season interval between inventories. Stand basal area increased from 28 to 36.5 m^2 ha^{-1}, with the understory accounting for most of the increase (Table 1). Understory population stocking decreased 38 percent from 2499 to 1540 stems ha^{-1}.

Table 1. Stocking of a two-story loblolly pine stand before and after a 12-growing season interval.

Species	1976 Density	1976 Basal Area	1987 Density	1987 Basal Area
	stems/ha	m^2/ha	stems/ha	m^2/ha
loblolly pine				
overstory[a]	87	10.4	81	11.4
understory	2499	14.4	1540	22.6
total	2586	24.8	1621	34.0
southern bayberry	1247	1.8	542	1.1
tallowtree[b]	117	0.4	32	0.1
sweetgum[c]	27	0.3	26	0.6
other	32	0.5	35	0.7
Total	4009	27.9	2256	36.5

[a] Stems >28cm DBH in 1976 or >34cm in 1987.
[b] <u>Sapium sebiferum</u>
[c] <u>Liquidambar styraciflua</u>

In contrast to the understory population, the overstory population changed little. Six of 87 trees died and basal area increased from 10.4 to 11.4 m^2 ha^{-1}.

Dbh distributions for both years were the typical reversed " J " shaped patterns indicative of all-aged populations. The overstory population was not noticeable in the 1976 dbh distribution and was a little more obvious in the 1987 distribution.

A natural log transformation of stem count in each diameter class made the overstory population more noticeable and linearized the understory population distribution (Figure 1). The log transformed distributions indicated understory population mortality and the formation of a more nearly normal distribution for both populations in 1987. Dbh growth of both populations is seen from Figure 1; both populations have shifted to the right.

Weibull modeling dbh distributions.

Weibull pdf parameters calculated by the percentile method are presented in Table 2.

Table 2. Weibull pdf parameters of a two-story loblolly pine stand in 1976 and 1987.

Year	Parameters		
	a	b	c
1976	3.99	3.54	0.822
1987	7.40	6.31	0.819

The Weibull location parameter, a, and scale parameter, b, were different for the two years, but the shape parameter, c, was the same. The increase of the location parameter probably reflects population growth as indicated by the shift to the right in Figure 1. Understory mortality is probably related to the change in the scale parameter. The stability of the shape parameter probably indicates that the untransformed dbh distribution for both years is still a reversed "J" shaped pattern.

The Weibull model poorly fit dbh distribution for both years (Figure 1). It underestimated the understory population and completely missed the overstory of the 1976 data. The 1987 data were modelled more closely than the 1976 data, but both populations were underestimated.

The bimodal shape of the transformed dbh distributions probably contributed heavily to the inability of the Weibull pdf to model the distributions. This was tested by calculating a,b, and c parameters of the Weibull pdf for the understory and overstory populations separately for both years (Table 3) and plotting the predicted distribution with the observed distribution (Figure 2).

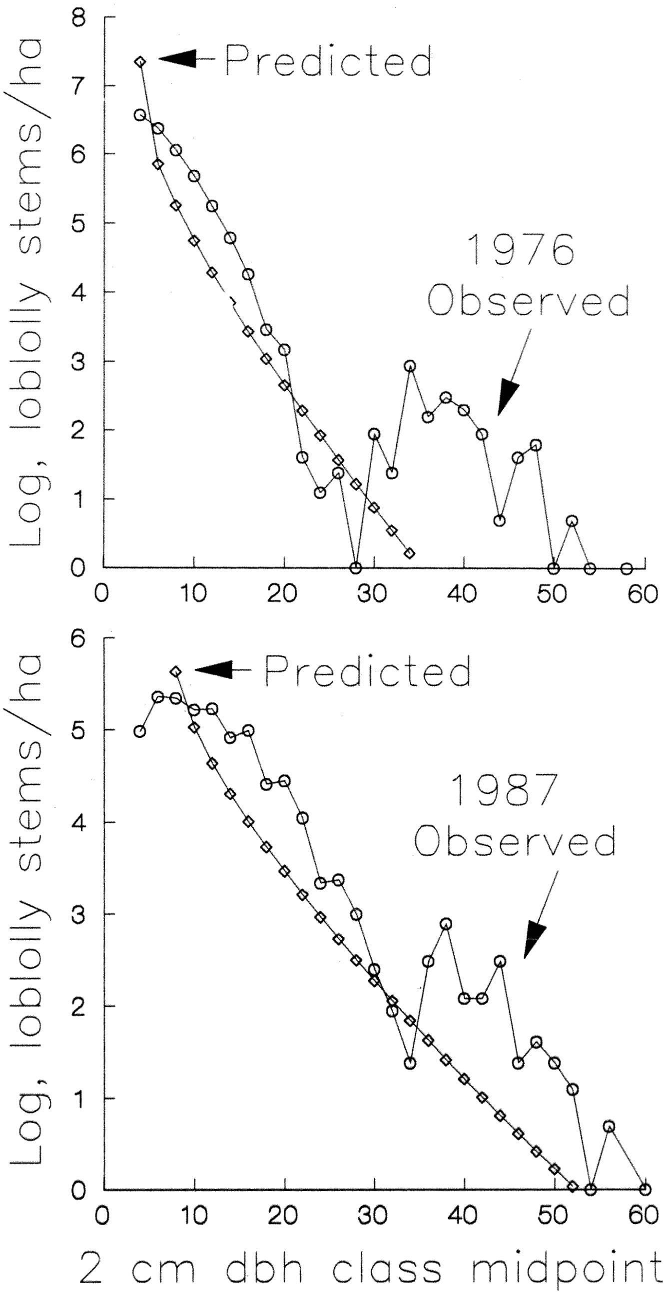

Figure 1. Dbh distribution patterns for loblolly pine in a two-story natural stand. Predicted densities were calculated from a three-parameter Weibull probability density function.

Table 3. Weibull pdf parameters for understory and overstory populations separately.

Year	Population	Parameters		
		a	b	c
1976	understory	3.78	3.44	0.951
	overstory	28.86	9.81	1.504
1987	understory	-.71	13.49	1.799
	overstory	31.64	10.91	1.704

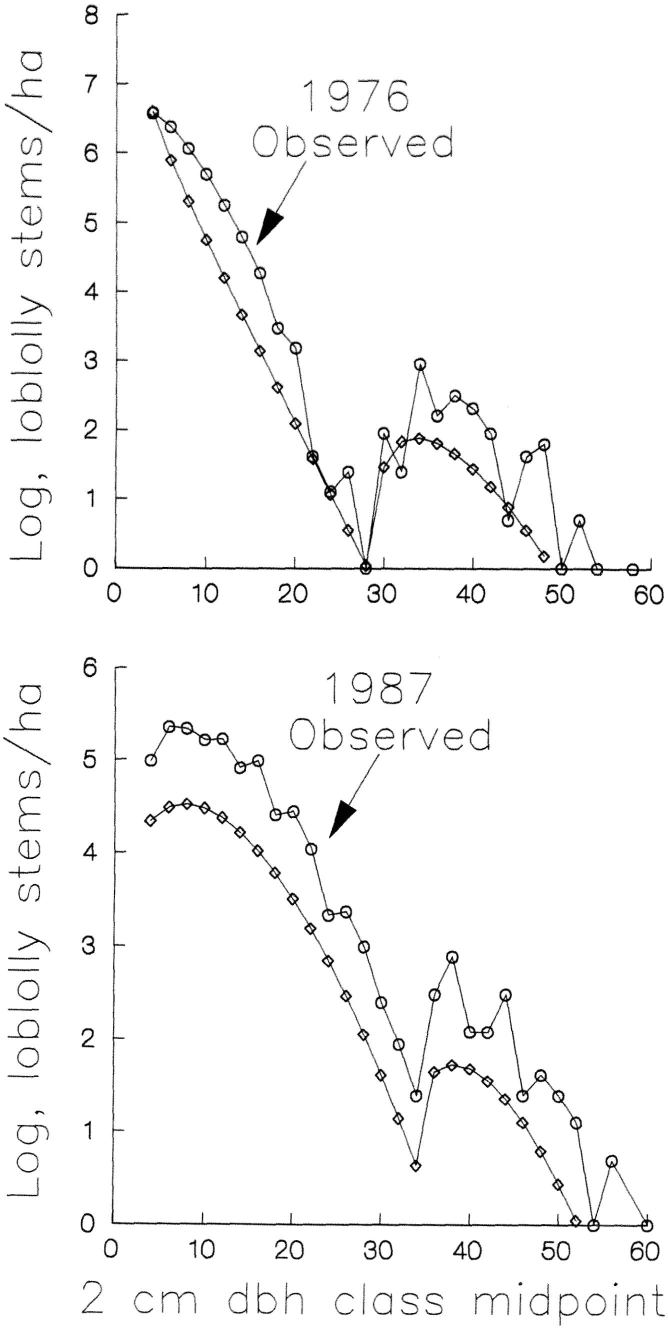

Figure 2. Dbh distribution patterns for loblolly pine in a two-story natural stand. Predicted densities were calculated for understory and overstory populations separately with a three-parameter Weibull probability density function then combined for each year.

The shape of the predicted 1976 overstory population, the predicted 1987 overstory and understory population dbh distributions are similar. Thus, the corresponding Weibull model c parameters (1.504, 1.799 and 1.704 respectively) are also similar. Biologically, this means that during the 12 growing season interval, the understory population's dbh distribution had developed from the reversed "J" shape, indicative of an all-aged population, to a normal distribution, indicative of an even-aged population. The overstory population retained the normal distribution dbh pattern (Figure 2).

The Weibull a parameter, the location parameter, related to population minimum dbh. The 1976 understory minimum measured dbh was 3.0 and the a parameter was 3.78. Likewise, the minimum measured dbh for the 1976 and 1987 overstory populations were 28cm and 34 cm respectively and the corresponding a parameters were 28.86 and 31.64 respectively. Why the 1987 understory population a parameter was -.71 while the minimum measured dbh was 3.0 cm is not clear.

Interpretation of the Weibull b parameter is not clear from these data.

Diameter class widths

The effect of varying diameter class widths on dbh distribution shape was also investigated. Small class widths resulted in very "noisy" dbh distributions because several classes had no stems in them. Large diameter class widths resulted in smooth dbh distributions, but several distribution peaks, representing distinguishable groups in the overstory population, were eliminated. With data in metric units, a 2-cm class width is recommended and one-inch widths are recommended for data in English units.

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MULTISTAND SIMULATION OF SILVICULTURAL PRACTICE

TO MEET MANAGEMENT TARGETS[1]

Albert R. Stage and Nicholas L. Crookston[2]

Abstract.--A multistand simulation model--the Parallel Processing Extension of the Prognosis Model for Stand Development--evaluates multiresource consequences of various management prescriptions. The system can be used, for example, in simulating effects of pests, treatment schedules, and forest planning.

Keywords: Prognosis Model, pest models, landscape models.

INTRODUCTION

Multistand simulation of many alternative policies is simplified by having the capability to describe the policies as a set of rules that apply to a large, heterogeneous set of stands. A multistand simulation model has been developed for the following applications: evaluating multiresource consequences of treatment schedules for collections of stands with spatial interactions, calculating pest impacts, and elaborating upon existing Forest Plans. We focus on how policies are described to the model such that analysts can readily generate a rich set of alternatives, each retaining ecological and spatial integrity.

The system is called the Parallel Processing Extension (PPE, Crookston and Stage 1989) of the Prognosis Model for Stand Development (Wykoff and others 1982, Wykoff 1986). The system has these capabilities:

1. Simulation of simultaneous development of 1,000 forest stands for 400 years including dynamic interactions between stands.

2. Simulation of any-aged silviculture with natural or artificial regeneration.

3. Efficient comparison of alternative management policies. Alternatives may differ in conditions under which treatments will be prescribed and in timing of application. In many cases, numerous policies can be evaluated in one simulation.

4. Evaluation of decision trees. If alternatives represent outcomes of uncertain events, then expected values are calculated using probabilities measuring the uncertainty as weights.

These capabilities depend on several key features:

1. A policy labeling scheme that (A) permits simulation of alternative policies without duplicating stand and management combinations, and (B) permits silvicultural prescriptions for the same policy to vary depending on stand location and condition.

2. Specification of management policies for the collection of stands. These multistand policies are defined by three elements: units-of-measure for targets, sequence of periodic targets (derived from a forestwide plan or computed as a function of stand attributes such as growth or volume), and an expression defining stand priorities for meeting targets depending on stand attributes.

3. Constraints on treatment so as to limit size of contiguous openings.

4. Coordinated treatments of sub-sets of stands.

5. Calculation of composite yield streams displaying responses of trees and other vegetation for multiresource evaluation.

[1]Presented at Systems Analysis in Forest Resources Symposium, Charleston, SC, March 3-7, 1991.

[2]Project Leader and Operations Research Analyst, respectively, Intermountain Research Station, Forest Service, U.S. Department of Agriculture, located at the Forestry Sciences Laboratory, Moscow, ID.

DESCRIBING POLICIES TO BE EVALUATED BY MULTISTAND SIMULATION

Evaluation of alternative policies by simulating individual stand development is a well-developed art in forest planning. But far less advanced is how to simulate policies that involve numerous stands, with interaction between stands and constraints on the characteristics of the aggregation. Policy analysis is restricted by the richness of alternatives that can be considered and compared. Because we are always limited in time for analysis, simulation procedures that facilitate the generation of wide arrays of alternatives are valuable tools for policy analysis. To this end, we have designed the Prognosis system so managers may easily vary the definition of management alternatives for large collections of stands. With this simulation capability, many diverse policies can be compared on a consistent basis.

We will describe a systematic way to define policies such that simulations including numerous interacting stands are facilitated. The protocol we describe is implemented in the Parallel Processing Extension (PPE) of the Prognosis Model for Stand Development. Because the system can simulate simultaneous development of 1,000 forest stands for 400 years, it can, for example, simulate effects of contagious pests and prescriptions that depend on conditions of surrounding stands and spatial relationships between stands.

Policies are defined to the PPE in terms of two components (figure 1): The first component specifies targets for aggregate attributes of the stands and their possible uses. Targets are most easily thought of as levels of output from the forest, but they may also be expressed in units of the resource in place. The second component consists of conditional stand prescriptions that depend on the geographic location (or other spatial characteristics) of the individual stands and upon the silvical attributes of the stand itself.

Variation between policies can be obtained by modifying one or both of these components. The components span a spatial hierarchy, from forestwide consideration of objectives for the aggregate, to more local consideration of a stand's immediate context, to consideration of the silvics of the stand itself. A system of labels links the policy components. Labels are attached to sets of activities, to stands, and to specifications of multistand policies.

Policies at the Landscape or Forest Level

Policy selection at the forest or landscape level usually results from evaluation of changes in forest conditions and outputs through time. This analysis requires comparing and selecting from among a diverse array of alternatives that differ in timing and other respects. Emphasis on timing translates into a problem of assigning priorities for selection among stand prescriptions that otherwise meet the conditions governing their application.

Another part of the policy at the forest level defines how the resource is to be described. Is the condition of the forest to be described by its inventory, by its output, or some other measure of utility.

Next, to create timing alternatives, one specifies a succession through time of targets for forest conditions. These targets are expressed as periodic values computed as user-specified algebraic expressions of sums or averages of stand variables. Other expressions define the contributions to the periodic targets of the stands if they are selected to meet the target, and an expression that defines relative priorities for being selected. Because the user defines the temporal series, the number of alternatives can increase rapidly when both level and temporal variation of the targets are modified.

The final component of the policy definition is to assign a label to each temporal series of targets. These four components of a multistand policy are summarized in figure 2.

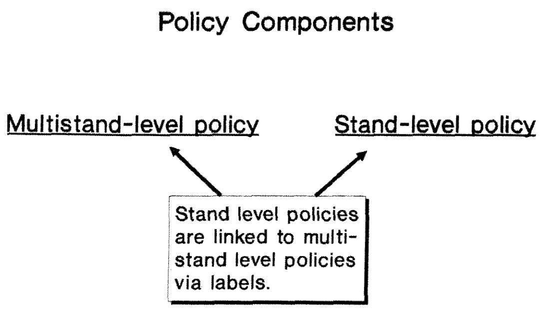
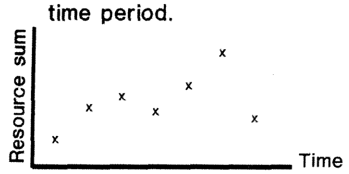


Figure 1.--Relations among policy components.

Multistand Policy Components

TARGET ▪ desired level of resource at each time period.



CREDIT ▪ resource provided by each stand (acres of cover, volume of timber).

PRIORITY ▪ a formula describing the relative priority for selecting stands.

MSPLABEL ▪ the policy name.

Figure 2.--Four subcomponents of multistand policy.

Prescription at Stand Level

Aggregation of stands in an analysis destroys spatial integrity. However, prescribing for several hundreds of stands without aggregating could be either tedious or superficial. A key to avoiding the need to aggregate lies in the ability to specify conditional prescriptions. We are all familiar with silvicultural prescriptions that call for specific regimens of treatment--say plant, precommercial thin at age 15, commercially thin at age 40 to a specified residual density, and then harvest. Thus specified, the prescription will be reasonable for quite a narrow range of sites and further requires that current age of stand be known so that the dates of the activities can be determined. Consequently, one is faced with need for numerous classes or substantial aggregation error will be incurred.

An alternative prescription format is to specify conditions that must be met before invoking a management activity. With this prescription format, the same conditional prescription can apply to many, diverse stands. A policy can thus consist of several such groups of activities, but only those applicable to specific states of nature will be invoked. During the simulation, individual stands will be treated--if, when, and how--as appropriate to the unique conditions of the stand.

The conditional prescription defines: "Under what conditions?" "Do what?" "For which policy?"

In figure 3 we illustrate the form of a pair of conditional prescriptions. In this example there are two policies that happen to rely on the same condition.

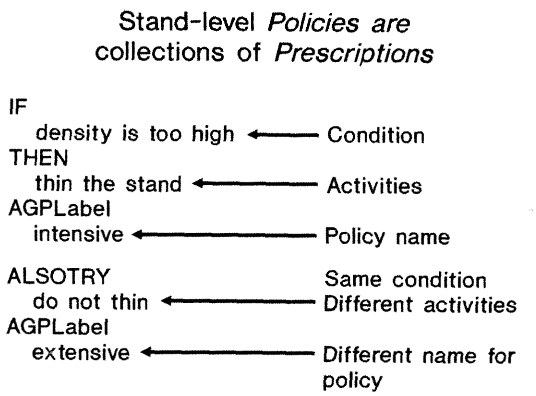


Figure 3.--Example of rules that make up a stand-level policy.

In the Prognosis Model for Stand Development, conditional prescriptions are processed by the Event Monitor (Crookston 1990). With it, many different policies can be formulated by associating policy labels with sets of conditional prescriptions. Furthermore, the triggering conditions can be logical expressions defined by the silviculturist using algebraic relations involving a wide array of stand and site variables.

Prescriptions Within a Geographic Context

Policies vary not only in their relation to site and stand conditions, but also by the context in which stands occur. For example, identical stands might be treated differently if one is within a corridor to be protected under one policy and not under another. Corridors for animal migration, stream-side protection, or travel routes (either roads or trails) would be designated on maps and their location transmitted to the simulation by labeling the stands involved. Then the stand label becomes part of the conditional prescription. Prescriptions are implemented only if the label of the prescription matches at least one of the labels of the stand.

CONSIDERATION OF AGGREGATION ERROR

Because the Parallel Processing Extension simulates site-specific and stand-specific prescriptions, prescription errors due to aggregation are greatly reduced. Analysts will be quick to point out that the reduction in aggregation error comes at a cost of time to calculate numerous stand simulations followed by the time to aggregate results. Computation savings are possible with the PPE. The system takes advantage of the possibility that when analyzing numerous alternative policies, particular stands may proceed for substantial portions of simulated time under the same schedule of activities (or no activity). If so, redundant calculation is avoided because the PPE organizes the simulation as a collection of decision trees. Branches of the trees are created only if the conditional prescription invokes an activity the analyst wishes to consider in addition to some alternative (such as no treatment or defer treatment). The PPE has capabilities to sort the branches of the decision trees by policy to produce aggregate simulations for each different policy. Of course, for a single stand, each branch would correspond to a unique subset of the policies being compared. However, branches may also be created by stochastic events causing different courses of stand development to be simulated under a single policy. Then, the aggregation process is one of calculating the statistical expectation.

EXAMPLE

In a summary example (figure 4), we evaluate a policy that emphasizes retaining cover near water. The multistand policy labeled "Water" consists of a temporal series of targets for acreage of vegetation that meets a definition of cover. Priority for retention of cover is to be given to stands near water. If stand density within stands also labeled "Water" is lower than some critical value, then the prescription is to prepare the site for interplanting. Other stands in the same ecosystem, but not labeled "Water," will not contribute to meeting the required cover targets. Their treatments will be simulated in accord with other appropriately labeled prescriptions.

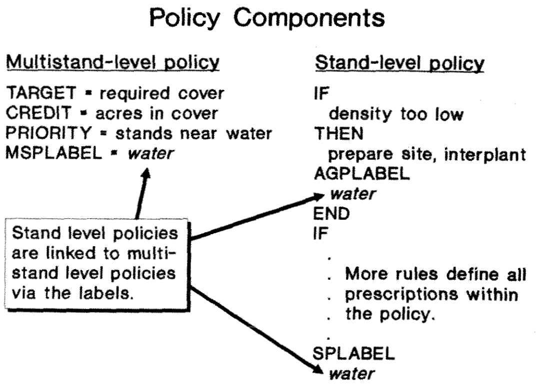


Figure 4.--Labels link the multistand-level policy, the stand-level policy, and the particular stand to which they apply.

The end product of the multistand simulation is a table of aggregate statistics describing the course of development of the ecosystem and its treatments through future time. Then, by making changes in the policy definitions and running a new simulation, the rich assortment of alternatives that lead to effective management can be displayed.

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NONINDUSTRIAL TIMBER SUPPLY IN THE SOUTH:

A PROBABILISTIC EVALUATION FOR EAST TEXAS[1]

Kelly Bell and Marian Eriksson[2]

Abstract.-- Harvest and reforestation decisions for two private timberland ownership classes are being modeled using USDA Forest Service FIA data and logistic regression techniques. Biological and economic conditions are hypothesized as being the key determinants of harvesting and reforestation behavior. Timber supply functions specific to a given ownership can be developed from the estimated probability density functions.

Keywords: logistic regression, timber supply, NIPF.

INTRODUCTION

The forest products manufacturing industry holds a very important place in the southern economy. In 1982, employment and income from wood-based manufacturing industries across the South exceeded those of other major manufacturing industries. In terms of value of production for manufacturing industries, timber harvested in 1984 ranked first in six southern states, second in three states and third in the remaining three states (USDA Forest Service 1988).

Raw material for the industry's manufacturing facilities is obtained from both private and public timberland owners. The two private timberland ownership classes include the forest products industry and nonindustrial private forest (NIPF) landowners. The U.S. Forest Service divides the latter class into 3 groups--farmer, corporate and individual. Publicly-owned timber is primarily obtained from National Forests under the supervision of the U.S. Forest Service.

Timber and land management behavior patterns of forest products companies are motivated by a need to assure present and future raw material supplies (Jackson 1980). Since 1970, industry's share of timber supply in the South has been 50 percent greater than its share of the forest land base. Public pressure to give greater emphasis to alternative forest outputs, including the protection of the red cockaded woodpecker, from southern National Forests and other public lands has led to reduced harvest levels on those lands. While the public's share of the timberland base has grown, its share of timber supplied has declined.

The NIPF landowner is the major raw material supplier to southern mills, yet his share of both standing inventory and supplied timber is less than his share of the timberland base. The broad policy question that motivates this study is: How will private timberland owners in the South, especially the large nonindustrial ownership class, respond to opportunities to sustain the forest products manufacturing industry's need for raw material?

The Texas Case

Texas is currently facing a number of forest policy issues that could substantially affect the available supply of timber to the state's processing facilities in the future. Harvest volume in Texas' National Forests have steadily declined since 1986, primarily as a result of habitat protection for the endangered red-cockaded woodpecker. Clearcutting as a harvest method has come under fire from citizen interest groups, leading to appeal of the Land Management Plans for those forests. Under such circumstances, it is unlikely that the National Forests in Texas will achieve their planned increases in harvest levels (Table 1).

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[1] Presented at the Systems Analysis in Forest Resources Symposium, Charleston, SC, March 3-7, 1991.

[2] Graduate Assistant and Assistant Professor, Department of Forest Science, Texas A&M University, College Station, TX.

Table 1.--Projected percentage increase in softwood volume removals by ownership and various southern regions 1984-2000.

Ownership	South	South Central	West Gulf	Texas
Forest Industry	26	18	19	-5
Natl. Forests	63	69	73	132
Other Public	22	27	74	100
NIPF:				
Individual	2	4	17	8
Farmer	-16	13	42	67
Corporate	13	17	25	12

Source: USDA Forest Service 1988

Under the U.S. Fish and Wildlife Service's current definition of wetlands, approximately 600,000 acres of east Texas timberland could be subject to regulatory management by state agencies, affecting efficient timber production on those acres. Other forest policy issues on the horizon in Texas that could increase the cost of production include increased property taxation and local regulation of timber management practices. The effect of policy changes made by the state to address such issues may differ when viewed from the level of a local timber economy. There may be substantial variation in the biological and ownership characteristics of the forest resource among sub-state regions. For example, while acreage and softwood growing stock volume statewide in Texas generally reflect that of broader southern regions, they vary significantly between the southeast (Unit 1) and northeast (Unit 2) regions of the state (Table 2).

Table 2.--Acreage and softwood growing stock volume breakdowns by ownership and various southern regions, 1986.

Acreage Breakdown (Percent)						
				Texas		
Ownership	South	South Central	West Gulf	State	Unit 1	Unit 2
Industry	23	24	29	33	46	15
National Forests	6	6	8	5	8	2
Other Public	4	3	4	1	1	2
NIPF:						
Individ.	36	38	39	43	31	58
Farmer	22	20	12	12	8	17
Corp.	9	8	8	6	6	6

Softwood Growing Stock Volume (Percent)						
				Texas		
Ownership	South	South Central	West Gulf	State	Unit 1	Unit 2
Industry	26	29	33	29	35	18
National Forests	8	11	13	13	20	5
Other Public	5	3	2	2	1	3
NIPF:						
Individ.	34	36	36	41	33	55
Farmer	18	14	6	7	4	13
Corp.	9	7	9	7	7	6

Source: USDA Forest Service 1988

THE GENERAL MODELS

Microeconomic theory is being used to construct simple theoretical models of harvesting and regeneration behavior for the period 1975 through 1986. It has been assumed that both the NIPF and industrial owner classes have a profit motive underlying their timberland management behavior. This assumption has not been tested empirically; however, if NIPF owners and industrial owners behave differently, that difference can be empirically quantified within the context of the general models by incorporating ownership classification variables.

Two models representing harvest behavior and one model representing investment behavior for two private timberland ownership classes in eastern Texas have been postulated. Hypotheses that the chosen biological and economic variables are key determinants of harvest and regeneration behavior of private timberland owners are being tested. Tests of hypotheses that there are no differences in harvesting and regeneration behavior between ownership classes are also being conducted. Resulting models will be used to predict future timber supplies by owner class based on the 1986 plot-level data.

Harvesting Behavior

The need for alternative models acknowledges the need for greater understanding of the degree to which economic variables are actually considered in the harvesting decision. Fecso et al. (1982) found maturity of the timber and offering price were the most important determinants of the decision to harvest for southern timberland owners. Our models quantify the probability of harvest as a function of stand characteristics, economic conditions and ownership class.

Harvest Model One

For the first harvest model, it is hypothesized for both ownerships that biological conditions, represented by net merchantable volume and the percentage growth rate of the stand, are the key variables influencing the harvest decision and that the economic variables have no influence on the harvesting decision. Landowners may require that a stand of timber have a minimum volume-per-acre before choosing to harvest the stand. Additionally, volume-per-acre may also be an important proxy variable for non-timber benefits. That is, for those NIPF landowners with non-timber, or non-financial, objectives, a higher standing volume would be expected than for industrial owners and other NIPF owners with timber, or financial, objectives.

Net annual growth percent serves as a proxy for the opportunity cost of invested capital. Under simple conditions of constant prices, the optimal harvest age for a single rotation occurs when the growth rate of the stand slows to equal the owner's alternate rate of return. If certain NIPF owners have a higher alternate rate of return than their industrial counterparts, then harvest would be expected to occur at an earlier age in the NIPF ownership (McMahon 1964). However, if the importance of non-timber benefits increases as the forest grows, then the optimal rotation age may be postponed, or indefinitely delayed, beyond the point where the biological growth rate is equal to the interest rate (Hartman 1976). Because the importance of non-timber considerations relative to financial considerations for the NIPF as a whole is not known, a higher probability of harvest for NIPF owners than industrial owners for a given growth rate cannot be assumed.

Harvest Model Two

Binkley (1981), Hyberg (1986), Jamnick and Beckett (1988), and Boyd (1984) fitted models using data from surveys of timberland owners. Stumpage prices were found to be significant determinants of the harvesting decision across all studies. The second harvest model hypothesizes that net value of the stand and net value growth percent are significant determinants of private harvesting behavior. These variables are derived by multiplying the market price for timber during the period of analysis by net merchantable volume and net growth percent. The value of the stand is considered as an explanatory variable because some landowners require that a stand represent a minimum value before harvesting can be considered feasible. This variable also serves as a proxy for non-timber, or non-financial, benefits as in the first model.

Net value growth percent may serve to approximate the return on capital invested in the standing timber. Net value growth percent represents the expected increase in value of the stand, or the value that will be foregone if the stand is harvested today. Under simple conditions of constant prices, the optimal harvest age for a single rotation occurs when the growth rate of the stand slows to equal the owner's alternate rate of return. Harvest may occur sooner on the NIPF ownership than the industrial ownership if NIPF owners have a financial objective and face higher alternate rates of return. Similarly, NIPF harvest may be delayed past financial maturity if non-timber benefits are growing as the forest grows.

Signs of the coefficients on the volume and value variables should be positive; that is, the higher the volume or value the more likely that the landowner will elect to harvest. The signs of the coefficients on the growth volume and growth value variables should be negative; that is, the faster the stand is growing, the lower the probability of harvest. If there is no difference in harvesting behavior by owner class, then all owner class coefficients will be equal to zero.

Reforestation Behavior

The factors that influence the choice to reforest or not to reforest a stand may be different than those for the harvest choice (Royer 1988). The reforestation model hypothesizes that a measure of site productivity and reforestation costs are the key factors influencing the reforestation decision. As site productivity increases, the volume grown per acre per year increases; consequently, the age at which the future stand will be ready to harvest declines as site productivity increases. As the rotation length decreases, investment in reforestation should then become more competitive with other investments.

Regeneration costs represent the largest single investment in the future stand. In southern forests, the final return often occurs 30 to 40 years after the capital is expended. Recent studies of NIPF investment behavior have found reforestation costs to be a highly significant determinant of reforestation behavior (Brooks 1985, Hyberg 1986, and Royer 1987).

Other factors not included in this model that have been observed to influence investment behavior include technical assistance and cost subsidies. In a survey of NIPF owners that harvested timber across the South from 1971 to 1981, Fecso et al. (1982) found that owners of 50 percent of the acres clearcut attributed the reason for no active regeneration effort to a belief that the site would regenerate itself. Omission of such influences could affect the study results.

The sign of the coefficient of the site productivity variable should be positive; that is, the more productive the site, the more likely the stand will be regenerated. The sign of the regeneration cost variable should be negative; that is, the higher the regeneration cost, the less likely that a choice to regenerate would be made. If there is no difference in regeneration behavior by owner class, then owner class coefficients will be equal to zero.

THE LOGISTIC APPROACH

The dependent variables for both harvest models and the regeneration model are dichotomous in nature; the choice to harvest, for example, takes on a value of 1 and the choice not to harvest takes on a value of 0. The models and hypotheses require an estimation procedure that can quantify the probabilities of each choice. Pindyck and Rubinfeld (1981), Amemiya (1981), and Judge et al. (1985) identify the logistic model as being a viable technique for analyzing problems of this type. Maximum likelihood procedures are being used in this study to estimate model parameters; model verification will be carried out using resampling methods such as those described by Efron and Gong (1983).

DATA

Data on private forest resources in eastern Texas are periodically collected by the U.S. Forest Service's FIA Unit based in Starkville, Mississippi. The two most recent forest surveys of eastern Texas were conducted during 1975 and 1986; the latter represents a remeasurement of the 1975 plots.

Both periodic and annualized data sets have been developed for the study. Neither is unambiguously superior to the other because results using each will have different interpretations. The periodic data set is being used for the estimation of the probabilities of harvest and regeneration given the prevailing biological and economic conditions over the remeasurement interval of the FIA data. The annual probabilities of harvest and regeneration given the prevailing biological and economic conditions during the years of harvest and regeneration is being estimated with the annualized data set. For both data sets, it has been assumed that the biological and economic conditions prevailing at the time harvest or regeneration activities actually occurred on the plot are suitable proxies for the conditions prevailing at the time the harvesting or regeneration decisions were made.

Biological and economic conditions prevailing at the time of initial inventory have been used to quantify volume, growth, price and cost variables in the periodic data set. The periodic data set is better suited to the case in which biological conditions alone are the dominant considerations in harvesting and regeneration decisions. The estimation of logistic models using maximum likelihood techniques assumes that the probabilities between observations are uncorrelated. This is the case for the periodic data set as long as there are no cross-sectional linkages between plots.

Since the 1986 FIA forest survey includes an estimate of the year of harvest, an annual time-series for each plot has been developed for the annualized data set. Annualized growth and removal data for each plot have been used to develop quantities for the biological variables. Stumpage price and regeneration cost data have been taken from other annual data sources. The annualized data set is better suited to the case in which economic conditions play an important part in harvesting and regeneration decisions. Timber prices varied substantially over the interval between the two inventories (Figure 1); the effect of price variation on the harvesting decision, if any, will be captured in the results estimated with this data set. Although regeneration costs have not fluctuated as much as timber prices over the interval, the reforestation model will capture any effect such variation might have on the regeneration decision. The unfavorable effect of serial correlation will be minimized or eliminated in the harvest models since growth and standing volume are included as variables (Binkley 1981).

The FIA data are not ideally suited to the estimation of the models in this study for several reasons. First, observations on the biological and economic conditions prevailing when the harvesting decision was made are unavailable. There also exists an unknown time lag

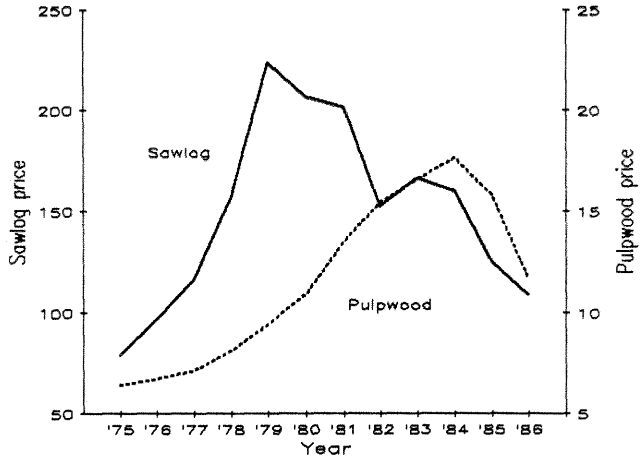

Figure 1.--Pulpwood and sawlog prices in the West Gulf region, 1975-1986 (from LA Dept. of Agriculture).

between the decision to harvest and the date harvesting begins. Second, the current three NIPF ownership groups are not adequately distinguished from one another in terms of forest land management behavior. Third, information is not currently collected about certain variables, such as the tract size represented by the plot, that have been found to influence forest management behavior (Binkley 1981).

The advantages offered by the FIA database outweigh the limitations. For timber supply modeling purposes, it is the most comprehensive data available on national, regional or even sub-state levels. There is relative consistency from period to period and across states and regions regarding the data collection methods used. Finally, one of the goals of FIA is to decrease the survey cycle. Policy analysis, land management planning and timber supply projections using the results of the proposed work would benefit from a shorter survey cycle.

CONTRIBUTIONS

Efforts to develop timber supply projection models at state or local levels have generally incorporated broad assumptions regarding the harvesting and investment behavior of the private ownership classes (Flowers et al. 1987, Cubbage et al. 1988, Abt et al. 1988). The use of individual plot data from the U.S. Forest Service's FIA Unit as sample observations presents an opportunity to achieve a timber supply projection model with greater behavioral realism in a disaggregated framework (Connaugton et al. 1988).

The results of this study will incorporate an empirically-based portrayal of the harvest and reforestation behavior of the two private timberland ownership classes within a timber supply model. Timber supply projections will be improved through a better understanding of the degree to which the NIPF and the industrial ownership classes harvest and reforest stands in the South in response to economic and biological conditions. Policy analysts will benefit from an increased awareness of the potential for the NIPF ownership class to contribute to future timber supplies. This type of analysis will contribute to improved projection methodologies by estimating probability density functions appropriate to such behavior for individually identifiable forest stands for the different landowner classes. Timber supply functions specific to a given ownership class can then be developed from such probability density functions.

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COMPARING INDUSTRIAL AND NONINDUSTRIAL HARVESTING BEHAVIOR: A PROBABILISTIC APPROACH[1/]

Kent P. Connaughton, C. Duncan Campbell [2/]

Abstract.--Surveys show that nonindustrial owners manage their forests for a variety of purposes, while industrial owners manage their forests for timber production. Logit regression was used to determine whether the probability of harvesting a stand varied by ownership in western Oregon. Results showed that the probability was the same for nonindustrial and industrial ownerships, and that the probabity function did not vary subregionally over a wide variety of forest conditions. Because many stands in the nonindustrial ownership are nearing maturity, the results implied that substantial increases in harvest on the nonindustrial ownership could be anticipated.

Keywords: timber supply, logit regression, western Oregon

What is timber supply in western Oregon likely to be over the next two decades? The answer depends heavily on industrial (and corporate) and nonindustrial owners, who together have supplied about one-half of the region's total harvest of about six billion board feet during recent years. The answer is important to the wood-using industry, because raw material availability may decline on federal lands in response to changing social and environmental conditions (Greber et al. 1990).

Currently, industrial owners manage about two-thirds of western Oregon's private forestland, from which ninety-two percent of the region's private timber flows; nonindustrial owners have one-third of the land base, from which eight percent of private timber flows (Gedney 1982). Part of the difference in harvest rates is due to differences in forest conditions, with generally lower stocking and higher levels of management opportunities found on the nonindustrial ownership (Gedney 1988). MacLean (1988) estimates that the productive potential of nonindustrial forests is 235 million cubic feet per year, which is four times greater than the recent harvest of about 52 million cubic feet per year. Differences in objectives and personal characteristics of individual owners have also been cited as reasons for nonindustrial behave in a varied, and perhaps unpredictable manner (Clawson 1975, Towell 1982).

The objective of this research was to find out whether harvesting behavior differed by ownership. Methods allowed a comparison of the probability of harvest, by ownership, while controlling for key stand variables affecting the harvest decision. Because timber harvest over the next two decades must come from stands that are already growing, results provide the behavioral basis for projecting short-run timber supply.

APPROACH

The approach, like that of Clawson (1979), used the harvesting behavior of the industrial ownership as the standard of comparison for the nonindustrial ownership. The premise was that industrial forests are operated for profit. The approach contrasts with other research (for example, Binkley 1981 or Dennis 1989) that begins with the derivation of a utility maximization model of nonindustrial landowner behavior.

Principles drawn from forest economics were used to identify stand variables that were important for the economically efficient harvesting decision (Davis and Johnson 1987).

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2/ Authors are Research Foresters, USDA Forest Service, Pacific Northwest Research Station, P.O. Box 3890, Portland, OR 97208.

In the simplest case of financial maturity, the economically efficient time to harvest a stand is when the growth rate of the stand's value equals the landowner's alternate rate of return. Symbolically, harvest occurs when

$$\Delta(PV - C\ (V))/(P_tV_t - C_tV_t) = i$$

where P_t is the price per unit of the harvested timber, $C_t(V_t)$ is the variable unit cost of harvest at time t, $\Delta(PV - C(V))$ quantifies the anticipated change in net stand value, $(P_tV_t - C_t(V_t))$ measures the stand value net of variable costs of harvest at time t, and i is the landowner's alternate rate of return.

Stands with net value growth rates higher than the landowner's alternate rate of rate of return would remain unharvested. Net value growth rates are affected singly or collectively by anticipated changes in volume, prices, or costs. For example, if the landowner expects high rates of price appreciation, a stand whose volume is growing at low rates would not be harvested.

A second condition that must be satisfied from both the landowner and timber purchaser's perspectives, is that the value of the harvested stand must equal or exceed the costs, both variable and fixed, of harvest. Symbolically,

$$(P_tV_t - C_t(V_t) - C_f) \geq 0$$

where C_f is the fixed costs of harvest. Stands with negative net value would remain unharvested. The latter condition is equivalent to requiring that stumpage prices be non-negative.

Not all landowners would implement the harvesting decision in the same way even if they behaved in an economically efficient manner. For example, alternate rates of return would differ among landowners, as would expectations of current and future stumpage prices. To capture this variation in behavior, we statistically estimated the probability of harvest as a function of observable variables, including ownership and stand conditions.

METHODS--MODEL SPECIFICATION AND ESTIMATION

The probability of harvest was conceptually a function of net stand value and the growth rate of net stand value. We had to specify an alternative model of the harvesting probability, because net stand value and its growth rate were not observable using existing data on the private timber resource in western Oregon.

Data on landowners' perceptions of price, costs, volume per acre and biological growth rates were unavailable. Close proxies were available for perceived volume per acre and biological growth rate. Volume per acre was available for a systematic sample of plots taken on industrial and nonindustrial forestlands in western Oregon by crews from the Forest Inventory and Analysis (FIA) Work Unit at the Pacific Northwest Research Station. Growth rate was simulated using data on tree characteristics collected by the field crews. Remeasurement of the field plots allowed us to monitor harvest.

We also used volume per acre and the compound annual growth rate over a ten-year interval as proxies for both net stand value and anticipated net stand value growth rate. The proxies were key components of the variables they were intended to represent, but an unknown bias may have resulted by not measuring the appropriate variables.

We tested the hypothesis that there was no difference in the probability of harvest between industrial and nonindustrial owners by estimating the following logit model (Maddala 1988):

$$\ln \frac{(Pr_i)}{(1-Pr_i)} = \alpha_0 + \alpha_1\ (Growth\ Rate)_i + \alpha_2\ (Vol/Ac)_i + \alpha_3\ (Owner)_i + \alpha_4\ (Owner\ X\ Growth\ Rate)_i + \alpha_5\ (Owner\ X\ Vol/Ac)_i + \varepsilon_i \qquad (1)$$

where Pr_i is the probability of harvest for the i-th plot, $\ln (Pr_i/(1-Pr_i))$ is the logarithm of the odds of harvest; $(Owner)_i$ is an owner code with 1=Industrial and 0=Nonindustrial; $(Owner\ X\ Growth\ Rate)_i$ is an interaction term that takes a value of 0 when the plot is in nonindustrial ownership and takes the simulated growth rate when the plot is in the industrial ownership; $(Owner\ X\ Vol/Ac)_i$ is the interaction term for volume per acre; and ε_i is a random error term for the i-th plot.

The expected signs of the coefficients for growth rate and volume per acre were

$$\alpha_1 < 0,\ \alpha_2 > 0.$$

The first condition implied that the probability of harvest was inversely proportional to growth rate (in net value), or that slow growing stands were more likely to be harvested than fast growing stands. The second condition implied that the probability of harvest was directly proportional to volume (net value) per acre, or that stands with high volume per acre were more likely to be harvested than stands with low volume per acre.

The owner and owner interaction terms (α_3, α_4, α_5) were included to capture as many differences between nonindustrial and industrial behavior as possible. The intercept shifter, α_3, permitted us to recognize differences in probabilities not related to either growth rate or volume per acre; the growth rate shifter, α_4, permitted us to recognize differences in whether the nonindustrial ownership harvested stands later or earlier during stand development than the industrial ownership; finally, the volume per acre shifter, α_5, permitted us to recognize differences in whether the nonindustrial ownership had a preference for either more or less stocking than the industrial ownership.

The owner and owner interaction terms were consistent with several behavioral scenarios that have been used to explain nonindustrial forestry (Clawson 1979):

Behavioral scenario	Expected coefficient
Nonindustrial has higher alternate rate of return than industrial	$\alpha_4 < 0$
Nonindustrial owners are cash short	$\alpha_4 < 0$, $\alpha_5 < 0$
Nonindustrial owners are unpredictable and have many objectives	$\alpha_3 \neq 0$, $\alpha_4 \neq 0$, $\alpha_5 \neq 0$
Nonindustrial owners have an amenity preference for mature stand conditions	$\alpha_4 > 0$, $\alpha_5 > 0$

Logit Estimation

The logit specification is based on the cumulative logistic function, which is nonlinear and bounded by zero and one. Logit estimation is commonly used when the dependent variable is dichotomous, or takes a value of zero or one. When harvest had occurred on a plot, we coded the dependent variable as one, with the variable set equal to zero when no harvest had occurred.

Hypothesis to be Tested

The null hypothesis, that there was no difference in the probability of harvest between ownerships, was equivalent to

$$\alpha_3 = \alpha_4 = \alpha_5 = 0.$$

The test statistic, which was

$$-2\ (\Delta \text{ log likelihood}) \qquad (2),$$

was distributed *chi-square* with three degrees of freedom; the appropriate *chi-square* test value was 7.81. The change in the logarithm of the likelihood function, (Δ log likelihood), was calculated by subtracting the logarithm of the likelihood function for equation (1) from the logarithm of the likelihood function of a restricted form of equation (1) wherein $\alpha_3=\alpha_4=\alpha_5=0$.

METHODS--DATA

Western Oregon's timber resources were inventoried between 1973 and 1976, and the non-federal resources were reinventoried during 1985 and 1986 (Gedney et al. 1986a, 1986b, 1987). Data on 756 of 799 possible forestland plots not classified as hardwood sites were used to estimate the logit equations. The forty-three plots not used were those that had a change in ownership category during the remeasurement interval. The 756 plots represented 5.6 million acres of the total possible 5.8 million acres of private forestland in western Oregon.

Plots in industrial ownership or corporate ownership received ownership codings of one, while all remaining plots received an ownership coding of zero. Corporate owners were similar to individual and farmer owners in that did not own conversion facilities. They differed, however, in that they held more than 5,000 acres of forestland. We followed recommendations of Gedney (1983), who concludes that corporate owners should be included with industrial owners for purposes of timber supply analysis.

For all plots except those in Jackson and Josephine Counties in southwest Oregon, a harvest code of one was assigned if they had received clearcut, salvage, or overstory removal treatment from 1976 to 1984. For Jackson and Josephine counties, a harvest code of one was assigned to all plots harvested from 1976 to 1984, regardless of harvest type.

Volume per acre was taken directly from the initial, mid-1970's data. The compound annual growth rate for growing stock was simulated using the ORGANON (Hester et al. 1989) stand simulator for those plots in Jackson and Josephine Counties, and plots in Douglas County with substantial volumes in pine and mixed conifer species. The Stand Projection System or SPS (Arney 1985) was used for all other plots in western Oregon.

Plots harvested during the remeasurement interval had lower growth rates and higher volumes per acre than unharvested plots (table 1). *Growth rates for harvested nonindustrial* plots tended to be slightly higher than the growth rates for harvested industrial plots, while the average per-acre volumes for harvested nonindustrial plots was lower than for industrial plots.

Table 1.--A comparison of compound annual growth rates, volume per acre, and sample size for harvested and unharvested plots on the nonindustrial and industrial ownerships in western Oregon.

Ownership	Harvested plots			Unharvested plots		
	Growth rate	Volume per acre	Sample size	Growth rate	Volume per acre	Sample size
		Cubic feet per acre			Cubic feet per acre	
Nonindustrial	.038	3409	28	.067	2219	207
Industrial	.027	7245	70	.066	2291	451

RESULTS

Estimated coefficients (with standard errors shown in parentheses) for restricted and unrestricted forms of the logit model were:

Coefficient	Restricted Model	Unrestricted Model
Constant	-2.401*	-1.657*
	(.259)	(.489)
Growth rate	-11.24*	-16.255*
	(3.881)	(7.353)
Volume/acre	.000264*	.000162
	(.00004)	(.00009)
Owner	--	-1.007
		(.583)
Owner X Growth rate	--	6.123
		(8.736)
Owner X Volume per acre	--	.00013
		(.0001)

*Significant at .05 level

The logarithm of the likelihood function of the restricted model was -235.998, and the logarithm of the likelihood function of the unrestricted model was -234.35.

INTERPRETATION

The test statistic, -2 (Δ log likelihood), was equal to 3.296, which was less than the critical *chi-square* value of 7.81 (α=.05). We concluded, therefore, that there was insufficient information to reject the null hypothesis of no difference in the probability of harvest for industrial and nonindustrial ownerships.

The coefficients on growth rate and volume per acre were of the expected sign and were statistically significant (α=.05).

Diagnostics

How much confidence do we have that the results were a reliable indicator of harvesting behavior in western Oregon? We conducted two simple diagnostic tests to explore this question. The first test was to compare the observed harvest volume from harvested plots with the predicted harvest volume. The second was to test whether the probability model was different for any or all of eight subregions within western Oregon. Forest conditions and harvest frequencies varied substantially within the subregions, and the unanswered question was whether the probability function would be sufficiently robust to account for this intraregional variation.

The observed and predicted harvest volumes were within one percent of each other. The observed harvest volume (4333.48 million cubic feet) was calculated by multiplying the acreage expansion factor of harvested plots by the 1976 volume per acre of growing stock. The predicted harvest volume was calculated with the following relation:

$$\sum_i Pr_i A_i V_i$$

where Pr_i is the probability of harvest given the growth rate and volume per acre for the i-th plot; A_i is the acreage expansion factor for the plot; and V_i is the 1976 growing stock volume for the plot. The closeness of actual and predicted indicated that the estimated probability equation was successful in predicting a variable closely allied with the harvest/no-harvest decision for the data set used to estimate the model.

The second test, an intraregional comparison of harvest probabilities, was more demanding. Seven timber supply and processing subregions are separately identified for timber supply and demand analysis in western Oregon (Connaughton and Cathcart 1991). Forest conditions and institutional arrangements affecting the wood product's economy within each subregion vary. For example, northwestern Oregon's timber resources are younger with more land in private ownership than the Douglas County subregion. Resource-related and institutional differences are somewhat reflected in the frequency of plots harvested during the 1976-84 interval:

Subregion	Number of Plots	Proportion Harvested
Linn/Marion Counties	74	.054
Coos/Curry Counties	111	.081
North Willamette	54	.111
Northwest Counties	134	.127
Central Coast	98	.133
Lane County	103	.146
Douglas County	111	.162
Jackson/Josephine	71	.225

The null hypothesis was that there was no difference in harvesting behavior by subregion. The approach was comparable to the ownership comparison, and began with the estimation of an unrestricted equation:

$$\ln \frac{(Pr_i)}{(1-Pr_i)} = \alpha_0 + \alpha_1 \ (Growth\ Rate)_i + \alpha_2 \ (Vol/Ac)_i + \sum_j \beta_{1j} \ (Subregion_j)_i + \sum_j \beta_{2j} \ (Subregion_j \ X \ Growth\ Rate)_i + \sum_j \beta_{3j} \ (Subregion_j \ X \ Volume/acre)_i + \delta_i \quad (3),$$

where $(Subregion_j)_i$, for j=1...7, is a dichotomous variable that takes a value of one when the i-th plot is located in the j-th subregion and a value of zero otherwise; $(Subregion_j\ X\ Growth\ Rate)_i$ is an interaction term that takes the value of the growth rate of the i-th plot when the plot is located in the j-the region; $(Subregion_j\ X\ Volume/acre)_i$ is an interaction term that takes the value of the volume per acre of the i-th plot when the plot is located in the j-th region; and δ_i is a random error term.

The β_{1j}, β_{2j}, and β_{3j} had interpretations similar to the coefficients associated with ownership and ownership interaction variables in the ownership probability analysis. For example, if one or more of the β_{2j} terms had been statistically significant, it would have indicated that timber was harvested during earlier (or later) stages of stand development than in other subregions.

The test of hypothesis was conducted by calculating equation (2) from the logarithm of the likelihood function for equation (3) and the logarithm for the likelihood function of the restricted form of equation (3) ($\beta_{1j}=\beta_{2j}=\beta_{3j}=0$, for all j).

Results showed that there was insufficient evidence to reject the null hypothesis that the probability of harvest was the same across all subregions. The calculated test statistic was 24.076, which is less than the critical *chi-square* value of 32.7 (21 degrees of freedom, α=.05). We concluded, therefore, that the probability function was applicable across and within western Oregon. The implication was that the probability function was stable under an array of resource and institutional conditions that vary geographically--conditions not captured by the specification of the original probability model.

CONCLUSIONS

Gedney (1983) reports statistically significant differences in the harvesting rates among owners in western Oregon. Our results suggested that these differences were due to differences in forest condition rather than ownership. The likelihood of a stand being harvested, therefore, was the same in western Oregon regardless of the plot's ownership category.

Our research was directed at enlarging the forestry profession's understanding of harvesting behavior, and cannot be extrapolated to stand management behavior. Indeed, a needed extension of this research is to see whether the probabilities of stand management--regeneration, and stocking level control practices--are the same across ownerships. The differences in treatment opportunities (MacLean 1988) suggest that nonindustrial and industrial stand management may differ.

Our results suggested that the recent increases in nonindustrial harvests were not random occurrences. Instead, recent nonindustrial harvest levels of almost 600 million board feet would be expected in the future given that nonindustrial stands are maturing and are becoming candidates for harvest. Given the age class distribution in the nonindustrial ownership, this higher harvesting rate is likely sustainable over the critical next two decades, which allows time for young, industrially-owned stands to mature. These harvest increases could not come at a better time for western Oregon as it faces large downward adjustments in federal timber availability.

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A CENSORED REGRESSION APPROACH
TO MODELING HARVEST BEHAVIOR[1/]

Donald F. Dennis[2/]

Abstract.--This study provides insight into private sector timber supply through development of both theoretical and empirical models of harvest behavior. A microeconomic model is used to examine the harvest decision for owners who value both forest amenities and monetary income. Results of censored regression (Tobit) analyses highlight the influence of landowner affluence and certain forest characteristics on harvesting. Decomposition of the Tobit coefficients indicates that changes in timber supply are expected to occur primarily at the extensive rather than intensive margin.

Keywords: Tobit, timber supply.

INTRODUCTION

The Northeast's standing timber volume has increased substantially over the past few decades. Growth that averaged approximately twice annual harvests led to a 73-percent increase in growing stock volumes between 1952 and 1987 (USDA For. Serv. 1988). Expansion of the region's wood products industry could stimulate the regional economy and breathe economic life into many rural communities.

Nonindustrial private forest landowners hold almost three-quarters of the Northeastern region's timberland (USDA For. Serv. 1988). Although crucial in assessing expansion opportunities within the wood products industry, the multiple objective and dynamic nature of private ownership makes estimation of timber availability from this sector extremely difficult. There are concerns that changing demographic patterns of landownership and increasing affluence will adversely affect timber supply. Changes in the forest as well as the economic climate within which landowners make decisions will also influence timber availability.

This study provides insight into the determinants of timber supply from private forests through development of both theoretical and empirical models of harvest behavior. A microeconomic model encompasses the multiple objective nature of private ownership by examining the harvest decision for landowners who derive utility from forest amenities and from income used for the consumption of other goods. Censored regression (Tobit) analysis is used to estimate the relationship between harvest behavior and forest, owner, and economic characteristics from cross-sectional data for individual forest plots in New Hampshire.

A MICROECONOMIC MODEL OF HARVEST BEHAVIOR

This model is an adaptation of Becker's (1965) model that analyzed an individual's choice in allocating time between work and leisure. Binkley (1981), Boyd (1984), Johansson and Lofgren (1985), and Max and Lehman (1988) also used variations of the household production model to study timber supply.

Landowner's maximize utility from nontimber or forest-related amenities and from the generalized purchasing power of income, subject to two constraints:

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[2/]Forest Economist, Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, Burlington, VT.

$$\max U(A,I) \qquad (1)$$

subject to

$$I = PH + E \text{ and } A = V - H$$

where $U(A,I)$ = utility defined over A and I,
A = volume of timber reserved for amenities,
I = total income,
P = stumpage price,
H = volume of timber harvest,
E = exogenous income,
and V = initial timber inventory.

The first constraint defines total income as the sum of timber income and exogenous income and the second limits the amount of timber either sold or retained to the total available. We also assume that benefits increase in both variables but at a decreasing rate and that amenities are a luxury good ($\partial U/\partial I$, $\partial U/\partial A < 0$, $\partial^2 U/\partial A \partial I \geq 0$).

The first-order conditions of the Lagrangian solution for utility maximization indicate that at the optimum:

$$P\frac{\partial U}{\partial I} = -\frac{\partial U}{\partial A}\frac{\partial A}{\partial H} \qquad (2)$$

At this solution the landowner chooses the combination of timber reserved for amenities and income for which the psychic rate of tradeoff between the two is equal to the rate at which they can be traded in the market. The utility derived from additional timber income will equal the utility foregone from amenities to obtain that income.

Comparative statics analyses are performed by differentiating the first-order condition (Equation 2) with respect to the variable of interest. These results provide insight into how changes in the level of a variable will effect timber supply. Binkley (1981) and Dennis (1989) provide detailed discussions of the comparative statics results concerning timber supply. The comparative statics results are in general agreement and the more important inferences are included below.

Changes in stumpage prices have an ambiguous effect on harvesting due to the opposing influences of substitution and income effects, which are characterized by the well-known Slutsky equation. Increased prices reduce the level of harvest necessary to maintain a given income and at the same time raise the cost of reserving timber for amenities. Determining which effect dominates is an important empirical question.

The comparative statics results for timber inventory (V) and exogenous income (E) have the expected positive and negative signs, respectively. Greater initial inventories provide more timber for allocation between harvest and amenity use. Increased exogenous income reduces the relative value of additional timber income and makes harvesting less desirable.

Although theoretical models provide insight into harvesting decisions, usefulness is limited by the simplifying assumptions required to make the models tractable. Additional insight can be provided empirically.

DATA SOURCES AND CHARACTERISTICS

Forest data were obtained from 68 fixed-radius (1/5 acre) sample plots measured by the USDA Forest Service during its periodic survey of New Hampshire. Each sample plot was measured in 1973 and again in 1983, with all trees being accounted

Table 1.--Descriptive statistics (N = 68)

Variables[a]	Units	Mean	Standard deviation of variable	Harvested mean	Non-harvested mean
Timber harvest	bd. ft./acre	111	332	628	0
Timber volume	bd. ft./acre	961	949	1,597	824
Volume (white pine)	bd. ft./acre	477	934	1,275	306
Ratio (white pine)	Proportion	0.41	0.42	0.73	0.34
Volume (red oak)	bd. ft./acre	79	197	136	67
Ratio (red oak)	Proportion	0.10	0.24	0.15	0.08
Sawlog price index	1983 Dollars	55.9	4.1	57.5	55.6
Education	Years	15.9	3.8	13.7	16.4
Landowner age	Years	59	12	60	58
Tenure	Years	23	13	23	23
Dummy variables:					
Professional	Proportion	0.44	0.50	0.33	0.46
Income greater than $30,000[b]	Proportion	0.57	0.50	0.33	0.61
New Hampshire resident	Proportion	0.72	0.45	0.75	0.71

[a]See Table 2 for definitions of selected variables.

[b]N = 58.

for (e.g. harvest or mortality). Species composition and a variety of other forest characteristics were determined. Frieswyk and Malley (1985) provide a detailed discussion of survey procedures and descriptive statistics are provided in Table 1.

A questionnaire, sent to each landowner, provided data on ownership characteristics (Birch 1988). These data included information on size of holding, education, income, tenure of ownership, age, occupation, whether the owner was raised in an urban or rural environment, and several other owner characteristics.

Stumpage prices are from the New Hampshire Forest Market Reports, published annually by the New Hampshire Cooperative Extension Service. Data were derived from annual surveys conducted by county foresters. Because of variation in stumpage prices due to quality, location, accessibility, and other factors, ranges in prices were reported. Sawtimber prices were reported by county and species and were measured in dollars per thousand board feet (International 1/4-inch rule).

The exact price that each landowner was offered was unknown, so price indices were constructed to proxy for offer prices. The midpoints in the annual range of prices for six sawlog species--spruce/fir, hemlock, white pine, hard maple, paper birch, and red oak--were used to construct weighted average county-level stumpage price indices. The weights are the relative proportion of total timber removals for each species during 1983, as reported by Frieswyk and Malley (1985) and Nevel, Engalichev, and Gove (1986). Together these species comprised 92.5 percent of total sawlog removals in New Hampshire in 1983. Nominal prices were converted to real prices (1983 dollars) using the Producer Price Index.

ANALYSIS OF CENSORED SAMPLES

We assume that landowners harvest timber when their desire to do so reaches a certain level and that a measure of that desire is provided by the quantity of timber harvested. Because no measure of an owner's desire to harvest is obtained if there is no harvest the sample is censored at zero. A censored sample is one in which some observations of the dependent variable corresponding to known sets of independent variables are not observable (Judge et al. 1985). Least-squares estimation procedures produce biased and inconsistent estimates for censored samples because the conditional expectation of the error term is not zero. Tobin's (1958) pioneering analyses of censored samples, with respect to consumer durables, has led to these models being termed "Tobit models". Amemiya (1984) provides a thorough survey of censored regression models.

McDonald and Moffitt (1980) offer an innovativ procedure for interpreting Tobit coefficients. They show how Tobit analysis can be used to estimate both changes in the probability of being above the limit, zero in the case at hand, and changes in the dependent variable if it is already above the limit. Thus, estimated timber supply responses resulting from marginal changes in an explanatory variable may be decomposed into changes in harvesting intensity expected to result at the intensive and extensive margins. A more detailed discussion of procedures for analyzing censored samples, with specific reference to timber supply, is provided by Dennis (1989).

RESULTS

Table 2 provides a brief description of each variable and Table 3 shows the regression results. Ten landowners did not answer the income question, so these observations were deleted from the sample when income was used as an explanatory variable. These results are reported in the lower portion of Table 3. The results are discussed first with respect to the estimated signs and statistical significance of the coefficients and then with respect to magnitude and interpretation.

Table 2.--Variable summary

Variable	Definition (unit)
MBF	Timber volume (Mbf/acre).
RP	Proportion of white pine; ratio = [volume of white pine (Mbf/acre)/MBF].[a]
RO	Proportion of oak; ratio = [volume of oak (Mbf/acre)/MBF].
SPI	Sawlog price index [real (1983) dollars, weighted by state level production].
ED	Years of formal education.
INC	Dummy variable, coded 1 if landowner's income was greater than $30,000/year, and 0 otherwise.
PRO	Dummy variable, coded 1 if landowner was employed in a white collar occupation.

[a]Includes red, white, and black oak.

The presence of commercially valuable species, such as white pine and red oak, were expected to enhance the probability of harvest. The empirical results supported this hypothesis. Positive and statistically significant coefficients were obtained for variables measuring the proportion of total timber volumes represented by these species.

Stands that were subsequently harvested contained an average of 50 percent of their total volumes in white pine and 18 percent in red, white, or black oak. This was more than double the percentages of these species present in stands that were not harvested.

Table 3.--Tobit results (Dependent variable: volume (Mbf) of timber harvest during the period 1973-1983)

Explanatory variables	Coefficient	Standard error
N = 68		
Constant	-2.765	2.319
RP	1.810**	0.693
RO	1.432*	0.764
MBF	0.320**	0.119
SPI	0.040	0.036
ED	-0.127**	0.053
RO	0.585	0.381
N = 58[a]		
Constant	-4.533	2.804
RP	1.955**	0.796
MBF	0.472**	0.134
SPI	0.039	0.041
INC	-1.007**	0.418
PRO	0.707*	0.421

**Significant at 5 percent level.

*Significant at 10 percent level.

[a]Excludes observations without income information.

Individual Coefficients

A positive relationship was anticipated between per-acre timber volume and timber harvesting due to economies of scale and the assumption of decreasing marginal utility of timber reserved for amenities. Mean per-acre volumes prior to harvest were 1.6 Mbf for harvested plots, compared to 0.9 Mbf for plots that were not subsequently harvested.

Positive, but not statistically significant, coefficients were obtained for the price variable. The apparent lack of price responsiveness may have resulted from the income and substitution effects effectively canceling one another. However, before accepting this conclusion consider a suspected "error in variables" problem. Price indices do not generally measure the exact price that a landowner was offered. If the price index measures the true offer price with a random error, then the statistical significance of the coefficient will be biased toward zero. Therefore, the probability of incorrectly rejecting the hypothesis that the coefficient is not zero is greater than the indicated level of significance.

The harvest decision is expected to be influenced by exogenous income and by the relative values landowners place on amenities and consumption. There is concern that changing demographic patterns of landownership may adversely affect timber availability. Several explanatory variables that measure a landowner's age, education, income, occupation, early life environment, tenure of ownership, and state residency were examined to provide insight into the merit of these concerns.

Education and income levels were used to examine the affect of affluence on timber harvesting. Coefficients were negative, but not significant at the 5-percent level, when both variables were included in the model. The lack of significance is probably due to the high collinearity between the two variables. The significance level for each variable improved beyond the 5-percent level when the other was deleted from the model.

There are several plausible explanations for the strong negative correlation found between education and timber harvesting. Education may directly influence the way individuals value amenities and income or it may proxy for social background or other factors that influence harvest behavior. Also, education may proxy for income, which theoretical analyses suggest reduce the marginal utility of income from timber harvesting.

The influence of occupation on timber harvesting was examined using two coded variables that indicated whether the landowner was a professional or was retired. A significant positive correlation was obtained for the professional variable for the analysis that included income (N = 58). Professionals may have a greater tendency to view their land as an income producing asset and therefore be more likely to harvest timber. No relationship between harvesting and whether or not the owner was retired was established.

Several other variables were examined, but none were found to be significantly correlated with harvesting at even the 20-percent level. These included the landowner's age, whether he or she was raised in an urban or rural environment, in-state residency, tenure of ownership, and whether or not the owner was involved in the purchase or sale of woodland within the previous 10 years.

Magnitude and Interpretation

Because the model is nonlinear the magnitude of the estimated responses to changes in the explanatory variables are influenced by the values for all the variables and coefficients. The model depicted in the upper portion of Table 3 was used to develop estimates at three points in the distribution of sample values: (1) $X_iB = -1.750$, the 31st percentile, arbitrarily chosen to represent the lower portion of sample values, (2) $X_iB = -1.098$, computed using the mean values of the explanatory variables, and (3) $X_iB = 0.038$, computed using the mean values for the harvested plots. Because the dependent variable measured harvest activity over the period 1973 to 1983 the estimates shown in Table 4 are per-acre values for an 11-year period.

The first row of Table 4 shows the expected harvest, which may be obtained by multiplying the probability of harvest by the conditional harvest, shown in the second and third rows, respectively. It is not surprising that each estimate was greater when evaluated at the means for the plots that were subsequently harvested. The expected harvest was approximately 18 times greater when evaluated at the means of the harvested plots versus the entire sample.

The probability of harvest was miniscule when computed at values in the lower third of the distribution and this led to an extremely low expected harvest. Furthermore, estimated marginal responses were also very small for these observations. Directing efforts to increase timber supply at more responsive portions of the population appears more fruitful. Further decomposition of the results indicates that marginal responses are expected to occur primarily at the extensive margin rather than intensive margin.

Table 5 shows the elasticities for the individual variables, computed at the sample mean and the mean values for the harvested plots. In each case the values for the variables other than the one of interest were held constant.

The elasticities for the forest characteristics varied considerably; roughly following a 1:2.5:5 ratio for RO, MBF, and RP, respectively. The estimated elasticity of 1.06 for the inventory variable corroborates the inventory elasticity of 1.0 assumed in several aggregate supply studies (e.g. Adams and Haynes 1980, Cardellichio and Veltkamp 1981, and Binkley and Cardellichio 1986).

Table 4.--Decomposition of Tobit results

	31st Percentile	Sample mean	Harvested plot mean
Estimates:			
Harvest (Mbf)[a]	.001	016	.293
Probability of harvest (proportion)	.005	.054	.522
Conditional harvest (Mbf)[b]	.219	.290	.561
Marginal response to a change in variable X_k:			
Harvest (kMbf)	$.005B_k$[c]	$.055B_k$	$.522B_k$
Probability of harvest (proportion)	$.022B_k$	$.161B_k$	$.581B_k$
Conditional harvest (Mbf)	$.084B_k$	$.143B_k$	$.376B_k$
Portion of marginal response resulting from:			
Per-acre harvest	8%	14%	38%
Probability of harvest	92%	86%	62%

[a]Estimated per-acre harvest across all plots at this point in the X_iB distribution.

[b]Estimated per-acre harvest for plots at this point in the distribution that are actually harvested.

[c]B_k is the estimated coefficient for the K^{th} explanatory variable.

Table 5.--Elasticities with respect to estimated per-acre harvest

Variable	Elasticity: At sample mean	Elasticity: At mean for harvested plots
RP**	2.554	2.340
RO*	0.475	0.381
MBF**	1.061	0.912
SPI	7.732	4.108
ED**	-6.964	-3.091
PRO	0.891	0.348

**Significant at 5% level.

*Significant at 10% level.

The large estimated elasticities for the education variable provide credence to concerns that increased affluence may adversely affect timber supply. The estimated effect of a 1-year increase in education was to decrease the expected harvest by 36 percent, the probability of harvest by 32 percent, and the conditional harvest by 6 percent when evaluated at the sample mean.

The model may also be used to simulate the effect of a continuation of past trends in the explanatory variables. The Northeastern forest is maturing; sawtimber volumes have increased 26 percent between 1973 and 1983 in New Hampshire (Frieswyk and Malley 1985). Sawlog quality has generally improved, but species composition is deteriorating. Together, eastern white pine and red, white, or black oak comprised 38 percent of New Hampshire's total sawlog volume in 1983 compared to 46 percent in 1973. Red maple, a relatively low valued species, increased by more than 137 percent since 1960 and ranked second to white pine in growing stock volume in 1983. Landowners are becoming increasingly more affluent and educated. In 1983 almost three-quarters of New Hampshire's individually owned forests were held by landowners who completed education beyond high school.

The assumptions for the simulation were: average sawtimber volumes will be 15 percent higher over the next decade, the proportions of white pine and red oak will decrease by 10 percent, average education levels will increase by one quarter year, and the proportions of "professionally" employed landowners and real stumpage prices will remain constant. The simulations and comparisons are computed at the sample mean.

The simulation yielded an expected harvest of 12.3 bd ft/ac, a 22-percent reduction. The expected probability of harvest decreased from 5.5 to 4.4 percent and the conditional harvest decreased from 290 to 283 bd ft/ac. Additional analyses indicate that a 3-percent increase in real stumpage prices would be required to maintain harvests at current levels, under these assumptions. Of course, other options, such as programs designed to enhance growth, improve species composition, or entice more affluent owners to harvest, might be used to avert the need for increased real stumpage prices.

CONCLUSIONS

Forest characteristics, which were generally lacking from previous empirical studies, were important determinants of harvest behavior. High per-acre volumes and the presence of commercially valuable species were strongly correlated with harvesting.

Concerns that an increasingly affluent population of landowners may be less willing to harvest timber were confirmed by both theoretical and empirical analyses. Timber harvesting was negatively correlated with both income and education. More educated landowners may value forest amenities higher or they may have larger incomes that reduce the marginal utility of timber income.

The empirical analyses also yielded a positive correlation between harvesting and employment in a "professional" position. Several other owner characteristics, such as, age, retirement status, tenure of ownership, whether the owner was raised in an urban or rural environment, and in-state residency, were not correlated with timber harvesting.

Positive coefficients and relatively high elasticities were obtained for stumpage prices; however, the results were not significant at the 10-percent level. The apparent lack of price responsiveness may be due to the opposing influences of income and substitution effects or it may be that problems of multicollinearity and measurement, inherent in these types of analyses, are obscuring the empirical results.

Although continued growth of the forest will have a positive effect on timber supply, a net negative effect is anticipated due to changes in species composition and the expectation that an increasingly affluent landowning population will be less likely to harvest timber. Decomposition of the Tobit coefficients indicates that changes in timber supply are expected to result primarily at the extensive, rather than intensive margin. Therefore, the net expected effect of a continuation of past trends is a decline in the number of acres from which timber is offered for sale within a given distance to mills. Unless these trends are reversed or their effects ameliorated, the forestry sector may undergo an adjustment resulting in an extension of operating areas or fewer mills.

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DYNAMIC YIELD CURVES TO ASSESS INVESTMENT OPPORTUNITIES[1]/

Stephen G. Boyce[2]/

Abstract---This paper proposes use of dynamic yield curves by age classes as a way to make models congruent with inventories and as a way to examine effects of different cultural practices on investment opportunities.

System dynamics, cash flow, cultural practices,

INTRODUCTION

Forecasts of investment opportunities in forestry depend on suppositions, such as: regional yield curves forecast future volumes of a forest in the region if future forests, cultural practices, and environments approximate average conditions of the past. These suppositions are not fulfilled when initial inventories are different from volumes in the regional yield tables and when future forests receive culture never before used, except experimentally. This paper proposes a way to base suppositions about yields and cash flows on inventories.

Usefulness of forecasts depend on beliefs in the suppositions (Armstrong 1985; Denning 1990). Beliefs about forests may include suppositions about physiological processes (Bossel and Schafer 1990) and about relationships found from progeny tests, thinnings, applications of fertilizer, weed control and other cultural practices. Regardless of the basis for beliefs, the underlying theorems assert that differential rates of mortality, resulting from inner functions of the trees and from removals by cultural practices, are the organizing mechanisms that determine future volumes. Investment opportunities depend on how cultural practices and removal of accumulated volumes organize a forest over time.

1/Presented at the 1991 Systems Analysis in Forest Resources Symposium, Charleston, SC, March 3-7, 1991.

2/ Retired Chief Forest Ecologist, USDA Forest Service, and Visiting Professor, School of the Environment, Duke University. This paper is prepared under the USDA Forest Service Volunteer Program.

Concepts in the preceding paragraph are used to develop dynamic yield curves. Development of the curves begins with inventories by 5-year age classes. For each age class, a yield curve is developed from relationships for physiology, genetics, yield records of past stands, regional yield curves and personal experiences. At time zero, volumes for each age class begin with values derived from the inventories. The wave form of each age-class yield curve is described mathematically and inserted into a simulation model of the forest to be managed. A forest-wide yield curve may be derived by selecting values across all age classes for a given future time. In the simulation model, estimates of yields change over time as cultural practices affect age classes.

An Illustration

Data from the Korstian Division, Duke University Forest are used to illustrate development and use of dynamic yield curves. The initial inventory of 977 acres of pine stands is for 1986 and simulations of dynamic yields begin in 1987 (Gilluly 1987). From data available in 1986, a forest-wide yield curve for loblolly pine stands on the Korstian Division is plotted along with smoothed data from regional yield curves (Table 4b, McClure and Knight 1984). The yield curves do not coincide, and future yields are not likely to coincide with the 1986 inventory and may never form a smoothed curve, such as the curve illustrated for the regional yield curve (fig. 1).

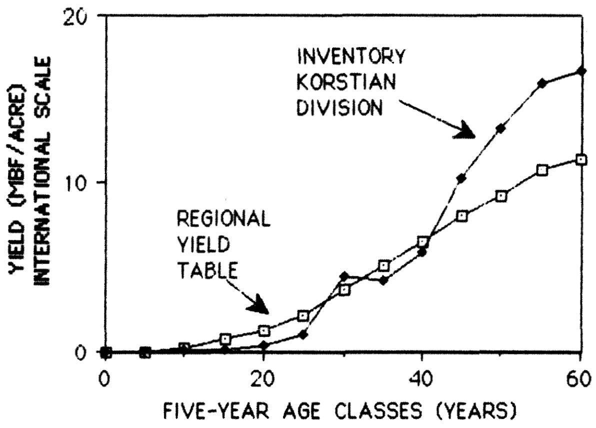

Figure 1---Inventory data for pine stands on the Korstian Division, Duke University Forest, 1986, plotted with smoothed regional yield curves (Table 4b, McClure and Knight 1984).

Consider the pine stands are established with new generations of genetically improved pine seedlings every 15 years and each new generation of genetically improved seedlings increases sawtimber yields 10 percent over the previous generation. This relationship can be plotted for each age class. For the 30-year age class, genetic effects appear in the yield curve as a "stair step" over a 5-year period at time 30 and again, 15 years later. For the 25-year age class, genetic effects on sawtimber volumes are relatively small (fig. 2).

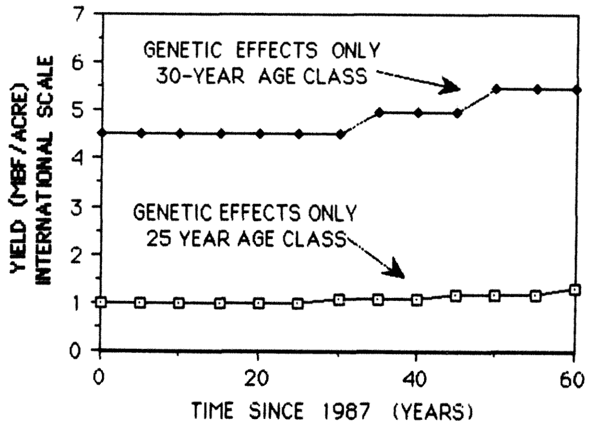

Figure 2---Expected changes in yields for 25- and 30-year age classes when natural stands are replaced with plantations of pines genetically improved every 15 years.

Next, consider changes in the 30-year age class when thinning and release in both natural and planted stands are followed by fertilization and harvested stands are replaced with plantations of seedlings which are genetically improved every 15 years. Curves for merged effects display suppositions based on interpretations of inventories, research results and expert experience and opinion. Combined effects expected from these practices for the 30-year age class are compared with the curve for genetic effects only (fig. 3).

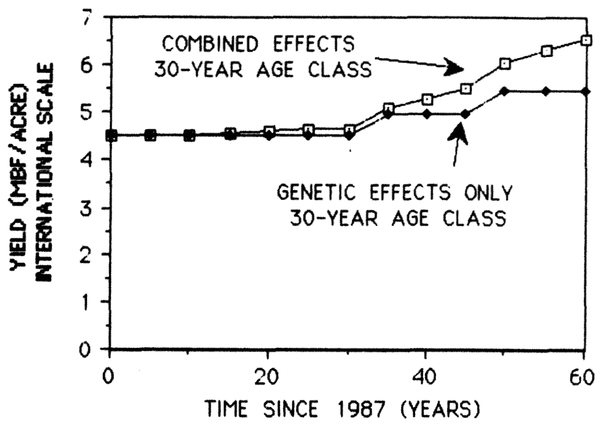

Figure 3---Dynamic yield curve expected for the 30-year age class when cultural practices are combined and when genetic effects are considered only. See text for a list of cultural practices.

Forest-wide yield curves change over time. Changes, simulated for the Korstian Division at times 20, 40 and 60 years, are compared with the 1986 inventory (fig. 4).

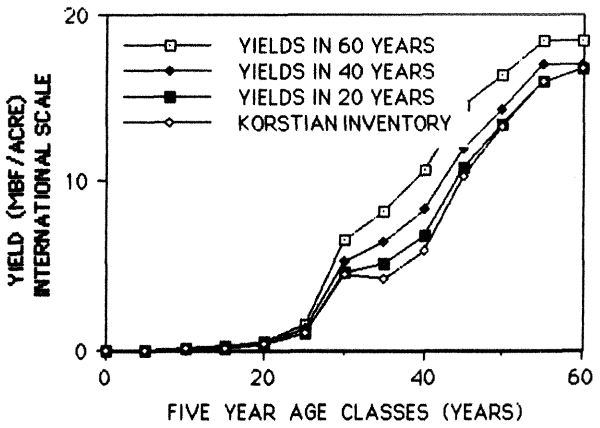

Figure 4---Simulated changes in forest-wide yield curves and the 1986 inventory for the Korstian Division.

Models are designed and fitted to specific forests with Professional DYNAMO Plus (Pugh-Roberts 1986) for IBM-PC and compatible machines and with STELLA (High Performance Systems 1987) for Macintosh machines (Boyce 1985). Outcomes are expressed in many forms, such as net cash flows, net present values, internal rates of return, standing volumes and volumes harvested by product class. Models are adjusted as data from new inventories and research become available.

For demonstration purposes, one option is to move pine stands on the Korstian Division toward a 32-year rotation period. This rate of harvest combined with the cultural practices previously described (figs. 2 and 3) are used to simulate cash flows using the dynamic and regional yield curves. For this option, simulations produce larger net cash flows with the dynamic curves than with the regional curves (fig. 5).

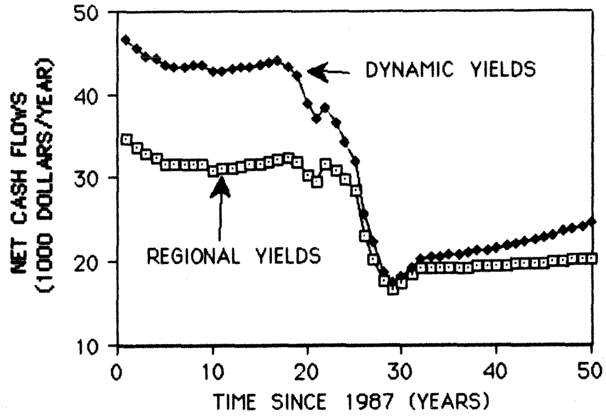

Figure 5---Net cash flows simulated with dynamic and regional yield curves (see figs. 2, 3, and 4).

This result occurs for this option because volumes in the initial inventory, for stands older than 40 years, are larger than volumes in the regional yield table (fig. 1) and because harvest of timber for the first 25 years is from stands older than 40 years. After year 32, the dynamic yield curves continue to simulate increases in cash flows as genetics and cultural practices continue to increase the harvested volumes. Different results will be obtained for different options and different forest. But, what is important is that cash flows for the next 10 to 20 years for a specific forest are more realistic when derived from dynamic yield curves that originate from inventory data than from regional yield curves (fig. 6).

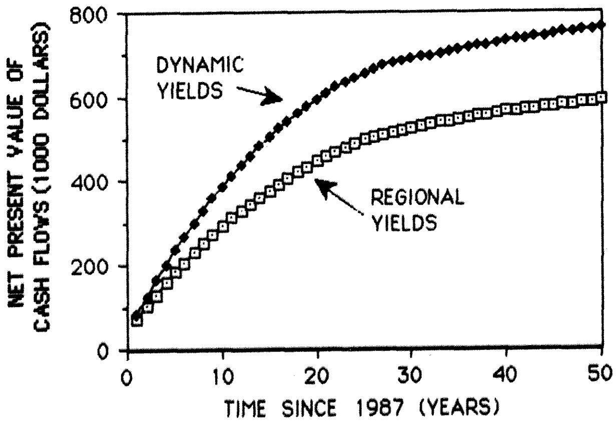

Figure 6---Net present values simulated with dynamic and regional yield curves.

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A MULTI-RESOURCE SILVICULTURAL DECISION MODEL FOR FORESTS OF THE NORTHEASTERN UNITED STATES[1]

David A. Marquis[2]

ABSTRACT.--A computerized decision model is under development for forests of the northeastern United States. The model will provide expert support for land managers charged with developing silvicultural prescriptions to achieve a wide variety of timber, water, wildlife, aesthetic, and environmental goals. Data on forest vegetation, site conditions, and management objectives are the basis for management recommendations generated by the program. These recommendations are based on knowledge and guidelines accumulated from many years of research on all major forest types throughout the region. In addition to generating an expert opinion on each stand and management unit, users may compare the recommended treatment and other alternatives through the stand growth simulators incorporated into the program. The comparisons can include analysis of economic returns and effects on forest stand development, wildlife habitat suitability, visual conditions, water yields, and environmental considerations.

Keywords: silvicultural systems, multiple-use, computer models

INTRODUCTION

Forests in the northeastern United States are used for a variety of purposes, including timber production, wildlife habitat, and all types of outdoor recreation. These forests are also of great importance for a multitude of other values, ranging from reserves for the preservation of biological diversity to the sources of most of our water supply. Although in the past timber management was often the primary goal of forest management, other values have become increasingly important. For many woodland owners, timber production is much less important than wildlife and recreational use of their land. Even those who hold land primarily for timber production usually attempt to integrate other resource uses into their management.

Research has provided a large amount of sophisticated information on forest management for these uses, but the information is scattered and difficult to apply across the many forest types in the region. Further, much of the information applies to a single resource use. Guidelines for integration of available knowledge for true multi-resource management are limited.

There are, for example, sophisticated silvicultural guides available for timber production of many of the commercially important forest types of the Northeast. These include guides and major summaries prepared for spruce-fir (Frank and Bjorkbom 1973), northern hardwoods (Leak and others 1987, Nyland 1987), paper birch (Safford 1983), Allegheny hardwoods (Marquis and others 1984), oak-hickory (Roach and Gingrich 1968), and Appalachian hardwoods (Smith and Eye 1986, Smith and others 1988). Others include those for stand management in the presence of severe disease or insect problems such as the gypsy moth (Gansner and others 1987, Gottschalk 1986). Numerous stand growth simulators are also available for northeastern forests. They include: NE-TWIGS for various forest types (Hilt and Teck 1988), SILVAH for Allegheny hardwoods (Marquis 1986), OAKSIM for oak-hickory (Hilt 1985a, 1985b), FIBER for

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[2]Principal Research Silviculturist, USDA Forest Service, Northeastern Forest Experiment Station, Forestry Sciences Laboratory, P.O. Box 928, Warren, PA 16365.

spruce-fir and northern hardwoods of New England (Solomon and others 1987), and GRO2 for New England forests (Sendak 1985).

Considerable information is available on harvesting methods and their impact on silviculture and management economics (LeDoux 1986, 1988; Reisenger and others 1988), and on the general economics of timber value changes (DeBald and Mendel 1976, Mendel and others 1976). Computer models that facilitate economic analyses of timber investment opportunities are readily available (Brooks and others 1984), including such programs as TWIGS (Blinn and others 1988), and MS-YIELD (Hepp 1988).

Specific guidelines on the management of forests for wildlife and aesthetics are not as well developed as those for timber production, although there is a considerable body of knowledge on these subjects, as well as much current research. Detailed information on wildlife species in New England has been compiled (DeGraaf and Rudis 1986), and general guidelines for management of wildlife trees and cavity trees are now available (DeGraaf and Shigo 1985, Tubbs and others 1987). Models to evaluate habitat suitability are also available for many wildlife species, such as the HEP models developed by the U. S. Department of the Interior Fish and Wildlife Service (Schamberger and Farmer 1978, U. S. Department of the Interior Fish and Wildlife Service 1981). General guidelines on landscape management practices suitable to meet various visual goals are also available (U. S. Department of Agriculture Forest Service 1980).

There is extensive literature on the management of forested watersheds, to increase water yields during periods of low flows and to minimize flooding during periods of high flows (Lull and Reinhart 1967, Lull and Reinhart 1972).

Considerable information is available on individual aspects of integrated forest management for multiple resources. Some examples include selection and retention of wildlife trees in relation to timber production (Tubbs and others 1987) and the distribution of harvest cuttings to meet the needs of both timber and deer (Roach 1974). Models designed to assist in forest-wide integration of multiple resource planning have also been developed, such as the DYNAST-MB model (Boyce 1977, Boyce and Cost 1978).

These information sources provide important knowledge for integrated resource management. The information, though, is scattered and incomplete. Site-specific guides for individual stands and larger forest units are not available. Guidelines for the integration of all forest resources and values applicable to specific tracts of land are totally unavailable. To meet these needs, the Northeastern Forest Experiment Station, U. S. Department of Agriculture, Forest Service, is developing a computerized multi-resource decision model (NE Decision Model) for the northeastern United States. The model will incorporate information on silviculture, growth and yield, harvesting, economics, wildlife habitat management, watershed management, landscape architecture, insect and disease management, and ecosystem protection and maintenance.

The primary function of the NE Decision Model is to provide expert recommendations to optimize multiple-use management in all major forest types and regions of the northeastern United States. Recommendations will be based on management goals specified by the user, along with data on site characteristics and vegetation in the stand and surrounding forest. A secondary function of the model is to provide the ability to test the effects of alternative management strategies on timber yields, wildlife habitat, aesthetics, water yields, and ecosystem characteristics. To accomplish this function, the NE Decision Model will include forest growth simulators appropriate to northeastern forests.

Development of the model will entail the consolidation of existing knowledge, making it more accessible to users, in readily-usable form. It will also provide direction for future research by exposing gaps in the existing knowledge, and by highlighting conflicts among resource uses. The structure and function of the NE Decision Model are described in this paper.

NE DECISION MODEL

Expert Recommendations

The first and most important function of the NE Decision Model is to provide expert opinion on multi-resource management for the important forest types in the Northeast. Recommendations, or prescriptions, are to be specific to individual stands managed for a particular set of management goals.

For example, an expert recommendation for a portion of aspen forest being managed for grouse habitat might call for an even-age silvicultural system on a short rotation, with the current treatment being a harvest cut in one stand to provide an area of dense young aspen stems for cover, and no cutting in the remaining stands to maintain dense canopy of larger aspen trees for winter food. Or, an expert recommendation for a portion of northern hardwood forest being managed to maintain a continuous mature forest cover for visual reasons, along with diversity of late successional wildlife and just enough timber harvesting to pay taxes and other costs of land ownership, might call for an uneven-age silvicultural system with stand structure parameters that feature large diameter trees and infrequent cuttings. A detailed expert opinion in such an area might call for a combination of single-tree and group selection cutting in a few stands and no cutting in the majority of stands.

Special efforts to create and maintain cavity trees and dead and down material, treatment of slash and other logging debris, and special care in riparian zones might all be recommended in those stands being harvested.

All recommendations will include two components: the silvicultural system to be used over the long term, and the current treatment for each individual stand. The silvicultural system will be selected on the basis of management goals and forest type. Current treatments within that system will be selected on the basis of current vegetation and site conditions in the selected stand and surrounding area. The recommended treatments will organize the vegetation within a group of stands managed together (a management unit) in order to achieve the optimum distribution of species, stand sizes, and stand structures over both time and space.

The initial data entered into the program will be the landowner's goals for the management unit. As currently formulated, the NE Decision Model will incorporate four timber management goals with two options under one of them, three wildlife management goals with five options under one and nine game species options under another, four primary aesthetic goals with six within-stand subgoals; three water goals, and five environmental goals: more than 300,000 possible combinations for any forest type. In addition, all goals may be applied under either a long (over 20 years) or short (20 years or less) time frame. These goals are:

Timber:

1) no explicit objective
2) recover management-ownership costs
3) maximize fiber production
4) maximize timber value
   a) maximize annual income
   b) maximize internal rate of return

Wildlife:

1) no explicit objective
2) enhance number of species for:
   a) all wildlife species
   b) wildlife species of intermingled farm and forest
   c) wildlife species of early successional vegetation
   d) wildlife species of late successional vegetation
   e) wildlife species of mixed deciduous-coniferous forests
3) optimize up to 3 of the following specific wildlife species
   f) white-tailed deer
   g) ruffed grouse
   h) snowshoe hare
   i) cottontail rabbit
   j) woodcock
   k) grey squirrel
   l) wild turkey
   m) black bear
   n) moose

Aesthetic:

1) no explicit objective
2) maintain a continuous mature forest cover
3) create variety and visual change within small areas (stands)
4) create variety and visual change within the landscape

Within-stand Aesthetic goals (Group 1):
   a) promote a large-tree appearance
   b) minimize slash and harvest disturbance
   c) feature special tree or shrub species

Within-stand Aesthetic goals (Group 2):
   d) create open-park-like appearance
   e) create dense screening vegetation
   f) maintain non-forest appearance

Water:

1) no explicit objective
2) increase water yield
3) limit peak flows

Environmental Considerations:

1) enhance fisheries/riparian resource
2) apply intensive water resource protection
3) maximize biological diversity
A) maintain the existing forest type
B) convert to a new forest type

The NE Decision Model will recognize eleven forest types, including:

1) spruce-fir
2) mixed wood (spruce-fir/beech-birch-maple)
3) northern hardwoods (beech-birch-maple)
4) Allegheny hardwoods (cherry-maple)
5) cove hardwoods (mixtures dominated by yellow-poplar in the Appalachians
6) oak/northern hardwood (beech-birch-maple/oak-hickory)
7) oak-hickory
8) oak/southern pine (oak-hickory and southern pine)
9) pine/hardwood (white pine/beech-birch-maple)
10) white pine
11) aspen-birch

See Table 1 for scientific names of tree species included in these forest types.

Table 1.--Common and scientific names of tree species.

Forest type and species	Scientific name
beech-birch-maple type	
American beech	-- Fagus grandifolia
yellow birch	-- Betula alleghaniensis
sugar maple	-- Acer saccharum
others of cherry-maple and cove types	
cherry-maple type	
black cherry	-- Prunus serotina
sugar maple	-- Acer saccharum
red maple	-- Acer rubrum
others of beech-birch-maple and cove types	
cove type	
yellow-poplar	-- Liriodendron tulipifera
white ash	-- Fraxinus american
cucumbertree	-- Magnolia accuminata
basswood	-- Tilia americana
others of beech-birch-maple and cherry-maple type	
oak-hickory type	
northern red oak	-- Quercus rubra
scarlet oak	-- Quercus coccinea
black oak	-- Quercus velutina
white oak	-- Quercus alba
chestnut oak	-- Quercus prinus
hickory	-- Carya spp.
aspen-birch type	
quaking aspen	-- Populus tremuloides
big-tooth aspen	-- Populus grandidentata
paper birch	-- Betula papyrifera
white pine type	
eastern white pine	-- Pinus strobus
southern pine type	
shortleaf pine	-- Pinus echinata
pitch pine	-- Pinus taeda
spruce-fir type	
red spruce	-- Picea rubens
balsam fir	-- Abies balsamea

There are seven major silvicultural systems recognized in the model:

1) no cutting
2) uneven-age silviculture with single-tree selection only
3) uneven-age silviculture with a combination of single-tree and group selection
4) uneven-age silviculture with patch cutting
5) two-age silviculture
6) even-age silviculture but no clearcutting
7) even-age silviculture with all traditional even-age harvest methods.

Many variations in cutting cycles, stand stocking and structure, rotation lengths, and other parameters are required to meet the full range of management objectives. In addition, there are numerous special treatments, including retention of particular kinds and numbers of trees or stands for wildlife and visual purposes, special treatment of riparian zones, treatment of slash, maintenance or creation of dead and down woody debris, removal of particular kinds of vegetation with herbicides, protection against animal damage, artificial regeneration, or other measures.

The model will select the silvicultural system to be applied in all stands of a management unit, using a series of decision charts developed by a team of natural resource professionals from all branches of the U. S. Forest Service and numerous outside agencies and individuals working in the Northeast. To develop these charts, the team will select the overall silvicultural system recommended to meet the management goals for each forest type. Then, appropriate treatments to be applied at various stages in stand development will be outlined within each silvicultural system - management goal - forest type combination.

Model Operation--Model operations begin by entering the landowner's goals for a particular management unit. Seasoned users will simply enter a set of codes that specify the combination of goals desired. But other users will need considerable help in understanding the implications of the many goal choices. A Management Goal Query Module will provide that help by asking a series of simple questions designed to determine the appropriate goal choices in each resource category. The direction of questioning will be determined by answers to previous questions, and potential resource conflicts created by the answers will be called to the user's attention for clarification.

Once the desired combination of goals has been determined, processing begins with the selection of a silvicultural system for the management unit. This determination is made using only the management goals and the forest type, based upon the knowledge base incorporated into the model.

Next, data on the individual stands within the management unit are entered into the model. Stand data will come from a systematic, multi-resource inventory, and will include information on site, topographic factors, overstory and understory vegetation, and conditions in areas surrounding the stand in question. These data may then be summarized to show a variety of important characteristics of each stand. Specific analyses will include:

a) general site and vegetation analyses, such as forest type; species composition, density and size class of the overstory; density, species composition, and height of the understory, soil and site characteristics, location, etc.
b) timber analyses, including volumes and values, potential for regeneration and future growth, etc.
c) wildlife analyses, including a description of food, cover, and breeding habitats found there, a listing of all wildlife species for which this stand/management unit provides suitable habitat, a habitat suitability index for each game species, an index to wildlife diversity for each of the five classes of wildlife diversity, etc.
d) aesthetic analyses, including indexes to large tree appearance, canopy continuity, opening density and dispersion, small- and large-scale variety, screening density of understory vegetation, flowering species present, etc.
e) water analyses, including index values to water yield and flood potential.
f) environmental analyses, including trends in forest type; presence of unique or especially valuable ecosystems; presence of habitat suitable for rare and endangered species; indexes to diversity of habitats, diversity and evenness of plant species distribution, etc.

Summary information from these analyses may be stored in a geographic information system/data base associated with the NE Decision Model. These summary data will be used again for management unit-level processing.

Current treatment recommendations may then be generated for each stand individually. Using the stand summary data described above, the model will analyze that data to determine the potential of each stand for regeneration, timber growth and yield, suitability as habitat for selected wildlife species, and ability to meet various visual, water, and environmental goals. A preliminary treatment is developed for each stand based on the individual stand's stage of development and current condition relative to the silvicultural system selected previously.

When preliminary treatment recommendations have been developed for all stands in the management unit, a management unit-level routine can then reconcile the desired distribution of vegetative types with the individual stand treatments (and with surrounding vegetative areas not being managed within the management unit). Thus, if the individual stand treatments provide too much or too little of a particular vegetative condition to meet the management objectives, the individual stand treatments will be modified accordingly. Desired distribution of vegetation is based on sustained yield and even-flow principles for all resources, and is an inherent part of the overall silvicultural system.

When preliminary treatment recommendations need modification to meet management unit-level requirements, the most suitable stands are selected for modification. For example, if additional stands are selected for harvest cutting to meet timber regulation needs or to provide adequate well-distributed, early-successional vegetation, the stands most appropriate to receive a harvest prescription will be chosen.

<u>Alternative Testing</u>

A second major function of the NE Decision Model is to permit alternative testing. While the model will provide expert opinions appropriate to common situations, there will often be a need to do "what if?" analyses. Unusual circumstances may cause this to be desirable for specific stands, and management planning exercises may require quantitative comparisons from which to select a desired management alternative. For example, such comparisons and analyses could provide yield information needed as input to optimization models, such as the US Forest Service's FORPLAN, used to allocate portions of a large forest to particular sets of management goals.

The NE Decision Model will provide several levels of alternative testing. In its simplest form, the model will allow the user to select from a wide range of possible treatments, and to compare the immediate effect (immediately after treatment or cutting) on parameters such as timber volumes and values, stand density, size, quality, and species composition, wildlife habitat for any of the included species, visual impacts, water effects, and environmental considerations. Evaluation of these immediate effects will often be important in deciding whether to use a particular treatment, or to modify a recommended treatment in individual stands and management units.

A more complex form of alternative testing will involve the projection of stand growth, mortality, and regeneration, permitting long-term comparisons among management strategies. Several existing stand growth simulators will be built into the model for that purpose. The user will be able to select any of these simulators, or to allow the model to make the selection on the basis of the simulator most accurate in that forest type and geographic region. The stands projected by the simulators can then be re-analyzed to determine their value for any of the resource values just as was done with the original data.

Economic analysis routines included in the model will permit automatic recording of costs and returns over the simulation period and will perform several common types of economic analyses for timber production. Wildlife, visual, water, and environmental effects will also be tracked over time, providing a measure of the long-term results of management on those resources.

To facilitate the use of several simulators, the NE Decision Model will provide a single data input format. That input data will be converted to the form needed by each simulator. The simulators will be used only to predict future stand development; projected tree numbers and sizes will be reconverted into the standard format for data summaries and analysis. Thus, all vegetation parameters and resource analyses will be calculated by the main program in a standard way, making outputs comparable regardless of the simulator used.

Model Structure

The overall model structure will consist of eight major components (Figure 1). The input data in the form of a tree list, understory counts, and site information, will be sent to a core module for processing. This central core module will control the flow of data through the stand analysis, prescription, and prediction modules, and will access input and output routines. The prescription module will utilize the summaries and results of the analysis modules to develop a recommended treatment. If desired, the user may then pass the data to the prediction module where either the recommended treatment, or alternatives, may be projected and the results analyzed.

Work on the NE Decision Model is well under way. Teams of scientists throughout the Northeast are organizing the existing information and are developing algorithms to accomplish the model's tasks. Two programmers are writing the source code for the computer program itself. Plans are to complete a simulator submodel by late 1991, and to have the final model with expert recommendations available by late 1993.

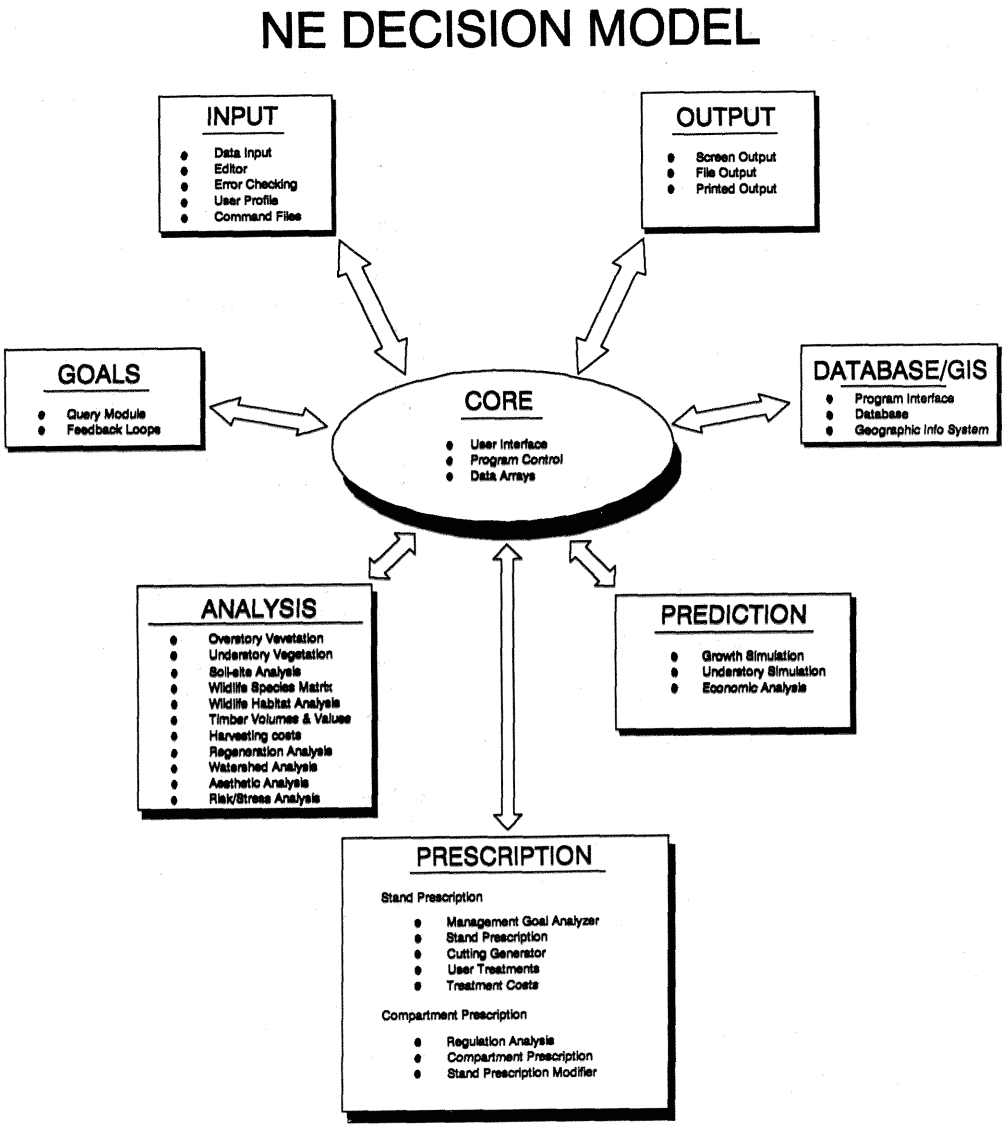

Figure 1.--NE Model Structure.

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DEVELOPMENT OF DAILY AIRTANKER DEPLOYMENT MODELS[1]

David L. Martell and A. Tithecott[2]

Abstract.--The authors describe a model designed to help decide upon the daily deployment of airtankers to bases in Ontario. The airtanker system is modelled as a finite capacity queueing system with fires as customers and airtankers as servers. A numerical model is used to approximate the time-dependent performance of the system and a more detailed simulation model is used to assess the accuracy of the numerical model.

Keywords: Forest fires, airtanker deployment, queues.

FOREST FIRE MANAGEMENT IN ONTARIO

The Ontario Ministry of Natural Resources (OMNR) is responsible for forest fire management in the province of Ontario. The province is partitioned into 8 administrative regions, 5 of which cover 879,997 square kilometres and account for most fires. An average of 1850 fires burned an average of 2,270 square kilometres per year during the years 1976 through 1988. Each summer the OMNR hires approximately 625 fire fighters who work in 3 or 4 person fire crews. The agency also makes extensive use of amphibious water bombers and transport helicopters.

The basic fixed cost of Ontario's forest fire management program is roughly 35 million dollars per year. The OMNR also incurs extra fire fighting (EFF) costs that result from overtime wages, extra flying, and other costs that result from suppression activities. EFF costs average 20 million dollars per year but can vary significantly from year to year depending upon weather.

The OMNR has a provincial fire centre (PFC) in Sault Ste. Marie and a regional fire centre in each of the 5 fire regions. The regional staff calls upon the PFC for additional resources as required. The OMNR has a computer-based fire management decision support system (FMDSS) with a minicomputer in the PFC linked to minis in the regions. The FMDSS is essentially a management information system (MIS) that provides fire managers with a daily overview of expected fire occurrence and behaviour during the next few days.

This paper describes an airtanker deployment model t' ': fire managers can use to help resolve decisions concerning the daily deployment of airtankers to the many initial attack airtanker bases located across Ontario. We begin with a brief description of the deployment problem and then describe the structure of the prototype queueing system model that we solve numerically. We then describe how a simulation model is used to help validate the numerical model which will be field tested during the 1991 fire season.

DAILY AIRTANKER DEPLOYMENT

The OMNR has a fleet of 9 CL-215 airtankers. This fleet can be augmented with aircraft that are shared under the terms of agreements with other forest fire management agencies. Each day the provincial duty officer and his regional counterparts must decide upon the size of the fleet and the number of airtankers to allocate to each airtanker base.

The initial attack airtanker system can be viewed as a spatially distributed queueing system with initial attack fires as customers

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[1] Presented at the Symposium on Systems Analysis in Forest Resources, March 3-7, 1991, Charleston, South Carolina.

[2] Associate Professor, Faculty of Forestry, University of Toronto, 33 Willcocks Street, Toronto, Ontario, Canada, M5S 3B3; Fire Technology Projects Officer, Aviation & Fire Management Centre, Ontario Ministry of Natural Resources, 747 Queen Street East, P.O. Box 310, Sault Ste. Marie, Ontario, Canada, P6A 5L8.

that arrive according to a Poisson process with arrival rates that vary throughout the day, and airtankers as servers that travel to their customers.

Fortin (1989) studied daily airtanker deployment in the province of Quebec which has a fleet of 21 airtankers. Her analysis was simplified by the fact that airtankers were used for initial attack on a relatively small proportion of the fires that occurred, and it was unlikely all 21 airtankers would ever be needed simultaneously. It was reasonable for her to assume each base operated independently and to model each airtanker base as an independent base with "many" aircraft. That made it possible for her to model initial attack airtanker operations at each base as a time-dependent $M/G/\infty$ queueing system.

Our preliminary analysis of airtanker operations in Northwestern Ontario suggested the "many airtanker" assumption would not be appropriate there. We found that airtankers were dispatched to more than 30 percent of fires that occurred in the Northwestern region during the 1988 and 1989 fire seasons and that region's airtanker system often operated at or near its capacity. Modelling of the airtanker system is further complicated by the following factors; the number of airtankers dispatched to a fire is not constant, duty officers often base initial attack dispatch decisions on very sparse information concerning the existence, behaviour, and values threatened by reported fires, and air attack officers may subsequently modify the size of the initial attack force. Since airtanker bases in the Northwestern region do not operate as independent facilities, since forest fire arrival rates are very non-homogeneous with respect to time, and since service times are long relative to variation in fire arrival rates, we could not reasonably partition the day into a small number of time intervals and use step functions and steady state results for each time interval. We therefore had to make several simplifying assumptions in order to develop a tractable model of the airtanker system in the Northwestern region.

THE PROTOTYPE AIRTANKER DEPLOYMENT MODEL

We partitioned the Northwestern region into 4 primary attack zones, each of which contained a single airtanker base. Users of the deployment model will subjectively modify the fire occurrence predictions produced by the existing FMDSS in order to "predict" the expected number of people and lightning caused fires per day in each zone. We assume fires occur according to a time-dependent Poisson fire arrival process. Let λ_{people} denote the expected number of people-caused and let $\lambda_{lightning}$ denote the expected number of lightning-caused fires per day. Then the expected number of fires per day is λ_{day}, which equals $\lambda_{people} + \lambda_{lightning}$. We used historical fire arrival patterns to model the time-dependent fire arrival process.

We constructed a step function as follows. Let p_i denote the fraction of fires that are reported during time interval $[i,i+1)$ and λ_t the expected number of fires that arrive during the *ith* time interval. Then the fire arrival rate at time t will be $\lambda_t = p_i \lambda_{day}$ for $i \leq t < i+1$. We will then have the duty officer subjectively assess the fraction of the fires reported each day that will require airtankers. λ_t is then multiplied by that fraction to determine the arrival rate of "airtanker" fires at time t.

We used historical fire report and air attack data to model airtanker operations and found it was reasonable to assume the service time distribution was Erlang with parameters that vary by fire danger and the anticipated number of fires. The average service time varied from 1.2 to 1.8 hours.

We assumed the duty officer would dispatch the same number of airtankers to all the "airtanker" fires that occur during any given day, but that number might vary from day to day depending upon fire weather and the anticipated fire load. We used a time-dependent $M/G/\infty$ model to determine how many airtankers would be busy fighting fires at different times throughout the day if there were many airtankers deployed at each base.

The user combines the $M/G/\infty$ model results with other considerations and specifies how many airtankers to deploy at each base. We assume the service time distribution is exponential with the same mean as the Erlang distribution and the airtanker queueing system has a large finite capacity. Those simplifying assumptions enable us to specify a system of differential equations which describe the time-dependent behaviour of the queueing system. We then use the Runge-Kutta-Fehlberg method described in Gerald and Wheatley (1989), to solve the system of differential equations numerically. The solution provides us with $P_n(t)$, the probability there are n fires in the system at time t. We use that information to estimate $L_q(t)$, the expected number of fires waiting for service at time t, and $W_q(t)$, the expected waiting time of a fire that arrives at time t.

We assessed the validity of our exponential service time assumption by comparing our numerical results with the results produced by a more detailed simulation model with Erlang service times. The comparison indicated it was reasonable for us to use the exponential service time assumption in order to simplify our model.

FUTURE WORK

We plan to field test our prototype daily airtanker deployment model in the Northwestern region during the 1991 fire season. When we have enhanced and tested our model to the point where both we and our fire management clients are satisfied with its performance, we will derive a utility function that describes the relative importance of response times in different attack zones and regions. The deployment model and utility function will be incorporated in a stochastic dynamic programming model that will be designed to suggest how the available airtankers should be deployed to bases. We will then develop a provincial level deployment model that can be used to help decide where the available airtankers should be deployed each day and when airtankers should be borrowed from or loaned to other forest fire management agencies.

DISCUSSION

Operational researchers have developed many models that are designed to help deploy urban police, ambulance, and fire department resources (see for example, Larson and Odoni, 1981). Daily airtanker deployment poses many challenging problems that are somewhat similar to those that urban OR specialists have studied. However, forest fire management is complicated by the fact that weather has a tremendous impact on forest fires, fire arrival rates vary enormously over time and space, fires have relatively long service times, and planning horizons must extend over several days.

Forest fire management therefore poses a wealth of important new challenges to OR specialists and calls for renewed efforts to address its specific problems.

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FINANCIAL MATURITY: A BINOMIAL OPTIONS PRICING APPROACH[1/]

Thomas A. Thomson[2/]

ABSTRACT.--This paper applies the binomial option pricing model of finance is to determine how the financial maturity conditions for timber stands differ from the traditional Faustmann result. The binomial options approach computes at least as high, and generally a higher net present value of forest stands than does the Faustmann model and generally prescribes a longer rotation length.

INTRODUCTION

Financial maturity has long been presented as a criteria for choosing forest rotations as is evidenced in early forest management texts such as Matthews (1935). Recent work in financial maturity has considered the financial maturity question when stumpage prices fluctuate. Brazee and Mendelsohn (1988) present a model where timber prices fluctuate stochastically, with a known mean and standard deviation. In their model, timber is never sold unless it is above its mean price. This result demonstrates that their approach can only apply to a marginal and not a typical timber seller. A primary difference between the Brazee and Mendelsohn (1988) model and the binomial option pricing model presented here is that in their model the next period timber price is independent of the current timber price while in the binomial option pricing model, the next period price is directly tied to the current price. Washburn and Binkley (1990) present evidence that suggests the assumption of independence between sequential stumpage prices is inappropriate for modeling stumpage price behavior.

The now famous Black and Scholes (1973) paper presents a correct option pricing model. Since that landmark paper, the field of option pricing has grown into a substantial area of study in financial economics. The contribution of Black and Scholes was to combine a realistic stochastic price process model with the methodology to create a risk-free hedge, and thus provide the algorithm for computing option values. In their paper they propose a logarithmic price process for stocks and derive a closed form solution for the option valuation process.

Morck *et al.* (1989) apply option pricing to forestry. They compute the value of a mature forest with a stochastically increasing inventory, and a stochastic stumpage price. They solve two simultaneous stochastic processes, that of uncertain stumpage price, and uncertain forest growth. Stumpage price follows a lognormal stochastic process as is assumed in the Black-Scholes model. The growth in inventory follows Brownian motion. The resulting nonlinear partial differential equation is solved numerically. Because of the short time frame they model, 10 years, and the large assumed standing inventory, their paper can be interpreted as a study of the optimal depletion (mining) path for a mature forest rather than when to harvest a forest which is currently immature.

The proponents of using an options pricing approach for valuing natural resources allege two main advantages *vis a. vis* traditional discounted cash flow analysis. One is that as prices evolve over time, the relative riskiness of the project changes; thus, it is not appropriate to assume a single risk adjusted discount rate will adequately adjust for risk over time. The second advantage is that managers can react to whatever future unfolds. Within the stochastic process, all possible futures (assuming a correctly specified process) are allowed for in the computation of the NPV. This value assumes that managers will react optimally to whatever future unfolds. There is no such implication in the traditional discounted cash flow approaches. Brennan and Schwartz (1985), Paddock *et al.* (1988), and Morck *et al.* (1989) all note that with the wide price fluctuations present in natural resource commodities, traditional discounted cash flow methods may seriously underestimate the value of these resources.

Although the option pricing approach is touted as a superior methodology for evaluating the NPV of risky natural resources projects, it is uncommon to find examples where a close comparison of results among various approaches has been made. This paper is set up in a framework that allows direct comparison to the traditional discounted cash flow approach embodied in the Faustmann calculation.

What is an option?

An option, or more precisely a call option, is a financial security which gives the holder the right to purchase one stock for a specified price (called an exercise price or striking price) during a specified period. If the price of the security is above this exercise price, the option is said to be in the money as one could gain an immediate payoff through exercising the option and buying the share at the reduced price. If the price of the security never rises above the exercise price, then the option provides no payoff. An option, therefore, has the potential to have a positive future value, but it can

1/ Presented at the Symposium on Systems Analysis in Forest Resources, Charleston, SC, March 3-7, 1991.

2/ Assistant Professor of Forest Management, School of Natural Resources, The University of Michigan, Ann Arbor, MI 48109-1115.

never have a negative value. The value of the option depends on the likelihood of the stock price exceeding the exercise price. As long as stock prices are stochastic, there is some probability that the stock price will rise above the exercise price. The more variable the stock price, the greater the likelihood that the stock price will rise above the exercise price. If the exercise price is zero, the value of an option is the price of the stock for owning the stock allows you to acquire it in the future for a zero exercise price. To apply option pricing to timber stand valuation one must determine how the variable nature of timber prices will effect the optimal stand management decisions, and thus, the value of the stand.

The Black-Scholes Option Pricing Model

The Black Scholes option pricing model computes the value of a call option assuming that investors can create risk-free hedges with futures markets and that stock prices follow the stochastic process (Hull 1989):

$$dP = \mu P dt + \sigma P dz \tag{1}$$

where:
P = Stock price
t = time
μ = drift rate in stock price
σ = volatility of stock prices (instantaneous standard deviation)
dz = the increment of a Wiener process (or Brownian motion)

Because this paper does not use the Black-Scholes model to determine timber financial maturity the Black-Scholes solution is not presented here. The stochastic price process, however, is given as this paper assumes that stumpage prices follow such a process.

Problems in applying the Black-Scholes model to financial maturity

To use the Black-Scholes option pricing model one must accept a number of assumptions and compute several input parameters. Assumptions include the existence of a futures market, continuous trading of the security, a lognormally distributed stock price, a risk-free interest rate, an exercise price, and time to maturity. One must compute the volatility associated with the stock price distribution, and know the current stock price. Because the futures market allows investors to devise risk free hedges, the results are independent of risk preference. Because the results hold for any risk preference, they hold for risk neutral investors; thus, it is common for option pricing models to employ risk neutrality to simplify computations (Hull 1989). If the underlying asset has no systematic risk (beta=0) then the risk neutrality argument may be used even if no risk free hedging opportunities exist. To use the Black-Scholes approach for timber evaluations, one must either assume that hedging opportunities exist (i.e. a perfect hedge can be created between lumber futures and stumpage prices), or that timber prices follow unsystematic risk patterns. There is strong evidence for a zero or near zero beta for stumpage investments (see Thomson 1987, 1989, Binkley and Washburn 1988, Redmond and Cubbage 1988).

Paddock *et al.* (1988) show a correspondence between the Black-Scholes model inputs and the oil lease valuation problem. A similar correspondence for the timber option valuation problem is:

Black Scholes-assumption	Timber assumption
continuous time model	continuous time model
risk free interest rate	risk free interest rate
lognormal stock prices	lognormal stumpage prices
stock price volatility	stumpage price volatility
expiration date	harvest date
exercise price	forest management costs?
today's stock price	today's stumpage price?

Some of the variables are directly comparable, such as expiration date, a lognormal distribution of prices, and risk free interest rate. The continuous trading assumption seems a closer analogy for financial markets than timber markets. The exercise price analogy, in the Paddock *et al.* (1988) paper is the development cost of a new oil field. The closest analogy for the timber situation is the management costs of the stand between now and its harvest date. An important difference, however, is that one has the option to develop an oil field at some future date. One does not have the option of waiting to decide whether to develop the forest. The forest must be continually developed through the payment of annual forest management costs. Although one could argue that funds for current forest management could be borrowed and paid back when the stand is harvested (i.e. the payback of the loan could be seen as a striking price), this would not change the nature of the problem as the funds would be payable regardless of whether the forest could be profitably harvested. If a loan was taken out, the interest rate of that loan would reflect the possibility of loan default at harvest time (the occurrence that timber stand value was lower than the compound loan amount). A more useful approach is just to assume a $0 exercise price so that the value of the option is the value of the timber stand.

The final variable is the stock price today. A first inclination is to substitute today's stumpage price for the stock price. The problem with this approach is that today's stumpage price does not measure the same thing for timber that a stock price measures for stock. In the option pricing model, the stock price represents the market's willingness to pay for a stock that can be sold in the future for its value at that future date. It is **not** the value of liquidating the assets of the firm immediately. In other words, a stock price is the discounted value of a future sale. Today's stumpage price, however, is not a future value discounted to today. It is what timber can be sold for today if harvested immediately, or in other words it reflects the liquidation value of the stand. We want to determine the value of the stand if we choose to hold it into the future so that we can compare this discounted value to the value of immediate harvest. Our goal, therefore, is to take an option pricing approach to estimate the discounted value of future harvests because we cannot easily observe this in the market. We cannot use the Black-Scholes model to value our timber stand as we do not have a requisite input. After we first compute the present value of a timber stand, the Black-Scholes model may be appropriate for valuing some timber selling options.

THE BINOMIAL OPTIONS PRICING MODEL

Cox, Ross and Rubinstein (1979) and Rendleman and Bartter (1979) independently developed a two state option pricing model, that has come to be known as the binomial option pricing model. It is pedagogically instructive, and is a popular tool for the numerical analysis of option values where a closed form solution does not exist. The binomial option pricing model is formally derived as follows. Suppose stock price starts at P. In the next period it will either rise to u*P (up state) or fall to d*P (down state). The probability of an up move is π, thus, the probability of a down move is $1-\pi$. The parameter σ measures the volatility of stock prices, μ is the drift, and Δt represents the time interval. The model parameters, which will converge to equation (1) as $\Delta t \rightarrow 0$ are (Hull 1989):

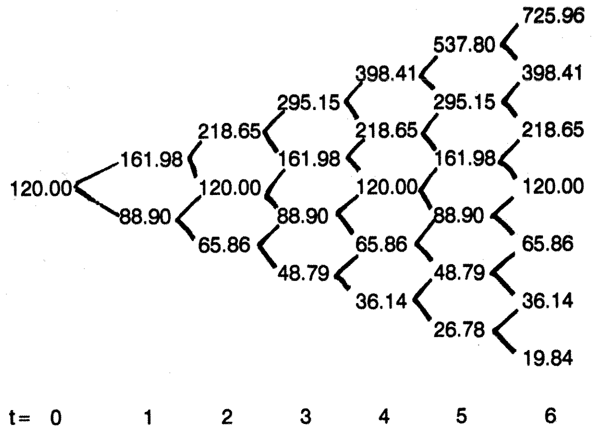
$$u = e^{\sigma\sqrt{\Delta t}} \tag{2}$$

$$d = \frac{1}{u} \tag{3}$$

$$\pi = \frac{e^{\mu \Delta t} - d}{u - d} \tag{4}$$

To employ this technique for the timber problem, one uses the current stumpage price as the starting price in a binomial process. The up state stumpage price and down state stumpage price are tied to the currently observed price by employing equations (2) and (3). Figure 1 shows an annual stumpage price lattice for a starting value of \$120/Mbf with σ = 30% per annum.

Figure 1. The binomial stumpage price tree (annual nodes) for a starting price of \$120 and a price volatility of 0.30.



Using this structure a binomial options pricing model was developed for computing timber stand values. The model results are compared to those of the standard Faustmann approach, to determine insights the option pricing approach adds to the study of financial maturity. The standard discounted value maximization criterion asks whether the value from immediate harvest exceeds the value of the stand discounted one period, which may be written as:

$$P_tQ_{t,j} + LEV_t > \frac{V[P_{t+1},Q_{t+1,j+1}] + LEV_{t+1} - C}{1+r} \tag{5}$$

where:

t = calendar time in periods, t=1,2,3, . . .

j = age of the timber stand in periods, j=1,2,3, . . .

P_t = stumpage price at time t

$Q_{t,j}$ = stumpage volume in period t for a stand of age j

LEV_t = land expectation value in period t (the maximum of zero and the discounted value of a series of costs and revenues from managing timber stands *ad infinitum,* given that there are currently no trees present.)

$V[P_{t+1},Q_{t+1,j+1}]$ = the value of standing timber one period from now. This may either be its immediate harvest value or its discounted future harvest value.

C = per period forest management costs

r = appropriate one period discount rate

The term $P_tQ_{t,j}$ is the harvest value of the standing inventory at time t for a timber stand that is age j, and the LEV is the value of bare land after such a harvest. When added together they comprise the total value generated if the stand is harvested today. This value is compared to the discounted value that will be received one year from now if harvest is delayed. To hold the timber stand another period requires the expenditure of a cost for land management, protection, and property taxes which must be subtracted from the harvest value.

If the stumpage price is stochastic one can only easily determine the stand's current harvest value as today's stumpage price is known. Today's LEV must consider the effect of uncertain prices through time. Equation (5) also requires the next period stumpage price and LEV to determine if it is best to harvest the current stand or allow it grow another period. At any point in time t, the stochastic process will be at a node that can be described using two states, the current stumpage price ($P_{t,j}$), and the current stand volume ($Q_{t,j}$). The binomial option pricing model specifies the price process; thus, the current harvest value and expected LEV can be explicitly determined at each node as long as the growth of stands is known. Two state option pricing models have been proposed by Boyle (1988), and Boyle, Evnine, and Gibbs (1989), which model two Brownian motion stochastic processes as a single multinomial diffusion process. Because tree growth does not follow Brownian motion, however, such an approach is not appropriate. Amin (1990) proposes an alternative specification which separates the two processes. This paper follows the approach proposed by Amin (1990), with the price state following the binomial options model and the growth state following a typical timber yield function.

In the binomial option pricing approach, one evaluates the harvest decision for the current node by considering that in the next period the stumpage price will proceed to one of two nodes (up state or down state) and the trees will grow by a one period increment. At each of the two next period price nodes (for a given volume) the decision maker must evaluate whether the stand is financially mature (in which case it will be harvested) or whether to let the trees growth continue. The probability of reaching each of the two next period price nodes is π and $1-\pi$. The probability of reaching the next period volume node is 1.0 as the stand either grows for one year or is harvested and the decision maker knows which outcome will occur. The value of reaching any of the next period nodes will be the higher of the harvest plus land value for that node, or the discounted value of all future harvests at that node. The next period managerial action (harvest or wait) with the highest value will be chosen for that period and its value discounted one period to determine if the present managerial action of harvest exceeds the value of waiting. When the value of immediate harvest exceeds the discounted value of waiting, the stand should be harvested, and a new stand established if the LEV at that price node is positive. If prices are too low to justify the establishment of a new stand, then the forestry enterprise will be abandoned. The following equation states the appropriate recursive financial maturity condition at any price and quantity node:

$$P_{t,i}Q_{t,j}+LEV_{t,i}>\frac{\pi*V[uP_{t,i},Q_{t+1,j+1}]+(1-\pi)*V[dP_{t,i},Q_{t+1,j+1}]-C}{1+r} \quad (6)$$

where:
$P_{t,i}$ = stumpage price in period t at price node i.
$Q_{t,j}$ = stumpage volume at period t for a stand of age j
$LEV_{t,i}$ = Land expectation value in period t, at price node i (Note: A j subscript is unnecessary here as the volume of timber on bare land is the volume for a stand of age 0, so Q_0 must equal 0 for LEV computations. LEV is the value of a stand for a given stumpage price when the stand volume=0 and regeneration costs are yet to be incurred.)
$V[uP_{t,i}Q_{t+1,j+1}]$ = the value of a stand one year from now given that the up state has occurred. This value can be expressed as:

$$\text{Max}\ [\text{Harvest}_u, \text{Wait}_u]$$

where:
Harvest_u = The value of the timber harvest plus LEV in period t+1 if the up state occurs (= $uP_{t,i}Q_{t+1,j+1}$ + $LEV_{t,iu}$. Note that the price the next period equals $uP_{t,i}$ if the up state occurs. The j subscript on Q is increased by 1 as the stand volume has increased by one period of growth. The price subscript for LEV is iu to note that it is the LEV for the price node after an up state occurs.)
Wait_u = The value of the stand in the next period if an up state occurs, but it is not yet optimal to harvest. It is the discounted expected value of the stand one more period in the future (t+2).
$V[dP_{t,i}Q_{t+1,j+1}]$ = the value of a stand one year from now given that the down state has occurred. It value is computed in a manner analogous to that for the up state.

Other variables are as noted earlier. If at any node, the value of expression on the left exceeds the value on the right, the stand should be harvested, and a new stand regenerated if the LEV is positive. If the LEV is negative, the forestry enterprise should be abandoned at this time.

One problem is apparent. The LEV, and the expected values of waiting depend on the future period values, so future periods must first be evaluated. As a consequence, the dynamic nature of the problem is appropriately solved by backward recursion. The problem, as set forth above, is an infinite horizon problem. To solve we replace the infinite horizon problem with a finite problem so that t=1,2,3, . . . T, where T is the final stage of the problem and is so distant in the future that the truncation will not affect today's values. Because no value will be gained by waiting an additional period beyond the final period, the optimal decision in the final period is to harvest all stands, regardless of their age, and to not regenerate them. Because of the nature of discounting and timber stand growth, it will be optimal to harvest within a finite time period (Brazee and Mendelsohn 1988). The recursion proceeds backwards from stage T and evaluates at each node whether the value of immediate harvest plus $LEV_{t,i}$ exceeds the discounted expected value of the next period and thus the recursion continues until the present. The problem can then be run again specifying a larger T. If a larger T value does not effect the solution, the optimal solution has been determined.

The value of the forest at the final stage is simply the product of the stumpage price and timber volume for each stumpage price and stand volume node:

$$P_{T,i}Q_{T,j} \qquad i = 1, 3, 5, \ldots I \qquad j = 1, 2, 3, \ldots J \quad (7)$$

where:
T = the final stage of the model
I = the total number of price nodes (= 2T - 1)
J = the maximum age stand (in periods) that will be allowed in the model. J should be chosen such that the computed results are invariant with J unless there is some alternate consideration such as maximum tree size that can be processed which places a practical constraint on J.

In stage T-1 stands may be harvested either immediately, or at T. The condition to determine if a stand should be harvested one node prior to the final harvest alternative is as shown in equation (6) except that the wait alternative does not exist.

In general, an LEV is computed as follows. If the stand is harvested this period, it will be replaced by a 1 period old stand the next period unless forestry is abandoned. If the value of having a 1 period old stand in the next period exceeds its regeneration costs plus one period of management costs, its LEV is the value of a 1 period old forest minus the management costs discounted 1 period, less the immediate regeneration cost. If this computation yields a negative number, a value of 0 is chosen for the LEV which signals that forestry has been abandoned. In this way the computed results include the option value of abandoning forestry if the stumpage price is too low. Formally the LEV is computed as:

$$LEV_{t,i}=\text{Max}\left\{\frac{\pi V[uP_{t,i},Q_{t+1,1}]+(1-\pi)V[dP_{t,i},Q_{t+1,1}]-C}{1+r}-R,\ 0\right\} \quad (8)$$

where:
R = the regeneration cost
and other variables are as previously defined.

The backward recursion proceeds as follows. Equation (7) is used to compute the harvest values for all P_i and Q_j at t=T. Then equation (6) is evaluated for all P_i and Q_j values at stage t=T-1. Choosing the greater of the left or right side of the inequality expresses the optimal management decisions (harvest or wait, and regenerate or don't regenerate if the harvest option is chosen); thus, the maximum value ($V[P_i,Q_j]$) is stored for each price and volume node for time t=T-1. If the stand is currently age J, then the decision to harvest must be chosen. The recursion continues via equation (6) until t=0. At t=0 there is only one price node (the starting price) and J quantity nodes. Each node has a value ($V[P_0,Q_j]$), computed recursively as described above. This value is the NPV of the timber plus land for the current price computed using the binomial options pricing approach. The same dynamic algorithm is used to compute the Faustmann values except that the stumpage price remains fixed over time. All differences in computed NPV, thus, are due to the volatile price assumption.

A FORTRAN program was written to solve the model described in equations (6) - (8). The model has been solved using IBM compatible microcomputers running MS-DOS. The problem size (i.e. number of time periods and number points on the volume function) is limited by the memory available using DOS; thus, the program truncates the binomial price process after 125 stages. Extensive testing has demonstrated that the numerical solutions in the presented results remain accurate to \$0.01/acre. The model computes the t=0 values, $V[P_0,Q_j]$, which are the NPV's per acre for a stand of age j, given the current price is P_0. In addition to reporting the NPV's, the program also notes if the stand is financially mature given the current stumpage price and stand age. The difference in NPV between the option pricing approach and the Faustmann approach are also computed and recorded, as is the age of Faustmann maturity for the given stumpage price.

An important managerial choice is the timing of the harvest. The Faustmann approach determines a single harvest date for a fixed price scenario. The binomial option pricing approach evaluates the harvest decision based on the node that is attained rather than stand age that has been reached. This allows managers to be flexible in their choices of both when to harvest the existing stand, and whether to establish another stand. For the current stumpage price, the model notes the age at which financial maturity is reached. If the stand age is greater than the age of maturity, it should be harvested; otherwise, it should be left to grow. One period from now the model would be rerun with the newly observed stumpage price and an updated evaluation of financial maturity made. This process would continue until it was optimal to harvest the stand. At that point a second managerial decision would be made, that of whether to continue the forestry enterprise by regenerating a new stand. If the LEV is positive for the stumpage price at that date, then regeneration should take place. Otherwise, the forestry enterprise should be abandoned. The two managerial decisions, when to harvest the current stand and whether to regenerate a new stand, are thus explicitly solved using the model.

Harvesting the stand at a relatively young age may be optimal for one of two reasons. Either the stumpage price is so high that the opportunity cost of forgoing the next rotation is high (i.e. the LEV is high; thus, the land rent is high for the current crop which can be thought of as a cost of managing the current crop). Alternatively, early harvest may occur because the price is too low; thus, it makes sense to abandon the forestry enterprise early rather than to continue investing the annual management fees.

Empirical trends in historical stumpage prices

Option pricing models require the input of measures of the volatility of prices and trends in prices (drift). Annual Douglas-fir stumpage prices over the 1926-85 period were garnered from various USDA Forest Service sources. These prices represent a common series because each source had some years overlapping with a previous source and prices were in agreement for such overlapping periods. The logarithm of these prices were regressed over time to estimate a constant drift to detrend them by. The logarithm of the detrended prices was computed and these results were subjected to a Lilliefors test which could not reject a null hypothesis of normality at the usual levels of statistical significance (p value = 0.174). Thus, a hypothesis of lognormality of stumpage prices cannot be rejected so it appears reasonable to use the price generating process of equation (1). Annual volatility (σ)was estimated as the standard deviation of the natural log of the price ratios between consecutive years (Hull 1989) at 0.338

Two examples

The timber stand binomial option pricing model requires the following parameters: beginning stumpage price, timber yield over time, per period forest management costs, risk-free discount rate, stumpage price volatility (σ), drift (μ), and step size (Δt). This analysis is done in real terms thus costs are assumed constant over time, and stumpage prices are real prices over time. The first example forest is for a Site II Douglas-fir stand. The initial stumpage price is \$120/Mbf with 0 drift, annual volatility is 0.30 and step size is 1 year. The assumed silvicultural system, required to compute LEV's, is artificial regeneration at a cost of \$250/acre (R) with annual costs of \$4/acre/year (C). Yield was simulated using the SPS model (Arney 1985) and the simulated results were then fitted using nonlinear regression to the functional form of Payandeh (1973) which provided the yield equation:

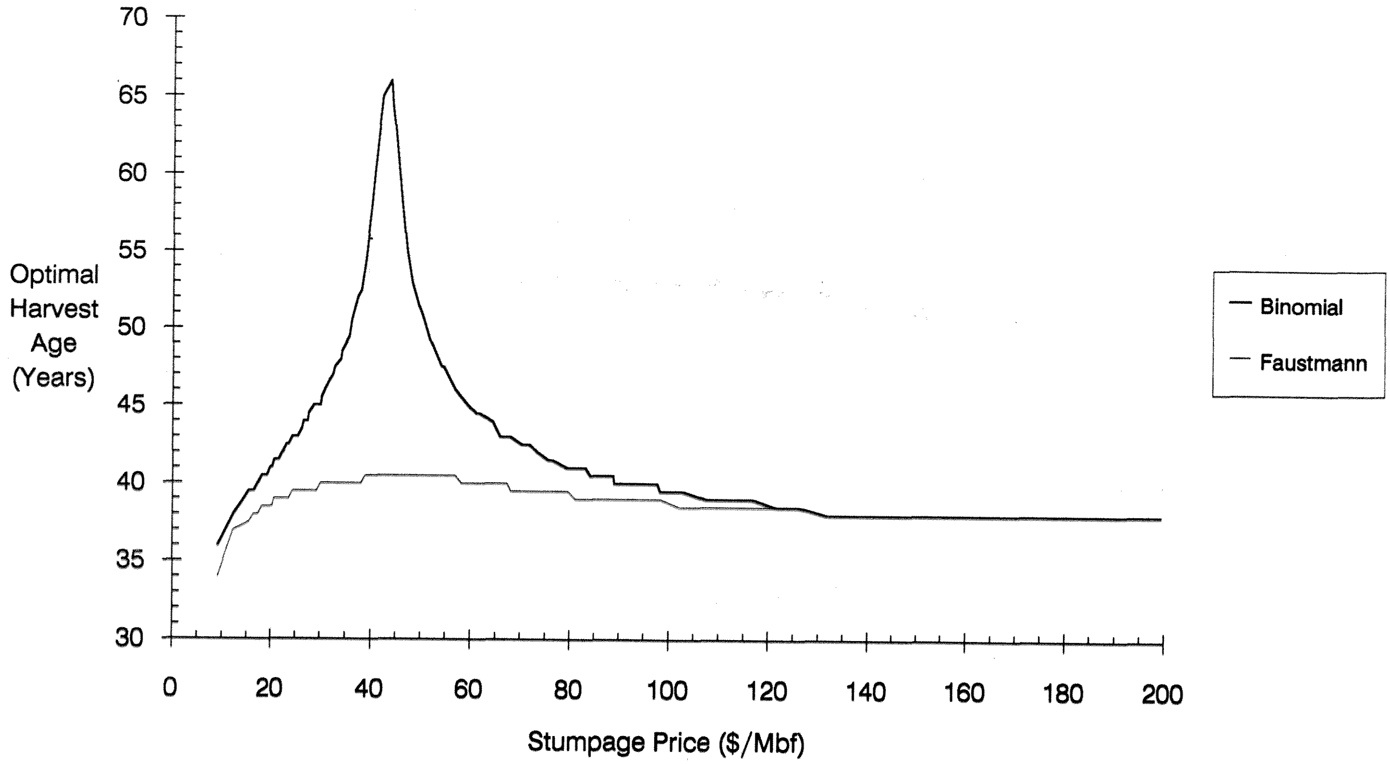
$$Vol_a = \exp(12.05-68.88/age) \qquad (9)$$

where:
Vol_a = timber yield in Mbf/acre at age a

The first question of interest is the rotation age predicted by each model. For the parameters given, the binomial options model prescribes a rotation age of 39 years whereas the Faustmann model chooses 38 years; thus, little difference is observed between models. The binomial model, however, is sensitive to the current stumpage price is, so it is natural to ask whether the results would have been more divergent if a different stumpage price was realized. To address this question the model was run using a series of starting stumpage prices to see how the optimal rotation changes as stumpage price change.

Figure 2 shows the financial maturity relationship between the Faustmann and binomial options models by plotting the optimal rotation age as a function of current stumpage price. Both the Faustmann and options models suggest that rotation age will be longer at a relatively moderate price. For very low prices, the Faustmann rotation is somewhat shorter than the options rotation. For stumpage prices above \$130/Mbf, the rotation length prescribed by either model is the same, 38 years. A large difference in prescribed rotation length occurs if stumpage prices are about \$45/Mbf. In this range, the rotation length prescribed by the options approach is 65 years whereas the Faustmann rotation is 40. At first inclination this result suggests that the optimal harvest age may be quite different among the models. In reality though, the probability of attaining a 65 year harvest is near zero as prices are volatile. Time appears on the vertical axis, so one can think of a growing tree as proceeding vertically on the figure. The price keeps changing as the stand grows. When one hits the boundary (a price and age point) shown on the Figure 2, the stand should be harvested. It is very difficult, with a stochastic price, to not hit the boundary before age 65; thus, it is likely that the realized rotation age will not vary greatly between models. The options results specify growing the stand somewhat longer unless the stumpage price is greater than \$130/Mbf near the time of financial maturity. The expected rotation age, therefore, will be somewhat longer.

Figure 2. Optimal Douglas-fir rotation age as a function of stumpage price for the Binomial and Faustmann models.



The second question it is natural to ask is whether the two models compute different stand NPV's. As suggested above, the binomial options model should compute a higher stand value as it explicitly values the superior managerial choices that will be made in response the changing prices whereas the Faustmann results are based on a static scenario. The model results bear this out. The LEV of the forest described above is $59.90/acre higher when computed using the binomial options model ($607.50/acre versus the $547.60/acre computed using the Faustmann model). The increase in NPV is plotted for a range of stand ages in Figure 3 which shows that gain in NPV varies by stand age. For a financially mature stand, the gain in NPV is the gain in LEV as the current stand should be harvested, and one is left with the LEV. The greatest divergence in value is for a stand near the middle of a rotation. This is because the manager still has many options open regarding choices for that stand.

Douglas-fir is a valuable timber species with a high growth rate. For comparison, the model was also applied to a stand of midwestern northern hardwoods. While the stumpage value of northern hardwoods is high, its growth rate is not. The model parameters estimated for northern hardwoods are a step size of 0.5 years, an annual cost of $5/acre/year, a regeneration cost of $10/acre, an initial stumpage price of $100 with 0 drift, and a stumpage price volatility of 0.47. A a yield equation was fitted using nonlinear least squares to the good site data of Gevorkiantz and Duerr (1938, p49) providing:

$$Vol_a = 27.583(1-\exp(-0.019*age))^{3.492}$$

Figure 3. Increase in Douglas-fir NPV ($/acre) computed using the binomial options pricing model v. stand age.

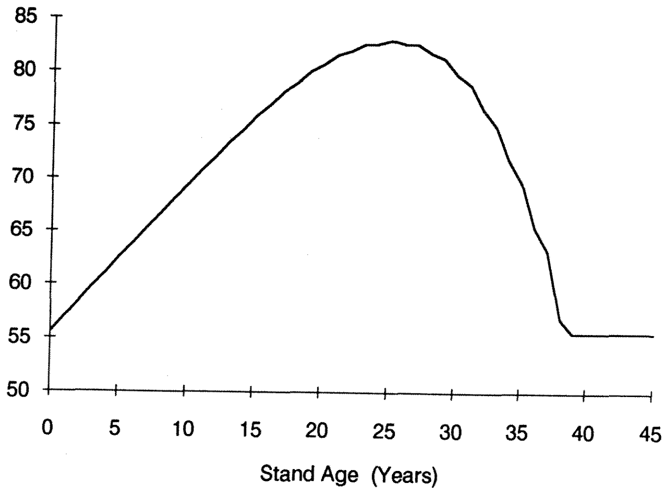
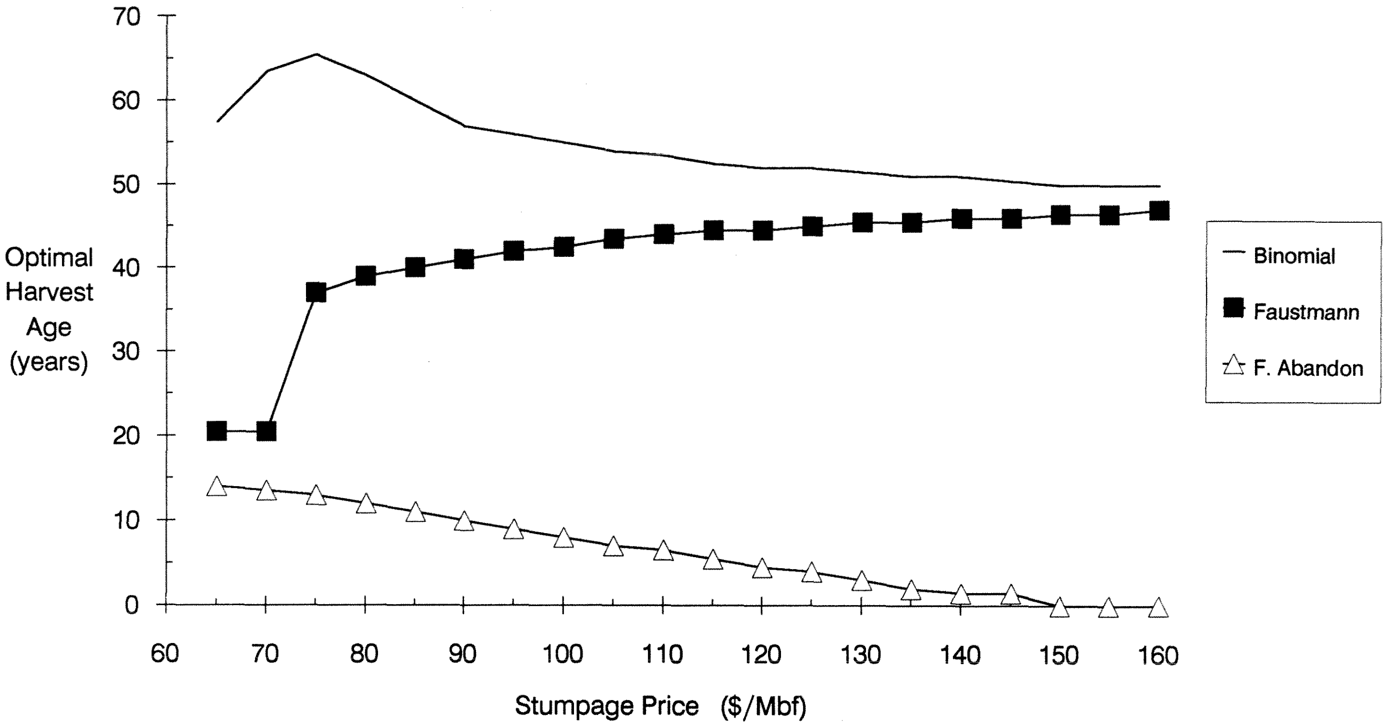


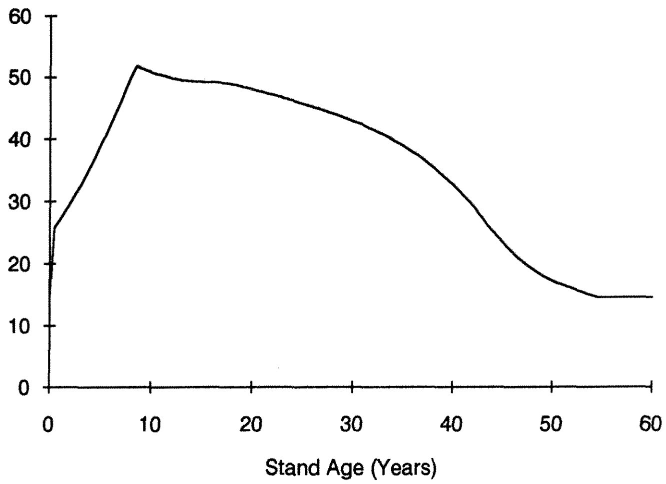
Figure 4. Optimal northern hardwood harvest age as a function of stumpage price for the Binomial and Fastmann models. The lower line represents the region below which it is Faustmann optimal to abandon the stand.



The difference in results between the two models is more divergent than for the Douglas-fir example. Figure 4 shows that the rotation age differences are quite large unless stumpage prices are quite high. More startling is the Faustmann criteria prescribes abandoning stands younger than 8-15 years old if stumpage price is below $100/Mbf. In fact, stumpage price would need to be $150/Mbf or greater to not abandon any young stands. Not only does the binomial model prescribe holding stands the Faustmann model would abandon, it also prescribes harvesting them at a much later age. For a stumpage price of $75 for example, the binomial model would harvest at age 65 while the Faustmann model would harvest at age 38. At least a 10 year difference in optimal rotation age exists for stumpage prices less than $105/Mbf.

We can again determine the difference in computed stand value as a function of stand age. Figure 5 shows a somewhat different result than was observed for the Douglas-fir example. In the Northern Hardwood case there is a great divergence in the computed values at low ages as the Faustmann value of the stands is zero and the binomial options values are positive. The peak shown in Figure 5 is where the Faustmann stand value begins its positive region.

Figure 5. Increase in northern hardwood NPV ($/acre) computed using the binomial options pricing model v. stand age.



SUMMARY

This paper has shown how the binomial options pricing model of finance can be applied to the study of financial maturity of timber stands. Use of the binomial options model allows flexibility in response to an evolving stumpage price for two managerial decisions; that of choice of rotation age, and whether to abandon forestry after the current stand has been harvested. Stand NPV computed using the binomial option pricing model is as high or somewhat higher than that computed using the traditional Faustmann method. The difference in computed stand values reaches a maximum for stands in the mid-rotation range. The optimal harvest age was demonstrated to be older using the options model unless the stumpage price is high, in which case the harvest age is the same for either model.

The good news is that when evaluating fast growing timber stand such as Douglas-fir where the Faustmann approach computes high stand values, there is little gain in using the more computationally intense binomial options pricing model. If stumpage prices are relatively low, however, the Faustmann rotation age prescription may be too low. For slower growing species such as northern hardwoods, it seems prudent to use the binomial options pricing approach to prevent abandoning young stands that are still valuable or harvesting mature timber too soon.

ACKNOWLEDGEMENTS

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MODELING THE EFFECTS OF CLIMATE WARMING ON WILDFIRE SEVERITY IN CALIFORNIA[1]

Jeremy S. Fried and Margaret S. Torn[2]

Abstract.--Simulations of climate warming impacts with the Changed Climate Fire Modeling System in Northern California consistently projected increases in area burned and in the frequency of escaped fires. However, the magnitude of those increases was strongly influenced by vegetation type, choice of General Circulation (Climate) Model, and which weather attributes were treated as variables. The greatest projected increase in fire severity occurred in grasslands, using the Princeton Geophysical Fluid Dynamics Laboratory GCM, with wind speed, temperature, humidity and precipitation treated as variables.

Keywords: Greenhouse effect, wildland fire, vegetation.

INTRODUCTION

Although paleontological (Clark 1988, 1990) and historical evidence suggests that the changes in climate predicted to occur in the next century will be accompanied by changes in regional fire regimes, there has been virtually no analysis of how climate warming would affect fire danger, let alone quantitative estimates of changes in the area burned by wildfire. Attempts at such predictions are hindered by the disparity in spatial and temporal scales between models of climate and fire behavior (Fried and Torn 1990) and complicated by fire suppression. Climate change impacts on wildland fire severity have been estimated using sensitivity analyses based on historical weather records and potential climate scenarios generated by either a priori adjustment of historical weather parameters (Beer et al. 1988) or adjustment of seasonal averages of weather variables using general circulation model (GCM) output (Simard and Main 1987). Because these studies rely on correlations of annual averages of fire and weather data, they provide no insight into the potential for changes in the frequency of extreme fire events and fail to consider interactive effects of changes in multiple weather variables.

Motivated by the fact that most of the impacts of wildfires result from extreme, rather than average, events, we departed from such traditional statistical approaches. We relied instead upon GCM data, daily weather records and mechanistic fire behavior and fire suppression models to simulate a range of representative fires, including relatively infrequent, fast-spreading fires. A reliance on climate scenarios in which four climate variables vary simultaneously further differentiates the approach presented here from previous analyses of fire and global warming. The Changed Climate Fire Modeling System (CCFMS), described in detail by Fried and Torn (1990), was designed to estimate the changes in fire behavior and fire outcomes that would result from climate change. The research reported here consists of a comparison of global warming simulations based on three different GCMs to assesses the sensitivity of CCFMS predictions to the choice of GCM, and an exploration of the system's sensitivity to four vegetation types and four climate variables.

METHODS

An Overview of CCFMS

The Changed Climate Fire Modeling System consists of software and protocols for linking GCM output with the California Department of Forestry and Fire Protection's (CDF) Fire Protection Planning System (FPPS). FPPS is a collection of micro- computer based, deterministic, and largely mechanistic computer models of fire behavior and fire suppression. The system is designed to assess the impact of

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[2]Ph.D. candidate, Forest Systems and Economics, University of California, Berkeley, and Ph.D. candidate, Energy and Resources, University of California, Berkeley.

climate change on fire in analysis zones that are relatively homogeneous with respect to fuels, topography, and the density of buildings and natural resources that are at risk to fire. CDF administrative units consist of aggregates of analysis zones, which in California are typically 1200 to 125,000 hectares. For example, the Santa Clara Ranger Unit is divided into 6 such zones.

GCM output has low temporal resolution (e.g., output is commonly available as monthly averages of surface temperature, precipitation, humidity, pressure, and wind speed) and low spatial resolution (e.g., each average represents a grid cell of at least 4 x 5 degrees) resolution. By contrast, fire behavior models require data of much finer resolution, including the minimum and maximum daily temperature at the scene of a fire. In CCFMS, this disparity in resolution is addressed by calculating monthly scaling factors for temperature, precipitation, humidity, and wind speed. Each monthly scaling factor is a ratio constructed by dividing output from a GCM simulation of an enhanced greenhouse effect by output from a present climate simulation. Climate change weather series are generated by multiplying historical, daily, local observations of temperature, precipitation, humidity, and wind speed by these scaling factors.

The fire behavior module of CCFMS combines weather records with site descriptions to calculate daily fire rate of spread (ROS) potential at representative locations. ROS and burning index (BI), which is used in the fire suppression module to determine the kinds and amounts of fire-fighting equipment to dispatch, are calculated via an MS-DOS based implementation of the Fire Behavior Prediction System (Andrews and Chase 1989) for each climate scenario and combination of vegetation and slope present in the analysis zone.

Each fire ignition in the historical record is matched to the ROS and BI modeled for its date, time and location to generate a ROS distribution for the analysis zone. The California Fire Economics Simulator (CFES) simulates fire growth and initial attack fire suppression on representative fires with spread rates selected from this distribution. In each simulation, initial attack forces are dispatched to contain a growing fire until the fire is either contained or exceeds specified size or time limits. For example, in grass fuel, the simulation limits are 100 acres or two hours. If a simulated fire is contained within those bounds, its final size is recorded; otherwise, it is classified as an escape. The size and time limits are specified by the CDF to represent the threshold beyond which supplementary (as opposed to initial attack) forces would be dispatched and beyond which the simplifying assumptions contained in CFES would no longer be valid.

While most fires in California are contained quickly and burn only a fraction of an acre, large escape fires account for nearly all the acreage burned by wildfire. There are no models available to simulate how many acres are burned by escapes, because large fires may become non-homogeneous in behavior, slope, aspect, wind, and vegetation.

The number of fires, as well as their date and location, is exactly the same in every model run. What differs is the climate scenario, which affects fire behavior and, ultimately, the proportion of fires that escape the first line of suppression efforts. The structure of CCFMS is outlined in Figure 1.

Analysis Region

This CCFMS analysis was conducted for the CDF's Santa Clara Ranger Unit in Central California's coastal valley region. The region's climate is moderated by its proximity to the ocean, but during the fire season, temperatures can be quite hot and precipitation is extremely rare. The dominant vegetation communities are represented by the fuel models chosen to model fire behavior: grassland with sparsely distributed oak trees, two heights of chaparral, and redwoods. These fuel types correspond to NFDRS fuel models A, B, F, and G, respectively (Bradshaw et al. 1983). In the Santa Clara ranger unit, landholdings are quite diverse in size and use and much of the area is undergoing suburban encroachment.

Data

Daily weather records from the period 1980-1985, for four weather stations in the region, form the basis of all climate scenarios used in this analysis[3]. Analysis of the Present Climate scenario proceeds through the sequence of modules in CCFMS without any modification of this historical weather data. All other scenarios are produced by modifying this data with scaling factors generated from GCM output for climate simulations of a mid-1900's atmosphere and of global warming with double that atmospheric concentration of greenhouse gases. Three scenarios were produced by scaling historical temperature, humidity, precipitation, and wind speed values based on output from three different GCMs: NASA Goddard Institute for Space Studies (GISS) (fine scale model, Hansen et al. 1988), Princeton Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald 1980), and the United Kingdom Meteorological Organization (UKMO) (Wilson and Mitchell 1987)[4]. In addition, four scenarios were developed by scaling only one weather variable in the historical record using output from the GISS model: temperature,

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3/ Weather Station data were retrieved from the National Fire Weather Data Library via the Administrative Forest Fire Information and Retrieval Management System (AFFIRMS, Furman and Brink 1975).

4/ Output from all general circulation models was obtained from the National Center for Atmospheric Research, Boulder, CO.

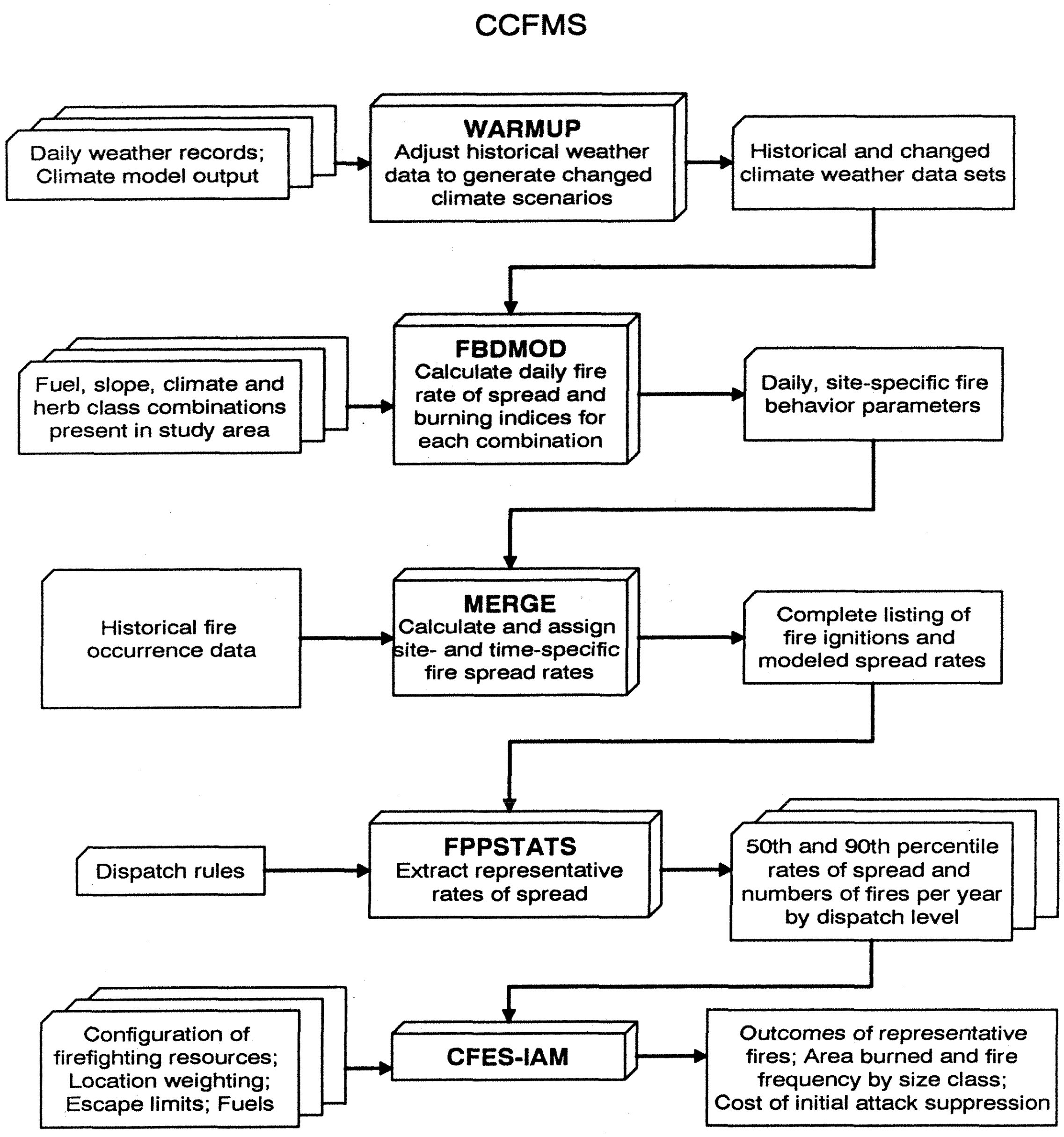

Figure 1.--Data-flow diagram for the Changed Climate Fire Modeling System. Micro-computer programs are indicated in bold face.

precipitation, humidity or wind speed. All historical fire records and data required as input to CFES, the initial attack model, were obtained from the CDF's Fire Protection Planning staff and field personnel[5].

RESULTS

Three types of CCFMS sensitivity were explored by evaluating changes in the frequency distributions of fire rates of spread (ROS) and comparing projected annual summary statistics (area burned and frequency of "escaped" fires). First, we assessed the effect of GCM choice by comparing system response to simulations of climate change from three different GCMs in a grass-fuel analysis zone. Second, we compared the sensitivity of all four fuel models to climate change scenarios generated from the GISS GCM. Third, we analyzed the individual effects of changes in temperature, precipitation, humidity, and wind speed on grass and redwood vegetation types, using output from the GISS GCM.

Escape frequencies and annual area burned in contained fires are the most comprehensive, "bottom line" assessments of changes in wildfire severity in regions that practice fire suppression. Nevertheless, the complexities of fire suppression, and the fact that these wildfire statistics are weighted by the historical pattern of fire ignitions, preclude generalizations from these statistics to the impact of climate change on fire behavior. For example, since fire-fighting resources are dispatched according to population density in the fire vicinity, a fire in a densely populated analysis zone may result in a smaller area burned than a fire with the same behavior in a sparsely populated zone. Comparing potential rate of spread distributions for selected fuel model-slope class combinations under different climate scenarios is one way to quickly assess the impacts of climate change on fire behavior. To the extent that weather-station data represent synoptic, regional conditions, assessment of changes in potential fire behavior has validity beyond a particular ranger unit. For regions possessing little or no fire protection infrastructure (e.g., Baja California), potential ROS and burning index simulations constitute the limit of current analytic capability.

Sensitivity to Choice of General Circulation Model

When compared with the Present Climate scenario, each of the three GCMs' climate change simulations projects an increase in both the frequency of escapes and in area burned by contained fires in the grass-fuel analysis zone (Figure 2). Fire danger, as represented by potential rate of spread, is greater in every month of the fire season (Figure 3). Figure 4 shows that this increase in monthly mean ROS represents a substantial shift in the ROS distribution, with a considerable increase in the number of days with potential spread rates faster than 80 chains per hour (1 mile per hour). While the different GCM simulations of the greenhouse effect consistently predict an increase in fire severity, CCFMS results are sensitive to choice of GCM. By all measures, the GFDL model results in the most change in wildfire statistics while the UKMO model results in the least change. We chose the GISS model for the vegetation and climate-variable analyses because, among the three GCMs considered, it predicted intermediate sensitivity of fire behavior to climate change.

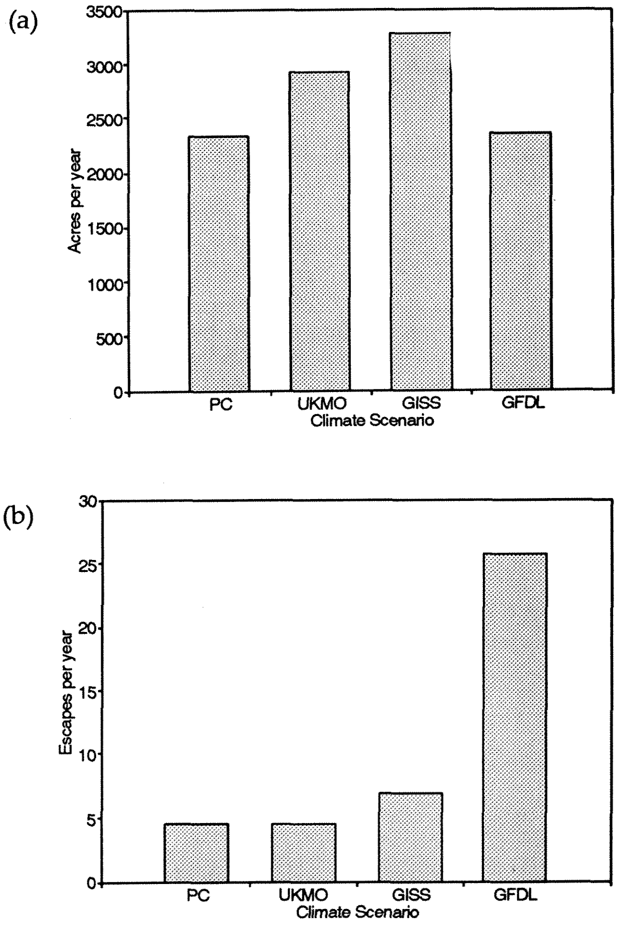

Figure 2.--(a) Area burned by contained fires and (b) frequency of escapes for the Present Climate (PC), and the GFDL, GISS, and UKMO climate warming scenarios in the grass fuel analysis zone, Santa Clara ranger unit.

5/ These data are now on file at CDF's headquarters in Sacramento and a system for archiving records of all fire incidents from 1980 on is now in place.

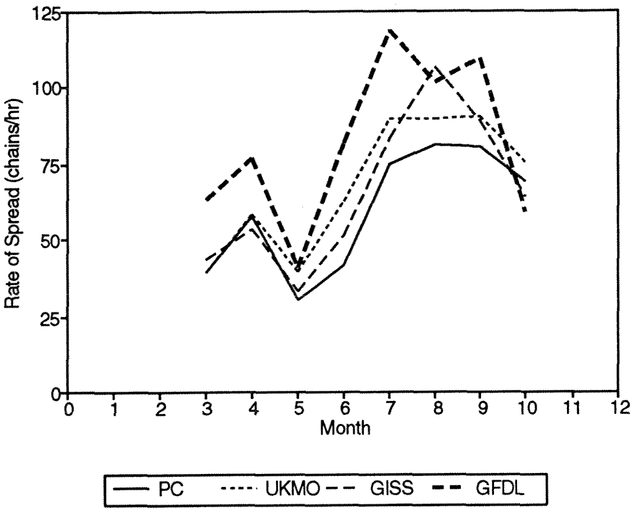

Figure 3.--Monthly average, 2PM rates of spread, modeled for 1980-1985 for the Present Climate (PC), and the GFDL, GISS, and UKMO climate warming scenarios on steep (48% slope) grass (fuel model A) in the Santa Clara ranger unit.

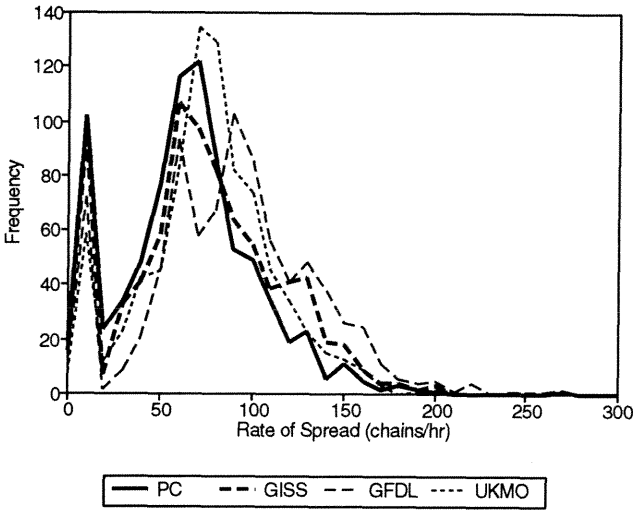

Figure 4.--Frequency of 2PM rates of spread, modeled for 1980-1985 for the Present Climate (PC), and the GFDL, GISS, and UKMO climate warming scenarios on steep (48% slope) grass (fuel model A) in the Santa Clara ranger unit.

Sensitivity to Vegetation Type

The four fuel types exhibited a differential response to climate warming, with grass fuels most sensitive, brush fuels intermediate and redwood forest relatively insensitive:

Fuel:	Present Climate	GISS Warming
	Acres burned	
Grass	2317.8	3278.4
Short Brush	9.8	13.1
Tall Brush	2.1	4.2
Redwood	2.1	2.2
	Escapes	
Grass	4.5	6.9
Short Brush	0.3	0.4
Tall Brush	0.0	0.0
Redwood	0.0	0.0

One possible explanation can be found in the contrasting micro-climates. The open, unprotected structure of grasslands, compared to forests, make them particularly responsive to increases in wind speeds; the still, humid air layer under a forest canopy can substantially mitigate synoptic weather changes. Another factor is the composition of the fuels. During the fire season, much of the flammable material in grasslands exhibits little, if any, lag in reaching a moisture equilibrium, so any increase in temperature or decrease in humidity would quickly affect its combustibility. By contrast, the large, woody debris that comprises redwood forest litter can take as long as 40 days to equilibrate after a change in humidity, effectively buffering the effects of any short periods of hot, dry, or windy conditions.

Sensitivity to Climate Variables

Global climate models predict that surface air temperatures will increase throughout the year in central California. Higher temperatures are typically associated with heightened fire danger, and indeed, CCFMS predicts higher rates of spread as a result of elevated temperatures (Figure 5). However, under a climate warming, temperature-only scenario, CFES simulations project a reduction in both area burned and escape frequency (Figures 6 and 7). This apparent paradox reflects enhanced fire suppression activity rather than diminished fire danger. As pointed out above, final results from CCFMS incorporate both fire behavior and fire suppression. Because elevated temperatures also increase burning index, the parameter on which dispatch is based, climate warming results in more fires at high dispatch level and fewer at low dispatch level. At high dispatch level, CFES dispatches additional fire-fighting resources, such as air tankers (at $2000 per mission), compensating for the increase in rate of spread caused by higher temperatures, but also increasing fire protection expenditures. An increase in the expected number of fires with high dispatch levels might lead to revisions in the allocation of fire suppression resources (Gilless and Fried, this Proceedings).

Climate warming will likely strengthen the hydrologic cycle, leading to increases in global precipitation (Hansen et al. 1983). Nevertheless, GCMs predict considerable regional and seasonal variation in how precipitation will change. For central California, GCMs predict that some months will be wetter and others drier under climate warming than they are today. For the Santa Clara ranger unit, CCFMS projected no discernable wildfire response to these

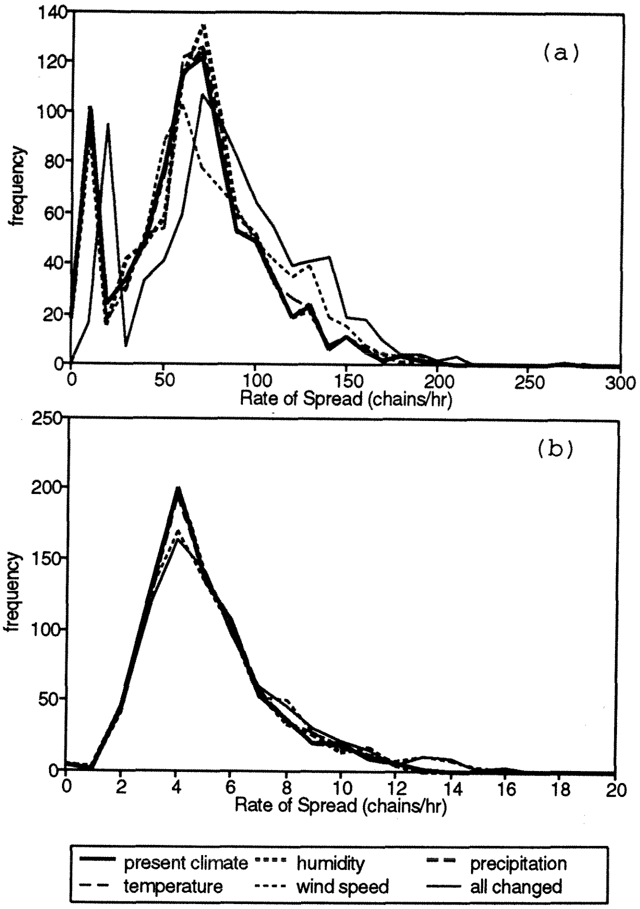

Figure 5.--Frequency of 2PM rates of spread, modeled for 1980-1985 for the Present Climate, GISS all changed, and GISS wind- , temperature- , humidity- and precipitation- only climate warming scenarios on (a) 48% slope grass and (b) flat redwood in the Santa Clara ranger unit.

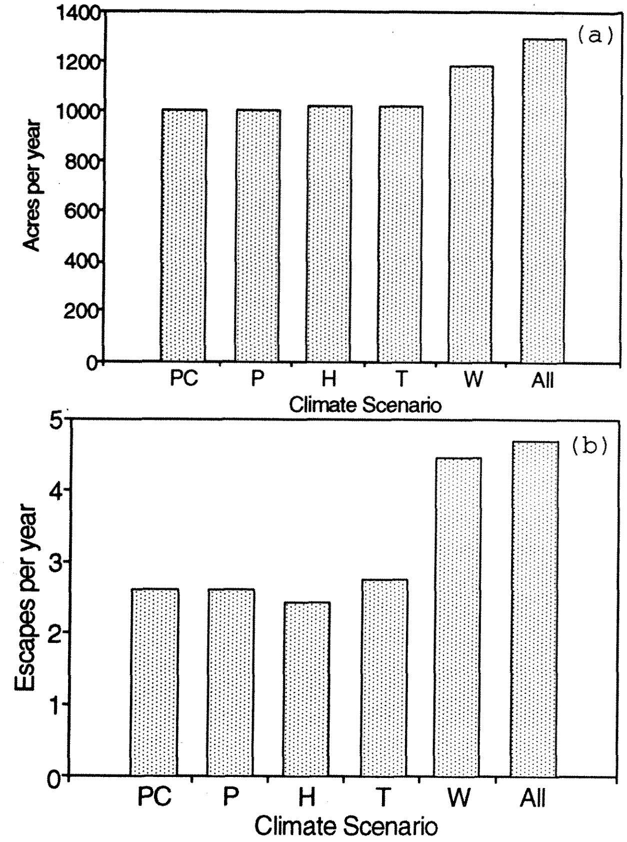

Figure 6.--(a) Area burned by contained fires and (b) frequency of escapes for the Present Climate (PC), the GISS all changed (ALL), and the GISS wind- (W), temperature- (T), humidity- (H) and precipitation- (P) only climate warming scenarios in the grass fuel analysis zone, Santa Clara ranger unit.

precipitation changes (Figures 6 and 7). Such results are not surprising given the region's Mediterranean climate, in which the fire season and rainy season have virtually no overlap. For example, even if GCMs predict a doubling of precipitation in February, there would still be virtually no fire occurrences during that month. Because there is no August precipitation in the historical record (and, therefore, no precipitation events to permit scaling), a GCM prediction of precipitation doubling in August would likewise have no effect on fire behavior in this example.

With increased evaporation and increased saturation vapor pressure, absolute humidity tended to increase in GCM simulations of the central California climate; however, relative humidity decreased due to warmer air temperatures. The net result was a slight increase in fire danger (Figure 5) and fire suppression intensity, but no major change in area burned (Figures 6 and 7).

GCM simulations project an increase in wind speeds during most of the year, as the Pacific high pressure cell is strengthened relative to the Central Valley low pressure system. Of the four climate variables tested, wind speed resulted in the greatest increase in rate of spread, area burned and frequency of escaped fires.

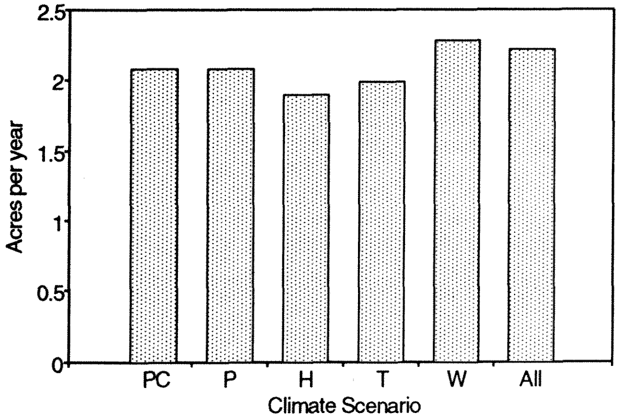

Figure 7.--Area burned by contained fires for the Present Climate (PC), the GISS all changed (ALL), and the GISS wind- (W), temperature- (T), humidity- (H) and precipitation- (P) only climate warming scenarios in the redwood fuel analysis zone, Santa Clara ranger unit. There were no escapes in any redwood fuel scenario.

DISCUSSION

By all measures, these simulations of climate warming predict an increase in fire severity in the Santa Clara ranger unit. However, the heightened fire danger is not uniformly distributed. Grasslands exhibit the greatest sensitivity to climate change, while redwood forests appear to be relatively unaffected. This kind of information should help fire protection policy-makers identify the regions most vulnerable to climate change. At least in California, the greatest increase in fire severity can be expected in areas vegetated with grass and brush (e.g., those that experience the greatest fire risk now). While this is good news for those most concerned about economic losses of forest resources, it bodes ill for the hundreds of thousands of residents of California's ubiquitous urban-wildland interface zones, which are typically situated in brush- and grass-covered foothills. Ecologically, the predicted changes in fire severity would certainly have complex impacts on vegetation and wildlife.

Since probable changes in wind speed appear to have the most pronounced effects on fire behavior, the treatment of wind in climate modeling deserves closer scrutiny. While climate modelers express confidence in their predictions of high altitude mass air flow, estimates of surface wind speeds, which are derived from high altitude winds and topographic and surface roughness parameters, are considered to be less reliable. A single value for surface roughness represents each grid cell, which in California, may span from open ocean surface to the Sierra foothills. Therefore, the resulting grid-average surface wind speed may not be representative of the area for which fires are being modeled.

The effect of wind averaging methods on estimates of changes in fire behavior is poorly understood. GCMs generate vectors representing wind speed and direction at time intervals on the order of 90-minutes. Most GCMs (e.g., GFDL and GISS) average these vectors to obtain a monthly wind vector from which scalar wind speed can be computed. Other GCMs (e.g., UKMO) compute scalar wind speed for each modeled time interval, then average these scalars to obtain monthly wind speeds. Unfortunately, shifts in wind direction over a month result in vector-derived average wind speeds that are less than averages of the scalars. For example, if the wind blew east for half of the month and west for the other half of the month, the vector derived monthly average wind speed would be reported as zero! Thus, wind speeds derived from averages of vector wind output would under-estimate fire danger relative to scalar-averaged output from the same GCM simulation. However, the conclusion that the ratio of changed to present climate would be systematically lower for vector- than for scalar-averaged wind speed output is unwarranted. Our results actually suggest the opposite. The scalar-averaged, UKMO GCM output predicted the smallest change in wildfire behavior.

Fire modelers relying on simulations based on GCM wind speed predictions should consider these limitations when selecting GCM data. Scalar wind speed data is reported by the UKMO model, and may be obtained from the GISS and OSU (Schlesinger and Zhao 1988) GCMs by special request. The lowest altitude of wind speed data provided by the NCAR Community Climate Model (Washington and Meehl 1984) is at 0.99 millibars atmospheric pressure (about 100m above the surface) and has not been tested for scaling surface winds in fire simulations.

GCMs cannot predict precipitation at a resolution (temporal and spatial) suitable for modeling ecological processes that are highly sensitive to rainfall, so changes in those processes may be difficult to predict rigorously (Harte et al. 1991). In addition, the monthly-average precipitation data that is reported by GCMs provides no basis for assessing changes in precipitation patterns, such as frequency and duration of storm events. While fire in sub-tropical and Mediterranean California is not especially sensitive to precipitation, this limitation could be important in areas where wet and dry seasons are less distinct. If this analysis had been conducted for the southeast United States, for example, the effect of GCM choice might have been more pronounced due to differences in treatment of precipitation among GCMs.

Anomalous patterns of precipitation, such as occur during El Nino or may occur with climate change, may alter wildfire regimes in California through effects on vegetation. The effect on wildfire of long-term changes in precipitation and soil moisture as predicted by GCMs could be modeled by re-mapping the distribution of vegetation communities. The wide range of wildfire response in grass, chaparral, and redwood fuel analysis zones suggests that vegetation communities do influence the response of an area to climate warming.

A fundamental revelation of the GCM sensitivity analysis is that the choice of climate model <u>does</u> matter. Their behavior and limitations are sufficiently diverse to merit thoughtful attention by prospective climate effects modelers, and reliance on whatever climate model data is most readily available is ill-advised. For example, the quality of wind speed data has been demonstrated to be of considerable importance when modeling fire, so a GCM with better wind modeling capabilities would make a wiser choice than a GCM that was best at simulating precipitation. However, if the simulation focus were on long term shifts in vegetation, a model known for high quality precipitation projections would be more attractive. Specific criteria for evaluating GCM suitability include how the data is averaged and whether and how the output has been validated.

There are several opportunities for improving GCM-based predictions that could be explored. Wider availability of scalar average wind speeds and daily or weekly averaging of 90-minute time-step output (rather than monthly averages) of climate variables would be highly desirable (Fried and Torn 1990). One alternative for enhancing site specificity of wind predictions would be to derive secondary, correlative models from high-altitude wind or pressure data and surface wind speed observations. These models could then be applied to GCM high-altitude wind output to generate surface winds.

An important result of the climate variable sensitivity analysis is the considerable influence of weather parameters other than temperature. This finding alone renders suspect most prior efforts that focused only on temperature change. Perhaps more startling is the apparent importance of evaluating the effects of a simultaneous change in all four climate variables. For both grass and redwood fuels, the cumulative effect of changing all four climate variables appeared to be more than additive in its effect on fire severity (Figure 5). Non-linear, interactive terms in the fire behavior models account for this phenomenon.

Because FPPS was designed as a model that would be valid for comparing alternative fire protection configurations and strategies, users of CCFMS can have the greatest confidence in its projections when comparing simulations based on alternative climate scenarios, even if the projections from any one scenario do not accurately mimic reality. CCFMS contains the assumption that all fires burn in pure, homogeneous fuels, on a constant slope and with a constant wind speed. Real fires often burn in spatially heterogeneous, mixed fuels, under shifting winds and uneven topography, often impeded by natural barriers, such as rock outcrops and roads. Despite these model simplifications, the projections of the present climate scenario constructed for this analysis correspond well with historical fire statistics. The CDF is currently using the FPPS throughout California and has found it to be a useful tool for relative comparisons such as those performed here (Gilless and Fried, this Proceedings).

It should be noted that these results represent a partial analysis of future wildfire severity in that they ignore probable changes in non-climate factors such as the frequency of fire starts generated by human activities.

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A KNOWLEDGE-BASED APPROACH TO THE EVALUATION OF FUTURE FOREST CONDITIONS

Donald E. Koten, Lee P. Herrington, Robert E. Chambers, and Craig J. Davis[1]

Abstract.--The temporal and spatial impacts of scheduled management activities on the forest structure are usually quite subtle and difficult to determine, especially for relatively large acreages. Traditional optimization-based harvest scheduling procedures often prove to be inadequate for evaluating the resulting spatial and temporal forest mosaics. The interactive decision support system (DSS) under development utilizes a geographic information system (GIS) and a knowledge-based system (KBS) to enable forest managers to assess harvest schedules and the resulting forest conditions in terms of wildlife habitat suitability. The system described in this paper consists of five modules: a functioning GIS that stores both thematic and spatial information about the forest; a KBS that contains habitat descriptions and requirements for wildlife species common to New York; a forest growth model; a harvest scheduling procedure; and a graphics interface that forms the linkage between the user and the system modules.

INTRODUCTION

The task of the forest manager is becoming increasingly complex and difficult. Increasing and sometimes conflicting demands are being placed on the managed forest to sustain higher levels of wildlife habitat, timber outputs, and recreation opportunities, while maintaining water quality and aesthetics. The forest manager achieves the desired level of outputs and use by visualizing future forest-wide conditions. These forest conditions consider vegetation and its spatial, age/stage/size, and species distribution. The conditions are created by identifying schedules of stand level treatment decisions that have forest-wide impacts on productivity and future forest conditions. The spatial and temporal impacts of these schedules of harvest activities occur over large acreages and are difficult to evaluate without analytical approaches. Of particular complexity is the evaluation of future forest conditions, in terms of wildlife habitat suitability, resulting from various harvest schedules. Many aspects of wildlife habitat involve the characteristics of a collection of stands and their spatial distribution. The microcomputer-based spatial Decision Support System (DSS) described in this paper is designed to assist the manager in evaluating future forest conditions, in terms of wildlife habitat, resulting from sets of harvesting schedules as applied in even-aged management. The DSS provides the manager with the timber outputs over time and a visual display of the future conditions resulting from a specific harvest schedule. The system described here is being developed as part of a larger, more complex system and we are reporting on the current status.

The spatial nature of habitat requirements for many wildlife species, the heuristic nature of many habitat descriptions, and the ability of some wildlife to exist in many habitats while others have very specific requirements, makes wildlife evaluation of forest conditions particularly difficult (Chambers, 1983). The evaluation of forest conditions for wildlife requires both spatial and aspatial data. The Decision Support System under development uses Geographic Information System (GIS), a relational (flatfile) database, and a Prolog knowledge base (KB). An overview of the systems design is provided to show the relationship of the various components.

[1] Koten and Herrington are professors, Faculty of Forestry; Chambers is professor, Faculty of Environmental and Forest Biology; Davis is assistant professor, Faculty of Forestry; College of Environmental Science and Forestry, Syracuse, NY.

SYSTEM DESIGN OVERVIEW

The DSS currently includes four system modules: a functioning GIS that stores and displays both thematic and spatial information about the forest, a KB that contains habitat descriptions and requirements for wildlife species common to New York, a forest growth model, and an interface that forms the linkage between the user and the system modules. Figure 1 illustrates the data file communications and relationship among the four modules. The STAND DATABASE stores information for each of the stands in a specific forest and includes stand information on forest type, area, age/stage, volume/acre, percentages of major species, basal area, average DBH, as well as special wildlife data such as the presence of water, snags, rock cliffs, open and brushy areas, etc. The GIS IMAGES include at a minimum the stand (management unit) maps, special wildlife conditions, and planimetric features such as roads. Desirable additional maps would include water, topography, and soils. The ACTIVITY FILE includes the complete forest-wide harvesting schedule for the time period of interest. This is a very detailed schedule, not only listing the year of entry into the individual stands, but defining a complete prescription for each stand which includes such detail as the desired residual basal area, the type of thinning, etc. Currently the activity set in this file is defined by the forest manager with a timber, wildlife, or joint goal in mind. A module is being developed to automate the scheduling of stands for treatment. The detail in the ACTIVITY FILE is necessary because the activity set becomes the control file to run the TWIGS (Northeast Version 3.01) growth model (Teck, 1990). NETWIGS has been modified to run under batch control and performs the desired treatment on each stand as defined in the activity set, and also grows every stand for a specified interval and planning horizon. The Turbo Prolog KNOWLEDGE BASE forms the basis for the wildlife suitability evaluation.

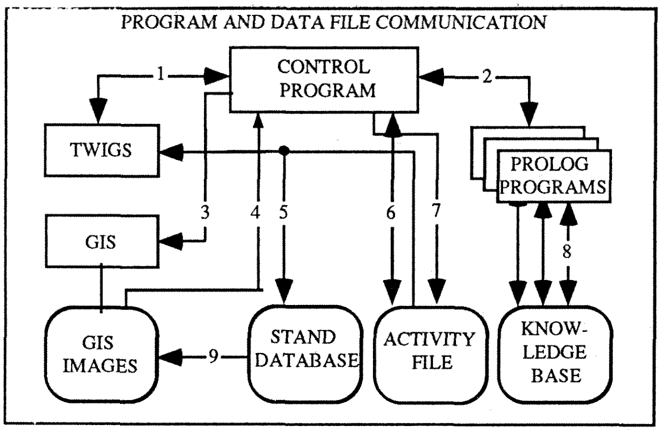

Figure 1. Major subsystems and data flows.

The attributes of the system can best be visualized by reference to Figure 2 which shows the functions of the interface or control module. INITIALIZE allows the user to select a database for the stands in a particular forest or to create a new stand database. DISPLAY provides the user's primary view of the forest via a map display. This graphic display is essentially a raster version of a simple polygon GIS. The display can be zoomed and panned, and queries can be made concerning the attributes of any stand by clicking on its polygon. The stand attributes are stored in the stand database (DB), and the flat file record for the stand is displayed. The DB can also be queried by entering SQL type statements for forest-wide queries. In this case the polygons which have attributes matching the query are highlighted. IDRISI type files are both used and created by DISPLAY. ACTIVITY enables the user to create or specify an activity set which is a sequence of management activities - a harvest schedule - for each stand in the forest. RUN applies the scheduled management activities to the initial forest conditions based on the activity set and then grows both treated and untreated stands for the desired planning horizon. The condition of each forest stand is predicted at specified time intervals and these intermediate and final stand conditions are stored in the database. The stand database is updated with new stand information after treatment and growth.

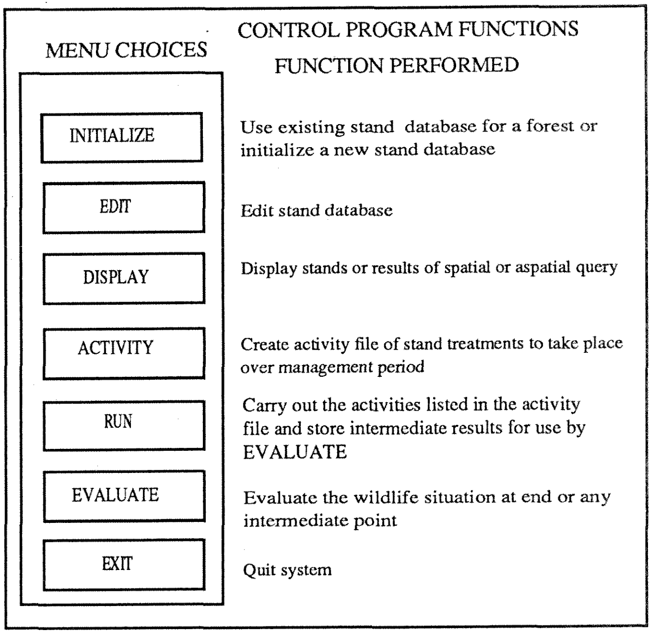

Figure 2. Functions of the control program.

Wildlife habitat quality is determined with EVALUATE. Wildlife habitat can be evaluated at the start, end, or at intermediate points in the management cycle. A summary over time is made of the timber outputs generated by the scheduled management activities. The manager can DISPLAY any attribute of a stand or the forest to observe the resulting forest mosaic. If the manager is dissatisfied with either the timber productivity or the timber or wildlife view of the condition of the forest, an edit of the activity set and/or the initial stand descriptions using ACTIVITY or EDIT, respectively, can be done and another RUN made.

The timber management subsystem uses proven techniques for harvest planning and growth estimation. Interactive attribute query and graphic results display have been added. The wildlife habitat evaluation system does not use proven techniques. Further description of the wildlife habitat evaluation of forest conditions follows.

WILDLIFE HABITAT EVALUATION

Assessment of wildlife habitats presents a variety of problems. The value of habitat to wildlife depends on many characteristics including the size of the area, the vegetative composition (cover types), the physical attributes (size or stage of development) of the vegetation, their spatial and temporal relationships, and the availability of special features in an area (Chambers, 1989). Different species thrive in various mixes and spatial arrangements of these characteristics. Further. the assessment of habitat is not static as the characteristics and value of the current habitat changes with growth, windthrow, losses from insects and disease, and management activities, including intermediate treatments.

Wildlife habitat goals are often best achieved by scheduled harvest treatments which modify current habitats in order to achieve some future habitat mosaic. The manager is faced with evaluating current conditions, monitoring changes with time, and predicting future consequences of management activities in order to evaluate the plan. For large acreages, all of these may be difficult.

The quality of forest-wide habitats may vary in terms of ability to sustain population levels. This study focuses on two levels of quality: (1) requirements deemed necessary for sustaining a viable population; and (2) habitats which could sustain an abundance of a species or group. The availability and/or quality of habitat does not always assure the presence of wildlife, as factors other than habitat - climate, competing species, disease and/or predators also influence distribution and abundance of wildlife.

The habitat assessment approach used is based on research (public) knowledge and expert knowledge gained from experience with habitat requirements for specific species or groups of species. There does exist for the Northeast, a reasonably accurate knowledge of habitat requirements in terms of stages of forest growth, cover types, area size, spatial arrangements, and special conditions (Chambers, 1983; DeGraaf, 1986). These two publications are the primary source of the public information used in the KB. Sources of expert experience will also be accessed to supplement the public data.

Design and Development of the Knowledge Base

During evaluation there are two kinds of questions which the forest manager might ask:

1) What wildlife species might find suitable habitats on the forest or within a stand, and
2) What would be the distribution and total area of the habitat suitable for a specific animal or group of animals?

Initial plans called for these queries to be carried out by the DB system using a second flat file data base containing the habitat requirements of wildlife common to the forest area. In this approach the timber stand flat file would be searched to find matches with the habitat requirements. Review of the available public data describing wildlife habitats (Chambers, 1983; DeGraaf, 1986) and the nature of those requirements quickly showed the problems with this approach. The data, in fact, suggested the KB approach described here.

There were four problems associated with the use of a wildlife habitat flat file database:

1) There are large differences in the forest stand requirements from species to species. Whereas one species might only require mature hardwood types, another species may require a mixture or combination of forest stand ages.
2) Some wildlife have special needs such as caves, soil types or aquatic types, which were not in the timber database but which might be inferred from soils, topological, and hydrological maps.
3) Some species have multiple habitat requirements within their home range for different activities.
4) There can be interactions between different wildlife residents of the forest.

Three species show some of these characteristics.

1) Beaver is favored by seedling/sapling and pole hardwood stands, aquatic habitat, and flat topography (Chambers, 1983). The habitat requirements can be determined from the stand DB and the KB. The water and topography requirements are spatial and require access to the

GIS.

2) The eastern cottontail requires stands in the early stages of succession with a brushy understory (Chambers, 1983; Allen, 1984) and has a home range of 4 hectares. This one is easy since successional stage can be inferred from stand age and the size of the home range is not important.

3) The ruffed grouse has a more complex set of requirements. It must have habitats for brood rearing, drumming, foraging, and thermal cover (Chambers, 1983; Cade and Sousa, 1985). Brood rearing and drumming require seedling, sapling, or pole stands: easily inferred from stand age.

   Foraging requires hardwood stands. Thermal cover is provided by stands of evergreen (conifer) species in those regions where snowburrowing opportunity is minimal. All of these requirements are best provided within a 4-10 hectare area.

The wide variation in habitat requirements and the somewhat qualitative nature of other requirements led us to adopt a KB approach based on the ease of incorporating the habitat data into a reasonable data structure. We considered flexibility to outweigh the slower speed with the KB relative to the use of two separate flat files. Using a KB would also allow us to incorporate complex rules and expert knowledge in the system, as well as ease of updating when new information becomes available.

Aspatial Habitat Analysis

The Turbo Prolog system was chosen for this application and a large KB of facts relating wildlife species to attributes like forest type, stand stage (age), species, understory vegetation, special needs, etc. was created from data in Chambers (1983). These facts were stored as simple clauses like for_type (squirrel, hardwoods).

Given predicates like

```
      can_live(critter,for_type,
age_class,special_cond,species)
      for_type(critter, type)
      for_stage(critter,age_class)
      special_needs(critter,special)
      species_needs(critter,species)
```

the clause

```
      can_live (Critter,Type,Age,Special,Species) if
            for_type(Critter, Type),
            for_stage(Critter,Age),
            special_needs(Critter,Special),
            species_needs(Critter, Species).
```

can be used to find the wildlife species (Critter) which would have habitat requirements which matched those of each stand when the Prolog program is provided with bindings for the variables Type, Stage, Special, Species. The above examples are, of course, greatly abbreviated. To find the wildlife which has habitat requirements which match those of a (or any) of the stands the control program simply passes a command line driven DOS call to the compiled Prolog program. The Prolog program writes its output to a file which is read by the control program. The output of this analysis is a listing of all species for which habitat exists on the forest or within a stand.

Spatial Habitat Analysis

Habitat analysis requiring spatial searching falls into two categories. As stated earlier, the beaver requires the correct hardwood stage, flat topography, and aquatic habitat. Using several of the IDRISI modules, which in the latest version can be called from other programs, image files are created which when overlaid (covered) on the stand map, provide an identification of stands and areas within the required distance to accessible water. The KB is queried about each stand's suitability for beaver habitat, and only the number of cells in each acceptable area are saved. These cells are then counted and the total area of acceptable beaver habitat reported. In this case DISPLAY can be used to display an image showing the location of the acceptable areas.

Species like the ruffed grouse create another problem since they require three cover types or age classes within their home range, as described above. Solution of these problems requires both GIS for the spatial aspects and KB for inference. Knowledge about the spatial aspects of the current inquiry are kept in a Prolog database file (PDB). This information is in the form of Prolog facts and rules which were generated as a result of spatial analysis. This file is accessed by the Prolog system whenever spatial information is needed. The file contains the results of various analyses which may have been carried out. These analyses may be general in nature or may be specific to a species. An edge analysis may be important spatial information for a number of species, while the analysis for ruffed grouse is very specific.

Whenever a growth projection or harvest is made, the PDB file specific to GIS spatial analysis is erased or saved under a different name. Thus Prolog can tell that the current situation has not changed, based on the presence or absence of this file. If the file exists, then it can be queried to see if the specific analysis needed has already been carried out, and, if so, utilize the results. If the analysis has not been carried out then Prolog rules direct the required analysis and the analysis results are added to the PDB. Programs have been developed which convert the spatial analysis to Prolog rules and place them in the PDB for access by the inference system. This approach has been devised to reduce computer time in recalculating analyses.

An algorithm was developed to find the edges between specific forest types. Once the edges specific to the species are found they are buffered to a distance related to the cruising radius of the animal and the area of each buffered edge is determined and output to an IDRISI values file. The values file is then accessed by a Pascal program to convert it to a Prolog rule or list and the new knowledge appended to the current spatial PDB file.

The case of the ruffed grouse requires an extension of the edge algorithm so that the edges between any combination of the three types required by the ruffed grouse can be found. The edges are again buffered an appropriate distance and intersected using a Pascal program, based on the IDRISI data structures, to find the intersection of the three buffered edges. Then, the IDRISI area function is applied to the intersection file and an entry is made to the spatial PDB file. Figure 3 illustrates this problem and shows the suitable habitat defined by broad lines.

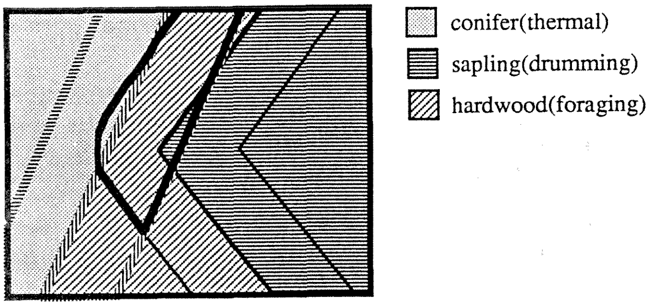

Figure 3. Ruffed grouse suitable habitat.

SUMMARY

This paper describes a microcomputer-based spatial Decision Support System that is under development. The System is designed to assist the manager in making decisions on sequences of forest-wide treatment activities to achieve sustainable forest conditions, uses, and outputs. Present development has focused on the timber management aspects to provide a base for predicting future forest conditions resulting from a schedule of treatments. The current wildlife knowledge base requires further expansion through the introduction of more complex rules and the addition of expert-based rules. The spatial analysis system will continue to be refined. The timber management activity sets will be expanded to include not only the manager-defined activities, but activities selected through a quantitative or "automated" approach.

Planned developments include the addition of a procedure where the desired future forest condition can be defined, and then activities or harvest schedules will be "automated" by the system to assist the manager in achieving those conditions.

Future development could also include spatial analysis for aesthetics evaluation through the use of the "test bed" of the timber system and the development of a knowledge base for aesthetics.

Based on progress to date, it appears that the spatial DSS with the knowledge base and GIS described in this paper should result in an effective low-cost system useful to the manager, of relatively large forests, in evaluating future forest conditions for wildlife habitat suitability and timber productivity.

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INTERACTIVE MULTICRITERION DECISION ANALYSIS

USING SHADOW PRICE AND PARAMETRIC PROGRAMMING[1/]

Gao Liu and Lawrence S. Davis[2/]

Abstract.--Experiences with forest planning models have indicated the needs to provide "what-if" insights by simulating alternative scenarios of reconciling goal conflicts. This paper presents an interactive procedure for using linear programs in a context of simulation to aid forest management under multiple objectives. Two modeling strategies are integrated in the procedure to facilitate a decision maker in searching the most preferred trade-offs. Solution groups are sequentially generated by performing parametric analysis. Criterion weights are progressively updated as the decision maker shifts from one local choice to another one, using a shadow price based weighting scheme.

INTRODUCTION

Analysis of multicriterion decision problems has received considerable attention in forestry during the last two decades. In problem situations with a large number of alternatives, a commonly analytical approach is to integrate mathematical programming (MP) with instruments representing trade-off preferences. Modeling techniques of this type include:

Weighting method in which the evaluation instruments are cardinal weights in a compresensive objective function;
Constraint method in which the evaluation instruments are the primary objective function and criterion achievement constraints;
Weighted goal programming in which the evaluation instruments are goal targets and goal weights; and
Lexicographic goal programming in which the evaluation instruments are goal targets and goal priority rankings.

Significantly, these methods extend MP's applicability as they allow the inclusion of multiple objectives while still being efficient in computation. The two variants of goal programming (GP) have been applied to a variety of decision problems in forestry (see Dykstra 1984 for a thorough overview). Through FORPLAN, constraint method has been extensively used in developing management plans for national forests (Teeguarden 1987).

It is well understood that these MP based models are subject to limitations. Of most concern are the practical difficulties of obtaining credible preference information prior to MP computation (Cohon 1978, Dyer et al. 1979, Zeleny 1981, Rosenthal 1983, Davis and Johnson 1987, Mendoza 1987). Trade-off preferences are inherently subjective. There is no convenient, nonarbitrary method for eliciting them properly in the absence of observed choices.

In the face of such a problem, one typical response is to perform parametric analysis, solving over a set of alternative value assumptions. So doing, a decision maker (DM) can be made better informed of the nature of criterion conflicts. This then should facilitate the DM in refining preferences among different trade-off options. Land-use planning models that involve parametric analysis can be found in Miller and Byers (1973), Bottoms and Bartlett (1975), Stuart (1977), Kao and Brodie (1979). Issues related to parametric GP modeling of multiple-use problems are discussed in Field et al. (1980) and Rustagi (1985).

Another response is to sequentially explore trade-off options in a context of DM-analyst interaction.until a most preferred one is found. This approach has two major advantages, as compared with single-stage parametric analysis. First, it enables the DM to learn more fully the range of trade-off alternatives without being

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2/ Graduate Student Researcher and Professor of Forest Management, respectively, University of California, Berkeley.

confronted with information overload. Second, the DM's evaluation feedback at a specific iteration serves to guide the searching task at its following stage. As a result, the procedure can promote the DM's active participation in the whole searching process. A number of interactive methods for multiobjective programming have been developed since the early 70's (see Hwang et. al 1979, and Evans 1984). Several authors have recently used the interactive approach to address decision problems in forest management. Steuer and Schuler (1978) employed an interactive criterion weighting-solution ranking approach for a national forest planning problem. Hotvedt et. al (1981) described a heuristic weighting method for GP models of harvest scheduling. Walker (1985) demonstrated a GP based reforestation planning model with iteratively adjusted cardinal weights. Duckstein et al. (1988) used an interactive, visual, and fuzzy GP procedure in their study of forest watershed management.

This paper presents an alternative interactive procedure for multiobjective linear programming problems. What make this method distinct from those in the literature are: 1) its use of shadow prices in inducing criterion weights that are implied by a specific choice, and 2) its use of parametric analysis in simulating alternative scenarios of criterion trade-offs. Motivation for the first strategy arose from the difficulties which a DM is likely to encounter in supplying direct assessment of subjective trade-off rates. Rationale for the second strategy come from the needs to provide sufficient "what-if" insights at each iteration and permit convergence on a non-vertex solution.

CONDITIONS FOR A MOST PREFERRED SOLUTION

In vector form, a multiple objective linear programming (MOLP) problem can be stated as:

$$\begin{aligned} &\max\ z_1(\mathbf{x}) = \mathbf{c}^1\mathbf{x} \\ &\cdots\cdots\cdots\cdots\cdots \\ &\max\ z_k(\mathbf{x}) = \mathbf{c}^k\mathbf{x} \\ &st\ \mathbf{Ax} \leq \mathbf{b} \\ &\quad \mathbf{x} \geq \mathbf{o} \end{aligned} \qquad [1]$$

where $\mathbf{x}$ is a vector of decision variables, $\mathbf{c}^i$ is a vector of parameters in the linear objective function $z_i(\mathbf{x})$ for $i = 1, \ldots, k$, $\mathbf{A}$ is a matrix of constraint coefficients, $\mathbf{b}$ is a vector of right-hand side (RHS) values, and $\mathbf{o}$ is a vector of zeros. Alternatively, the constraint set can take the form of $\mathbf{x} \varepsilon \mathbf{X}$, where $\mathbf{X}$ is the set of feasible solutions in [1], that is, $\mathbf{X} = \{ \mathbf{x} | \mathbf{Ax} \leq \mathbf{b}, \mathbf{x} \geq \mathbf{o} \}$.

The k distinct objective functions are all stated as functions to be maximized. This implies that the DM involved in resolving the MOLP problem prefers higher values of each z_i to lower ones. Such a notion will cause no loss of generality since an objective of min-type can easily be converted to an equivalent one of max-type.

Let $\mathbf{X_e}$ be the set of efficient solutions in $\mathbf{X}$. A solution $\mathbf{x}' \varepsilon \mathbf{X}$ is efficient if there is no other solution $\mathbf{x}'' \varepsilon \mathbf{X}$ that can increase one of the k objectives without decreasing at least one of the others. Further let $\mathbf{Z_e}$ be the set of nondominated vectors of criterion values, namely, the images of $\mathbf{X_e}$ under $\mathbf{z}()$. $\mathbf{Z_e}$ then contains all of the alternative combinations of criterion values that are attainable and might be considered by the DM. In other words, $\mathbf{Z_e}$ encompasses all of the points on the trade-off possibility surface that is embedded in the MOLP problem.

Assume that the possibility surface can be expressed in implicit form as, $T(z_1, \ldots, z_k) = 0$, analogous to the notion of product transformation function in microeconomic theory (Varian 1984). Assume also that the DM's choice between those on the surface is guided by an unknown, and perhaps nonlinear, value function $V(z_1, \ldots, z_k)$ (the existence of such a function is discussed in Keeney and Raiffa 1976). In concept, then, the original MOLP problem can be converted to

$$\begin{aligned} &\max\ V(z_1, \ldots, z_k) \\ &st\ T(z_1, \ldots, z_k) = 0 \end{aligned} \qquad [2]$$

an extension to the two-good model of production efficiency analysis in Nicholson (1985). Applying the Lagrangian multiplier method to the above model yields

$$\frac{\partial V/\partial z_i}{\partial V/\partial z_j} = \frac{\partial T/\partial z_i}{\partial T/\partial z_j} \qquad \begin{matrix} i = 1, \ldots, k \\ j = 1, \ldots, k \end{matrix} \qquad [3]$$

evaluated at $\mathbf{z}^*$, that is, the mix of criterion values which is most preferred by the DM.

Of the equation, the left-hand side is the DM's marginal rate of substitution between z_i and z_j (MRS_{ij}); the right-hand side is the marginal rate of transformation between z_i and z_j (MRT_{ij}). At the most preferred solution $\mathbf{z}^*$, thus, the rate at which the DM is willing to exchange z_i for z_j is the same as the rate at which z_i can technically be traded for z_j.

BACKWARD INDUCTION OF CRITERION WEIGHTS

Despite its seemingly abstract nature, the theorem *MRS* = *MRT* is not remote to MOLP modeling in the absence of reliable *a prior* information of preferences. The problem of how to estimate relative criterion weights is virtually nothing but that of how to elicit marginal rates of substitution (Geoffrion, Dyer, and Feinberg 1972). As suggested by the theorem, the task can be better served if the significance of *MRT* is taken into account. Central to this are 1) the association of *MRS* with implicit weighting in an observed choice; 2) the commonly-used method of local linearization of an implicit value function; and 3) the connection between *MRT* and shadow price.

To explain, suppose that a portion of the criterion vectors in $\mathbf{Z_e}$ are made available to the

DM for evaluation and selection. One of them, say **z'**, is preferred to the others. In addition, assume the corresponding decision vectors in $\mathbf{X}_e$ are all vertex points. Let us now try to find the locally relevant weights that must imply if **z'** turns out to be the "best" solution in $\mathbf{Z}_e$. Mathematically, this problem is to determine such an vector of non-negative scalars $(c_1, \ldots, c_k)$ that **z'** solves:

$$\begin{aligned} &max\ V = c_1 z_1 + \ldots + c_k z_k \\ &st\ T(z_1, \ldots, z_k) = 0 \end{aligned} \qquad [4]$$

A positive scaling of the objective function will have no effect on solving [4]. Hence, let us divide it by c_k, assuming $c_k > 0$. Define $w_k = c_i/c_k$, $i = 1, \ldots, k$. Then the above model can take the alternative form as:

$$\begin{aligned} &max\ V = w_1 z_1 + \ldots + w_{k-1} z_{k-1} + w_k z_k \\ &st\ T(z_1, \ldots, z_k) = 0 \end{aligned} \qquad [5]$$

Applying the Lagrangian multiplier method to [5] yields the following conditions

$$MRS_{ij} = w_i/w_j = MRT_{ij} \qquad i = 1, \ldots, k \quad j = 1, \ldots, k \qquad [6]$$

for **z'** to be an optimal solution in [5]

Particularly, for j = k, the equation [6] implies

$$\begin{aligned} &w_i = -\partial z_k/\partial z_i \qquad i = 1, \ldots, k-1 \\ &w_k = 1 \end{aligned} \qquad [7]$$

given that $MRT_{ik} = \partial z_k/\partial z_i$, as defined in Nicholson (1985).

Since **x'** is efficient and **z'** nondominated, (**x'**, **z'**) also solves the conventional LP model:

$$\begin{aligned} &max\ z_k(\mathbf{x}) \\ &st\ \mathbf{x} \varepsilon \mathbf{X} \\ &\quad z_i(\mathbf{x}) \geq z_i. \qquad i = 1, \ldots, k-1 \end{aligned} \qquad [8]$$

It follows that the technical trade-off rate MRT_{ik} can be estimated with the shadow price, that is, the value of the dual variable associated with the ith criterion constraint (Steuer 1986). Denote the shadow price as s_i. Then the equation [7] can be rewritten as:

$$\begin{aligned} &w_i = -s_i \qquad i = 1, \ldots, k-1 \\ &w_k = 1 \end{aligned} \qquad [9]$$

To sum up briefly, the relative weights implied by a specific choice of criterion value combination can be estimated via the shadow prices that are related to the choice. This method of indirect weighting provides a basis for progressively approximating a DM's value function. It plays an important role in the interactive procedure described in the next section.

AN INTERACTIVE MOLP PROCEDURE

In this section we introduce an interactive MOLP procedure in which parametric programming alternates with the DM's evaluation of nondominated solutions. The procedure requires no direct assessment of subjective trade-off rates. Rather, it uses the method of backward induction of criterion weights to approximate a DM's value function progressively. The procedure is basically designed for the situations where an DM-analyst interaction is achievable and the DM can

assign priorities to the relevant decision objectives in advance of MOLP modeling;
choose between the tradeoff options available at a specific stage in the procedure; and
decide whether or not the procedure should terminate at that stage, and if not, which criterion should receive particular attention at the next stage (thereafter such a criterion is referred as to "parametric criterion").

To initiate the procedure, solve the identified MOLP problem via lexicographic Linear programming (LLP) in which the given priority rankings are interpreted as orders of preemptive optimization. If the preemptive solution fails to be endorsed by or acceptable to the DM, the procedure initiates its second stage. First, convert the LLP model to an equivalent LP by deriving criterion weights from the shadow prices associated with the initial solution. After that, conduct RHS parametric analysis to portray how the mix of criterion values varies as the attainment in a prespecified parametric criterion is incrementally varied over a wide range. Finally, present the resulting trade-off alternatives to the DM for evaluation and selection.

Unless all of the criterion values in the second stage choice are perceived satisfactory by the DM, one or more iterations are needed to explore the potential of beneficial trade-offs. The pattern repeated at each succeeding stage, if any, is as follows. First, update criterion weights via shadow prices that are related to the prior stage choice. Second, reduce the size of option space by imposing a lower-bound constraint to the attainment of the prior parametric criterion, in accordance with the previous stage choice. After those two steps, search over a subset of the reduced option space in the same fashion as in the second stage. Last, ask the DM to determine whether any of the newly revealed options is preferred to the prior stage choice. The procedure should be capable of converging on a most preferred solution in about k iterations, where k is the number of criteria.

AN NUMERICAL EXAMPLE

The interactive procedure is now illustrated with a MOLP model that is constructed using the data set available from Bottoms and Bartlett (1974). The original case study, covering an area of 9050 acres of the Colorado State Forest, is framed in a lexicographic goal programming (LGP) model. The LGP formulation includes nine objectives and a total of 35 land use options for six vegetative types. Its feasible region is defined by a number of constraints on budget level and available acreage for each land type, and, notably, the nutrition flowing relationships between various management activities. The list of objectives used in the illustrative MOLP model is presented in Table 1, along with the initially estimated ranges of criterion values.

Stage I:Lexicographic Optimization

Suppose the priorities which the DM assigned to the five land-use objectives are as follows:

Land-use objective	Priority ranking
max z_1	1st
max z_2	2nd
max z_3	3rd
max z_4	4th
max z_5	5th

Given this priority information, the five objective functions are optimized sequentially, in order of the rankings. Each succeeding objective is maximized subject to that the proceeded objectives must be achieved at the optimal levels previously determined. Mathematically,

$$\max\ (z_j(\mathbf{x}) \mid \mathbf{x} \in \mathbf{X},\ z_i(\mathbf{x}) \geq z_i^{(1)} \text{ for all } i < j)\quad j = 1, \ldots, 5,$$

where $z_i^{(1)}$ the optimum of the objective function in the ith LP model for i = 1, ..., 4. The resulting management plan $\mathbf{x}^{(1)}$ is characterized with the criterion value vector:

$$\mathbf{z}^{(1)} = (1919\quad 5371\quad 1985\quad 0\quad 443085)$$

Such a solution is typical of lexicographic linear programming (LLP). Elk and deer grazing, the top-ranked objective, is attained to its fullest possible extent, whereas several objectives at lower rankings are achieved at the levels that are quite close to the lowest possible values as indicated in Table 1. In particular, there will exist no camping service in the area if the management plan $\mathbf{z}^{(1)}$ is implemented.

Because of the lack of camping capacity, suppose the plan is not well received from the DM. Also assume that the DM wants information on how the objectives trade off against each other prior to determining the preferred visitor days of camping. This leads the interactive procedure to its second stage.

Stage II:Model Conversion and Parametric Analysis

Recall that $\mathbf{z}^{(1)}$ is obtained by solving the

Table 1.-- Objective functions and their ranges of possible achievements in the illustrative MOLP model

Land-use objective	Unit of measure	Lower bound	Upper bound
max z_1	A.U.M.	1200	1919
max z_2	A.U.M.	4100	8403
max z_3	MBF	1950	3237
max z_4	visitor day	0	21685
max z_5	dollar	433000	733121

where

z_1 = Elk and deer months of grazing;
z_2 = Steer and cow-calf months of grazing;
z_3 = Lodgepole and spruce-fir timber volumes;
z_4 = Recreation user days of camping; and
z_5 = Profits

complete LLP problem

$$\max\ (z_5(\mathbf{x}) \mid \mathbf{x} \in \mathbf{X},\ z_i(\mathbf{x}) >= z_i^{(1)}\quad i = 1, \ldots, 4)$$

Associated with $\mathbf{z}^{(1)}$ is the following set of shadow prices:

$$(-11125.96\quad -81.39\quad -46.79\quad -19.01)$$

From the technical trade-off information, it can be seen that only a few months of elk-deer grazing have to be given up to acquire significantly more of the outputs at lower ranks. For instance, if the scale of elk-deer grazing is decreased by one month one can expect that this loss would be compensated with the addition of about 586 (11126/19) visitor days of camping.

Based on these partial trade-off rates, the initial LLP model is converted to an equivalent, conventional linear program:

$$\max\ 11125.96\ z_1(\mathbf{x}) + 81.39\ z_2(\mathbf{x}) + 46.79\ z_3(\mathbf{x}) + 19.01\ z_4(\mathbf{x}) + 1.00\ z_5(\mathbf{x})$$
$$st\ \mathbf{x} \in \mathbf{X}$$

Once this model is formulated it can be used to trace out how the mix of outputs varies as the camping service is varied over its range of allowable scales. More formally, this RHS parametric analysis is to solve

$$\max\ 11125.96\ z_1(\mathbf{x}) + 81.39\ z_2(\mathbf{x}) + 46.79\ z_3(\mathbf{x}) + 19.01\ z_4(\mathbf{x}) + 1.00\ z_5(\mathbf{x})$$
$$st\ \mathbf{x} \in \mathbf{X}$$
$$z_4(\mathbf{x}) \geq \underline{z}_4 \qquad 0 \leq \underline{z}_4 \leq 21685$$

Eight solutions are generated from the parametric analysis (Table 2). Half of them correspond to the so-called extreme efficient points and half the nonextreme ones. As with the reaction from the DM, suppose up to this point, the locally preferred solution from the eight candidates is

$$\mathbf{z}^{(2)} = (1882\quad 5181\quad 1980\quad 12000\quad 439725)$$

If all outputs in $\mathbf{z}^{(2)}$ are satisfactory as perceived by the DM, the interactive procedure would end at this round, with $(\mathbf{x}^{(2)}, \mathbf{z}^{(2)})$ as the final solution. Otherwise, at least one more

Table 2.-- Stage II solutions as visitor days of camping varied over the range (0, 21685)

z_1	z_2	z_3	z_4	z_5
1919	5371	1985	0	443083
1904	5562	1981	*7955*	442163
1893	5369	1980	*10000*	440929
1882	5181	1979	*12000*	439723
1871	4993	1979	*14000*	438516
1860	4804	1978	*16000*	437310
1850	4632	1978	*17826*	436208
1803	4192	1978	*19608*	433856
1722	3920	1978	*21685*	432498

iteration is needed to make further improvements. Assuming the decision maker is willing to trade elk-deer months for cow-steer ones, let us turn now to the next stage.

Stage III:Model Updation and Parametric Analysis

At the outset of this stage, the previous weight vector $\mathbf{w}^{(2)}$ is replaced with $\mathbf{w}^{(3)}$. The latter is derived from the shadow prices associated with the second stage solution $\mathbf{z}^{(2)}$. Moreover, a portion of the solution set $\mathbf{X}$ is eliminated from further consideration via the side condition $z_4(\mathbf{x}) >= 12000$. The RHS value of this constraint is equal to $z_4^{(2)}$.

Altogether, the linear program used for the second-round RHS parametric analysis can be written as

$$\max\ 2646.07\, z_1(\mathbf{x}) + 15.93\, z_2(\mathbf{x}) + 96.84\, z_3(\mathbf{x}) + 16.73\, z_4(\mathbf{x}) + 1.00\, z_5(\mathbf{x})$$

$$st\ \mathbf{x} \varepsilon \mathbf{X}$$

$$z_4(\mathbf{x}) \geq 12000$$

$$z_2(\mathbf{x}) \geq \underline{z}_2 \qquad 3900 \leq \underline{z}_2 \leq 8403$$

A total of ten solutions are generated from the analysis (Table 3). Of them, four are extreme efficient solutions and the rest nonextreme ones.

Table 3.-- Stage III solutions as cow-steer months of grazing varied over the range (5180, 8403)

z_1	z_2	z_3	z_4	z_5
1882	*5181*	1979	12000	439725
1881	*5250*	1979	12000	440033
1881	*5350*	1979	12000	440484
1850	*5456*	1980	12000	440990
1821	*5550*	1980	12000	441438
1791	*5650*	1980	12000	441916
1760	*5750*	1980	12000	442394
1730	*5850*	1980	12000	442871
1699	*5950*	1980	12000	443349
1647	*6120*	1981	12000	444161

As to the choice made in this stage, suppose that in view of the revealed side effects, 5600 months of cow-steer grazing are considered favorable by the DM. The locally preferred solution then turns out to be

$$\mathbf{z}^{(3)} = (1805 \quad 5600 \quad 1980 \quad 12000 \quad 441677)$$

Also assume that as indicated by the decision

Table 4.-- Changes in criterion weights, problem formulations, and locally preferred solutions over the five iterations

Stage	Critetion weight/ranking	Stage LP model	Stage choice
I	$P_j >>> P_{j+1}$ $j = 1,\ldots,4$	$lex\ max\ \mathbf{z}(\mathbf{x})$ $st\ \mathbf{x} \varepsilon \mathbf{X}$	$z_1^{(1)} = 1919$ $z_2^{(1)} = 5371$ $z_3^{(1)} = 1985$ $z_4^{(1)} = 0$ $z_5^{(1)} = 443085$
II	$w_1^{(2)} = 11126$ $w_2^{(2)} = 81$ $w_3^{(2)} = 47$ $w_4^{(2)} = 19$ $w_5^{(2)} = 1$	$max\ \mathbf{w}^{(2)}\mathbf{z}(\mathbf{x})$ $st\ \mathbf{x} \varepsilon \mathbf{X}$ $z_4(\mathbf{x}) \geq \underline{z}_4$	$z_1^{(2)} = 1882$ $z_2^{(2)} = 5181$ $z_3^{(2)} = 1980$ $z_4^{(2)} = 12000$ $z_5^{(2)} = 439725$
III	$w_1^{(3)} = 2646$ $w_2^{(3)} = 16$ $w_3^{(3)} = 97$ $w_4^{(3)} = 17$ $w_5^{(3)} = 1$	$max\ \mathbf{w}^{(3)}\mathbf{z}(\mathbf{x})$ $st\ \mathbf{x} \varepsilon \mathbf{X}$ $z_4(\mathbf{x}) \geq z_4^{(2)}$ $z_2(\mathbf{x}) \geq \underline{z}_2$	$z_1^{(3)} = 1805$ $z_2^{(3)} = 5600$ $z_3^{(3)} = 1980$ $z_4^{(3)} = 12000$ $z_5^{(3)} = 441677$
IV	$w_1^{(4)} = 667$ $w_2^{(4)} = 199$ $w_3^{(4)} = 98$ $w_4^{(4)} = 17$ $w_5^{(4)} = 1$	$max\ \mathbf{w}^{(4)}\mathbf{z}(\mathbf{x})$ $st\ \mathbf{x} \varepsilon \mathbf{X}$ $z_4(\mathbf{x}) \geq z_4^{(2)}$ $z_2(\mathbf{x}) \geq z_2^{(3)}$ $z_3(\mathbf{x}) \geq \underline{z}_3$	$z_1^{(4)} = 1722$ $z_2^{(4)} = 5600$ $z_3^{(4)} = 2150$ $z_4^{(4)} = 12000$ $z_5^{(4)} = 478265$
V	$w_1^{(5)} = 548$ $w_2^{(5)} = 178$ $w_3^{(5)} = 100$ $w_4^{(5)} = 17$ $w_5^{(5)} = 1$	$max\ \mathbf{w}^{(5)}\mathbf{z}(\mathbf{x})$ $st\ \mathbf{x} \varepsilon \mathbf{X}$ $z_4(\mathbf{x}) \geq z_4^{(2)}$ $z_2(\mathbf{x}) \geq z_2^{(3)}$ $z_3(\mathbf{x}) \geq z_3^{(4)}$ $z_5(\mathbf{x}) \geq \underline{z}_5$	$z_1^{(5)} = 1700$ $z_2^{(5)} = 5600$ $z_3^{(5)} = 2150$ $z_4^{(5)} = 12000$ $z_5^{(5)} = 490000$

maker, additional efforts are needed to examine whether or not it is sensible to let timber production and profit fare better.

The interactive procedure arrives at its termination after two more stages are completed. These iterations are carried out in the same fashion as in the third one. A summary is given in Table 4 to highlight the connections between the five stages.

CONCLUSION

In this paper we have proposed a procedure for solving multiple objective linear programming problems in a context of decision maker-analyst interaction. The procedure has two distinguishing features, namely, backward induction of criterion weights using shadow prices and illumination of trade-off implications using RHS parametric analysis. The procedure's main advantages are threefold. First, it requires no direct assessment of criterion weights; the use of shadow prices allows the weights to be induced from observed choices of a decision maker. Second, it enables the decision maker to be well informed of how the concerned objectives trade off against each other, prior to setting the aspiration level for a specific criterion. Third, it permits the decomposition of a complex multi-parametric programming model into a series single-parametric analysis problems and hence is relatively easy to use. For such, the procedure should represent a viable way of using optimization techniques to provide "what-if" insights for decision making in forestry and other areas.

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THE EFFECT OF UNCERTAIN PRICES ON STAND DENSITY AND ROTATION LENGTH DECISIONS[1/]

Lawrence Teeter and Greg Somers[2/]

Abstract.--A method is presented that uses stochastic dynamic programming and distributions of expected future stumpage prices to determine optimal thinning strategies and rotation lengths for stands established at various densities. Optimal management decisions determined using this model are compared to decisions obtained using a similar, deterministic pricing method.

Keywords: Stochastic dynamic programming, Markovian prices, optimal harvest strategies

INTRODUCTION

A complex decision faced by forest managers involves determining optimal stand densities at given points in time. Stand density or stocking level is a relative concept that embodies knowledge of the stand's age, the number of trees per acre and their size, and management objectives. As trees grow, their rate of growth is affected by their proximity to other trees, all of which are competing for limited site resources. One goal of forest management is to manipulate stand density in such a way as to maximize stand value.

Foresters know that stumpage prices determine the value of their timber. They also generally believe that future prices should play a role in developing a strategy for managing standing timber. For example, if future prices for sawtimber (per cubic foot) are expected to be high relative to future prices for pulpwood, it may make sense to let a young stand containing only pulpwood size material grow and mature into higher valued products. The uncertainty of future prices makes this a difficult problem. In addition, the large number of potential stocking states that a stand may pass through on its path to maximum profitability makes determining an optimal density management strategy very complex.

Traditionally, forest economists have used constant prices and deterministic methods to evaluate alternative thinning and final harvest decisions. However, since timber prices vary over time, deterministic methods may not be providing enough information to forest managers. The method described here uses dynamic programming and a distribution of expected future prices to determine the effect of uncertainty on the stand density management decision.

Hool (1966) was the first researcher to use dynamic programming (DP) to address the issue of risk in forest management. He modeled stand growth as a Markov process. Lembersky and Johnson (1975) and Lembersky (1976) also used Markovian relationships to model forest growth and productivity. In Lembersky and Johnson (1975) different future prices for timber were associated with scenarios of better or worse markets for lumber products in the future. Kao (1982, 1984), also incorporated risk elements in his DP models, but the research focused on biological risk and did not incorporate the risk associated with uncertain future prices.

METHODS

Our method provides a means for evaluating a large number of potential forest stocking situations managed through thinnings and final harvests. Potential thinning levels vary from 30 to 100 sq. ft. of basal area/acre (BA) provided that sufficient stand volume exists and the residual BA is at least 70 sq. ft/ac. Final harvests are an option at any time when the expected gain from waiting for additional value growth is not a profit maximizing decision.

[1/]Presented at the Systems Analysis in Forest Resources Symposium, Charleston, SC, March 3-6, 1991.

[2/]Assistant Professors of Forestry, Auburn University and Alabama Agricultural Experiment Station, Auburn, AL.

Although the constraints on thinnings may appear somewhat arbitrary, they are supported by common practice on industry managed lands in much of the South.

Data

Information used to analyze this problem consists of simulation results generated by WTHIN, a loblolly (Pinus taeda L.) pine growth and yield simulator developed by Cao, Burkhart and Lemin (1982), time-series statistics for southern pine stumpage sold on National Forests from 1950-1987 (Ulrich 1989), and planting cost estimates developed by Borders et al. (1991).

WTHIN was developed using data from 128 permanent plots in the Virginia Piedmont and Coastal Plain. Subsequent to its initial release it was modified and re-released as a PC-based growth and yield simulator called PCWTHIN. Forecasts from this model have been used to support numerous analyses of forest management activities in recent years. The model allows an analyst to characterize a stand by its age, site index, and either the number of trees per acre, the basal area per acre or both. Four thinning options are available: no thinning, row thinning, low thinning, and row thinning followed by low thinning. For the purposes of this study, first thinnings were assumed to be row thinning followed by low thinning to provide equipment access to the stand. Subsequent thinnings were low only.

Sawtimber stumpage prices were treated as stochastic and assumed to follow a first-order Markov process. Current prices are known, but the future prices necessary to evaluate the effects of a current year management decision are uncertain. According to Markov theory, the probability that price in a Markov model will move from a current state S_i to some future state S_j depends only on state S_i. Transition probabilities P_{ij} give the probability that a process will move from state S_i to S_j in one step (or time period) and must be determined for every ordered pair of states S_i, S_j.

Thirty-seven years of mean annual stumpage price data expressed in constant 1967 dollars (Figure 1) were used to develop the following model for expected (mean) price (t-statistics in parentheses):

[1] $$P_{t+1} = \underset{(2.37)}{12.376} + \underset{(5.88)}{.70731}\, P_t + e_{t+1}$$

Durbin-Watson d = 1.81

The magnitude of the t-statistic for the price coefficient is significant at the 0.001 level and indicates a strong Markovian structure for sawtimber stumpage prices. On a regional basis, the real price of pulpwood showed very little variation over the same 37 year period. For that reason, pulpwood prices were considered as constants in this analysis.

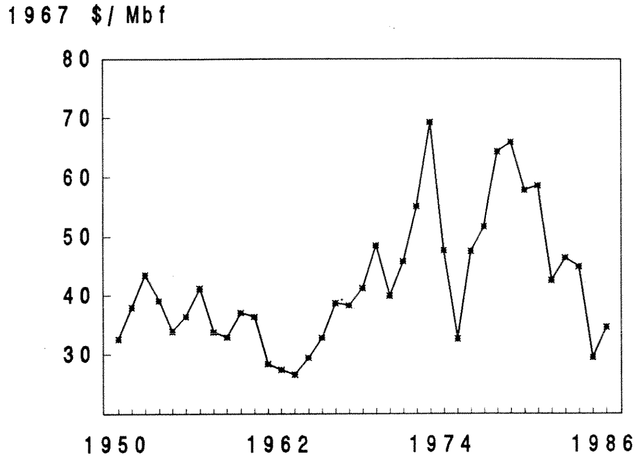

Figure 1 --Price trend for National Forest pine sawtimber stumpage in the South, 1950-1986.

The DP Model

A stochastic dynamic programming model based on annual decision intervals was specified and solved to determine optimal stocking levels. Thinning was considered to be an option at any time when stand basal area exceeded 100 sq. ft./ac. Variables used to characterize the state of the management system included: 1) stems per acre, 2) basal area, 3) current price for sawtimber, and 4) whether or not the stand had been previously thinned.

The general recursive relationship describing this system is:

[2] $$V_t(T_t, B_t, C_t, P_t) = \underset{D}{MAX}\left[\pi(T_t, B_t, C_t, P_t, D) + \beta \underset{P_{t+1}}{E}\, V(T_{t+1}, B_{t+1}, C_{t+1}, P_{t+1})\right]$$

Where:

- V_t = Expected present value of following the optimal policy from stage t to rotation age
- T_t = Trees per acre at time t
- B_t = Basal area per acre at time t
- C_t = 0-1 variable indicating whether a stand has been previously thinned
- P_t = Sawtimber price at time t
- MAX = Maximization operator
- D = The set of available thinning intensities
- π = Immediate net returns which depend on T_t, B_t, C_t, P_t, and D
- β = A discounting factor
- $E_{P_{t+1}}$ = A conditional expectations operator

Immediate returns include the value of pulpwood material harvested (assumed to have a fixed price of $6.67/cd [1967]). Equally spaced price intervals between $40/Mbf and $70/Mbf (1967) were used to represent sawtimber price variation. A price state transition probability matrix was constructed using an adaption of the method developed and described by Taylor (1984). The adaptation is required to fit the cumulative distribution for the errors (e_t) obtained from the OLS equation (Equation 1) for estimating P_t given P_{t-1}:

$$[3] \quad F(e_t) = .5 + .5 \tanh(.001961 + .114448\, e_t)$$

Combining (3) with (1) above yields the conditional cumulative probability distribution for sawtimber stumpage price:

$$[4] \quad F(P_{t+1} | P_t) = .5 + .5 \tanh(.001961 + .114448(P_{t+1} - 12.376 - .70731\, P_t))$$

Figure 2 graphically represents the state transition probabilities $[P_{i,j}]$ for a current price of \$40 (a) and \$70 (b) for the next two years.

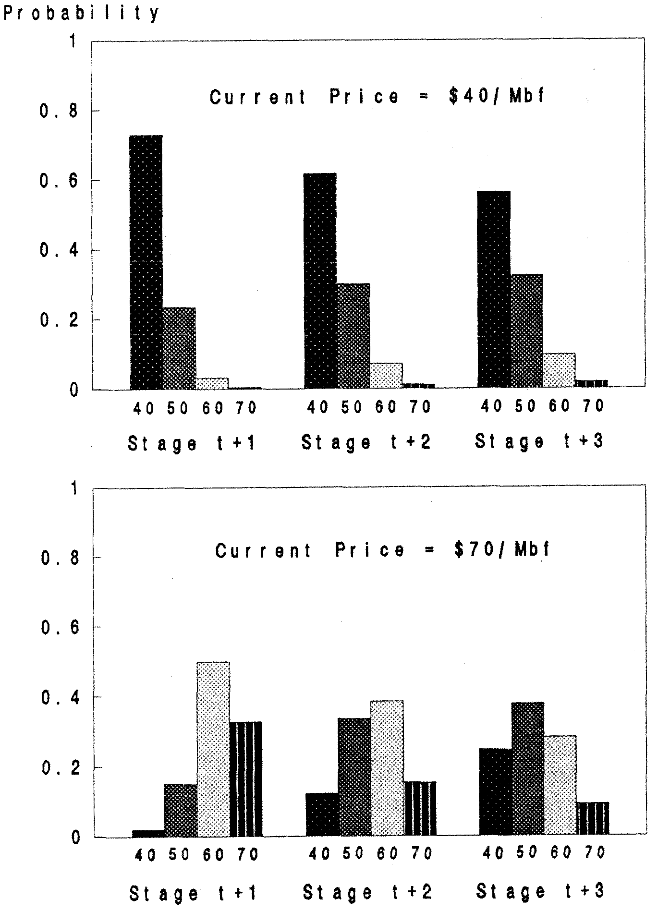

Figure 2 --Price state transition probabilities for two levels of current price and 3 future stages. In the top panel, given an initial price of \$40/Mbf, the probability of remaining at the \$40 level decreases as we look ahead 1, 2, or 3 stages. The probability of moving to either of the higher price states increases as we look ahead in time. A similar interpretation can be used for the probabilities represented in the bottom panel.

RESULTS

We limited our analysis by evaluating only one productivity class of land (SI 60_{25}) and using a single interest rate (6 percent). Regarding the state variables, the model considered basal area states from 70 to 170 sq. ft./ac. in 2.5 sq.ft. intervals, stems per acre ranged from 130 to 800 in 2.5 tree intervals, and sawtimber price ranged from \$40/Mbf to \$70/Mbf (1967) in \$10 intervals. Removals could be made in increments of 5 sq. ft. of basal area with a minimum removal level set at 30 sq.ft. and a minimum residuals level set at 70 sq.ft.

We compared results of the stochastic model (Equation 4) with results from using the deterministic equivalent (Equation 1 without the error term) to determine the effect of incorporating risk in the establishment and rotation decision. Figure 3 shows the NPV's that can be expected for a range of initial planting densities according to each model. Given our assumptions and these results, it appears that deterministic and stochastic methods can be used equally well to indicate profit maximizing early densities. NPV estimates, however, are approximately 20 percent higher using the stochastic model.

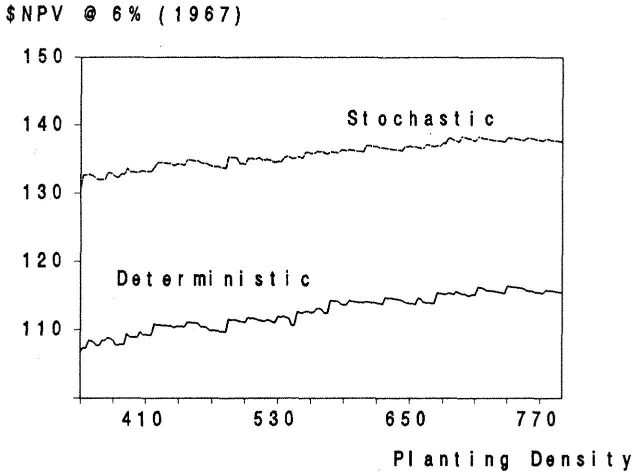

Figure 3 --Net present values associated with a range of initial planting densities for the stochastic and deterministic models. Return estimates account for differences in planting costs for different densities, \$100/ac site preparation costs and a 6 percent discount rate.

Although optimal planting densities can be determined using either model, planting is only one aspect of the density management problem. In fact, according to these results, the planting density decision does not seem to be very important. When the timing and intensity of intermediate and final harvests are optimal, NPV only varies about 5 percent and 3 percent respectively for the deterministic and stochastic models over a common range of planting densities (500-800).

However, the timing and intensity of intermediate and final harvests are important to gaining optimal NPV, and these can be quite different for the two models. Using deterministic methods, an analyst explicitly or implicitly specifies prices for future periods, and on the basis of that specification determines if a particular planting, thinning, and final harvest prescription is more profitable than another under the same assumptions. Determining the optimal set of harvest decisions for managing a stand from planting to rotation can be formulated as a straightforward dynamic programming problem if the analyst is willing to specify future product prices. Because particular price states are not known for future stages in the stochastic model, outlining the appropriate density management strategy from establishment to rotation would be problematic. At best, an analyst can make statements about the probability of being in a particular state in a future stage, and the density management decisions that should be made in that state to maximize expected NPV.

It is important to understand, however, that the stochastic model does determine the amount to thin at a given state and stage that will maximize expected NPV, and that the decisions required to obtain the maximum may differ from those found using the deterministic model. To try and assess some measure of the importance of considering stochastic prices when making these decisions, a test was developed that compared cut decisions prescribed by the deterministic model to decisions made using the stochastic model at the same state/stage combinations.

For example, Table 1 shows optimal cut decisions determined using each model for identical state combinations. The first entry for each pair represents a decision to thin a stand at age 24 that has 245 trees/acre, 110 sq.ft. of basal area/acre, and has not been thinned. For that combination of state variables, each model recommends the same thinning decision i.e., to remove 40 sq.ft. of basal area.

The second entry for each model represents the optimal decisions for a stand characterized as previously thinned and age 26, with 135 trees/acre and 88 sq.ft. of basal area/acre. According to the deterministic model, it is optimal to clearcut the stand at this stage. However, the stochastic model does not prescribe a final harvest at 26. The expected value of that decision (not to cut) is $534 and can be compared with an expected value of $442 associated with the final harvest decision of the deterministic model. This difference occurs because the stochastic model has determined that the expectation for returns from potential future decisions is greater at the next stage than the decisions evaluated using the deterministic model. Of the state combinations that resulted in positive cut decisions using the deterministic model (~120,000 "thins" and "final harvests"), approximately 25 percent were not matched using the stochastic DP method.

Table 1.--Example cut decisions for identical state combinations using the deterministic and stochastic models.

Deterministic Future Prices

AGE	TPA[a/]	BA[b/]	THINNED?[c/]	AMOUNT CUT[d/]	NPV@6%
24	245	110	1	40	$498
26	135	88	2	88	$442

Stochastic Future Prices

AGE	TPA[a/]	BA[b/]	THINNED?[c/]	AMOUNT CUT[d/]	NPV@6%
24	245	110	1	40	$598
26	135	88	2	0	$534

[a/]TPA = Trees/ac.
[b/]BA = Sq.ft. of basal area/ac.
[c/]Not previously thinned = 1; previously thinned =2
[d/]Cut amount in sq.ft. of basal area/ac.

DISCUSSION

Even on the basis of these somewhat limited results, it appears that incorporating risk in the stand management decision can affect the choice of an optimal strategy. Forest economists have generally ignored risk when evaluating the economic implications of different management strategies. This may be a harmless simplification when initial planting density is the only problem at hand. However, when the decision is whether or not to thin, how much to thin, or when to conduct a final harvest, a stochastic model will often indicate a different profit maximizing strategy than a deterministic model.

Although conclusions drawn from this study about the effects of including stochastic prices in an evaluation framework seem robust, strategies obtained by this study regarding the most profitable initial densities and rotation lengths may not be widely applicable for several reasons. This study looked at only one productivity class of land. Yields projected by WTHIN are based on data obtained from old-field plantations and may not be representative of the yields that can be expected on other types of sites. In particular, the projections are probably weakest for very low initial densities (below 400 trees/acre) since few plots with low tree counts were included in the original data. Finally, this study used a sawtimber price model based on sawtimber sold from U.S. National Forests in the South. Other price series may be more appropriate for modeling the effect of stochastic prices on the management of privately owned timberlands.

The purpose of this study was not to provide prescriptions for management. The purpose was to demonstrate how a stochastic model can be used to determine optimal density management strategies and how those strategies may differ from decisions obtained from an equivalent deterministic model. Because stochastic models embody more of the information contained in price series data, they should do a better job of providing profit maximizing thinning decisions than their deterministic counterparts.

Important areas for future research include: developing models of future price based on other price series (possibly Timber Mart South data) and incorporating them into the DP framework, assessing the effect of changing the interest rate or site index on thinning and final harvest decisions, including the effect of stochastic pulpwood prices in the model, and evaluating the effect of altering merchantability standards or incorporating quality premiums for timber in certain size classes.

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EVALUATION OF SILVICULTURAL INVESTMENTS UNDER UNCERTAINTY USING SIMULATION[1]

William A. Thompson and Ilan Vertinsky[2]

Abstract.--The long-term nature of silvicultural investments presents a variety of difficulties to their evaluation. One of these difficulties is the uncertainty associated with long-term relationships and parameters of the economic environment. A second difficulty is the involvement of multiple stakeholders with different and sometimes conflicting objectives. Simple optimization models rarely address these difficulties in an environment where preferences themselves may change over time. We have developed a methodology which uses a simulation model and system-oriented indices of performance to evaluate silvicultural investments. The simulation model captures both spatial elements and long-term dynamics of the biological, social and economic systems. The evaluation indices include both traditional measures which reflect the preferences of multiple stakeholders and considerations of equity, and innovative ecologically-oriented indices of biological, social and economic resilience. In this paper we describe the model and indices and present an application to reforestation problems in British Columbia.

Keywords: silvicultural investments, uncertainty, risk, conflicting objectives, resilience

INTRODUCTION

One of the major challenges to evaluating silvicultural investments is the uncertainty of the returns. While this uncertainty is almost universally recognized by foresters, there is no standard approach to incorporating risk into formal investment analyses of silvicultural investments. In part this lack of methods is a result of the multiplicity and variety of risks inherent in long-term silvicultural investments and the fact that silviculture often involves substantial public investments.

Decision situations involving risk can be divided into two qualitatively different classes which merit significantly different approaches: structured problems and unstructured problems (Mason and Mitroff 1973). Structured problems are those for which the possible outcomes from a given action and the state of the world are known. Risk is involved in such problems when the relationship between an action and its outcome cannot be defined with certainty, but rather with a probability distribution. Structured problems include both those for which the probability distribution is known and those for which it is not known at present, but could in principle be found given adequate data. Unstructured problems are those for which the outcomes from an action and the state of the world are unknown. Consequently, the relationship between action and outcome cannot be known in advance.

Both structured and unstructured problems arise in silvicultural decision-making. Many routine sivicultural choices involve alternatives whose outcomes are well understood, particularly at the individual stand level where objectives are usually well defined. However, many silvicultural decisions, especially those involving long-term investments, are unstructured. Significant risks arise from biophysical, economic, social and political uncertainties. The biophysical uncertainties are associated with our inadequate knowledge for predicting what the future forest will be for a given set of management inputs. These are augmented by our uncertainty about future environmental conditions. Economic uncertainties arise from our inability to accurately forecast future production costs and product values. The relatively inelastic short-term demand for many forest products means high variability in prices when even small shifts in supply occur. Longer-term impacts on costs and prices can result from technological changes and shifts in demands for forest products. Social and

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[2] Research Associate and Director, respectively, Forest Economics and Policy Analysis Research Unit, University of British Columbia, Vancouver, B.C., Canada.

political uncertainties follow from changes in social values and from the involvement of multiple stakeholders with different and sometimes competing objectives. We do not know what forest products the future society will value. A current example is the rapid shift in social and political value given to forest preservation, either for its own sake, for recreation, or for other benefits.

These sources of uncertainty and the challenges of managing for multiple objectives require a substantially different framework for risk assessment and management than the conventional one. We have been developing such a framework (Brumelle *et al.* 1990, 1991). In this paper we present our preliminary attempts to apply it to an analysis of reforestation investment policy in British Columbia.

FRAMEWORK FOR RISK ANALYSIS

Central to our framework for analysis of unstructured problems is the concept of resilience (Holling 1981, 1984). Balancing stability with variability, a resilient system adapts to change. Thus it maintains low vulnerability to catastrophe by virtue of its multiple options for adaptation. Management practices intended to maintain or increase resilience include those design to maintain (or create) variability and diversity, learning through experimentation, structural flexibility and slack.

Maintenance of variability and diversity not only provides options for adaptation to new environmental conditions, but also keeps open options to respond to new demand patterns and to exploit new technologies. We will be concerned in this study with measures of forest diversity. Learning depends upon an explicit attempt to gather new information and to translate it into management practice. While we do not explicitly consider the costs and benefits of learning, we do allow such passive experiments as those performed by natural disasters, i.e., large-scale forest destruction by fires or insects. Structural and managerial flexibility in silvicultural policy is required to meet the challenges of multiple stakeholders with multiple objectives for forest resources. In the socio-political realm, resilience depends upon decision processes and abilities to compensate groups when changes are introduced to the system. These concerns are not the subject of this paper, except in that obtaining monetary earnings from the forest and maintaining monetary reserves permits more flexibility in meeting disasters. Finally, slack, i.e. reserve resources, creates the potential for coping with unexpected problems. However, slack must be distinguished from inefficiency. The distinction is that slack is a reversible 'inefficiency', thus providing an operational safety margin.

In this study we employ a simulation model to project the consequences of alternative silvicultural investment policies under each of several different scenarios of future environmental, economic and social developments. The model, which was developed for the British Columbia's Ministry of Forests (hereafter, the Ministry), projects the forest inventory and timber harvest for a forest area, given specifications of the economic parameters, forest protection, silviculture strategies, harvest targets, priorities, and constraints (Phelps *et al.* 1990). These management specifications can be varied and the effects of different combinations of practices on the inventory and timber yield can be examined. The projected outcomes can then be used to evaluate alternative programs of silvicultural investments.

Comparisons of projected outcomes will be made on eight measures for each of three provincial regions (see below). Two measures of diversity are computed: diversity over forest age classes and diversity over species. Both diversity indices are computed using the Shannon-Weaner information index and divided by a constant to limit the index to range from 0 to 100. Explicitly

$$\text{Diversity} \doteq -100 \sum_{i=1}^{n} f_i \log_2 f_i / \log_2 n \qquad (1)$$

where n is the number of classes and f_i is the fraction of the forest in class i. The third resilience indicator is the percentage of old growth forest remaining after two hundred simulated years. For the purposes of this study, 'old growth' refers to all forests aged 120 years or more. This definition was necessitated by limitations of the model for projecting outcomes (see below). The remaining five measures, all of which focus on commercial timber production, are: average annual harvest volume; average forest employment (includes indirect and induced employment from commercial forestry activities); and net present value (NPV) of timber production over two hundred years at each of the three discount rates -- 2, 4, and 6 percent.

SCENARIOS

In this analysis we compare the performance of four silvicultural investment policies under four scenarios of the future environment (summarized in Table 1). The first scenario (BASE) is a simple projection of past trends. This scenario includes the following assumptions: environmental conditions will not change; log prices will increase one percent per annum (net of inflation); and the commercially available forest land base will not change. The other three scenarios each alter one of those assumptions. The second

Table 1.--Scenarios

Scenario	Fire Frequency	Log Price Trend	Old Growth Harvest
BASE	Historic rates	1% per annum	No restrictions
FIRE	Twice historic rates	1% per annum	No restrictions
PRICE	Historic rates	0% per annum	No restrictions
OLD GROWTH	Historic rates	1% per annum	50% of area removed from harvestable land base

scenario (FIRE) assumes that changes in environmental conditions and recreational use of the forests will result in a doubling of the number of forest fires in the province. The third scenario (PRICE) assumes that demand for wood products will stagnate, leaving log values constant at the current prices. The fourth scenario (OLD GROWTH) assumes that one half the old growth forest will be removed from the commercially available forest land base to satisfy the demands for nontimber forest uses.

MANAGEMENT OPTIONS

Four different silvicultural policies are to be compared. They differ in their investment in the following three classes of silvicultural activities: basic silviculture; backlog not sufficiently restocked (NSR) land rehabilitation; and incremental silviculture. Basic silviculture refers to the class of silvicultural activities undertaken to reforest a site following harvesting or other forest destruction. In British Columbia the timber harvester is required by law to satisfactorily reforest the cutover land. This is done about half the time by planting seedlings and half by natural regeneration. Various site preparation methods are employed as required by individual circumstances. The alternative to basic silviculture is no treatment following harvest. This often results in a delay of several decades before a new forest becomes established. Backlog NSR land rehabilitation refers to the reforestation of lands which were not successfully reforested in the past. The reestablishment of commercially valuable species on these lands is the responsibility of the Ministry. Major public expenditures are planned over the next ten years to return the better quality sites on these lands to the commercially available forest land base by brushing and planting. The alternative to backlog NSR land rehabilitation is to do no treatment, allowing these lands to follow a slower, natural succession, and leaving them out of the productive forest land base. The third silvicultural class, incremental silviculture, refers to forest tending and enhancement activities intended to improve the growth and/or commercial value of already established forests. In this analysis we will restrict that definition slightly to include only precommercial thinning, pruning and fertilization undertaken on young stands, that is from ages 10 to 40 years.

The first silvicultural policy considered is the current policy (CURRENT). Basic silviculture would be practiced on all harvested lands and the good and medium quality sites of backlog NSR lands would be reforested over the next ten years (i.e., by the year 2000). Reforestation programs to restore forests destroyed by logging, fire, insects and disease have been given high priority in British Columbia. Elimination of the accumulated backlog of better quality NSR land was given high priority in the recent inter-governmental forestry program (FRDA program, Canada - British Columbia 1985). The objective was to ensure that the reforestation effort on lands logged or otherwise denuded was sufficient to ensure no increase in the NSR backlog and to eliminate the backlog through specially directed rehabilitation effort over the forthcoming 20 years (Ministry of Forests 1988). The rehabilitation programs over the past five years have been highly successful in meeting their objectives and the Province expects to complete the rehabilitation of all medium and good backlog NSR sites by the year 2000 (Ministry of Forests 1990). Based on the Ministry's most recent Annual Report (1989), we estimated the cost of this reforestation effort as $560 million, i.e. $56 million per year for ten years.

The second silvicultural policy (NOSILV) assumes that no silviculture would be practiced. This policy is inconsistent with present Ministry regulations and provincial law. The third policy (BASIC) assumes that only basic silviculture would be practiced. This is the minimum silvicultural investment that is consistent with current regulation and law. The fourth policy (INCREM) assumes that incremental silviculture rather than backlog NSR rehabilitation would be practiced in B.C. The area to be treated under this policy was determined by assuming a constant annual expenditure of public funds at half the rate of the proposed expenditures on backlog NSR reforestation, i.e., $28 million per year.

The four silviculture policies are summarized in Table 2. As indicated there, a key difference between the scenarios is the difference in cost. The NOSILV policy is the least expensive, as it involves no expenditures on silviculture. The BASIC policy requires significant expenditures by the private sector, those expenses being roughly proportionate to the area harvested. The remaining two policies, CURRENT and INCREM, require significant investment of public funds in addition to the private costs of basic silviculture.

Table 2.--Silvicultural policies

	Class of Silvicultural Activities			Annual Cost (million $)[a]	
Policy	Basic	NSR	Incre-mental	Private	Public
CURRENT	Y	Y	N	330	56[b]
NOSILV	N	N	N	0	0
BASIC	Y	N	N	327	0
INCREM	Y	N	Y	328	28

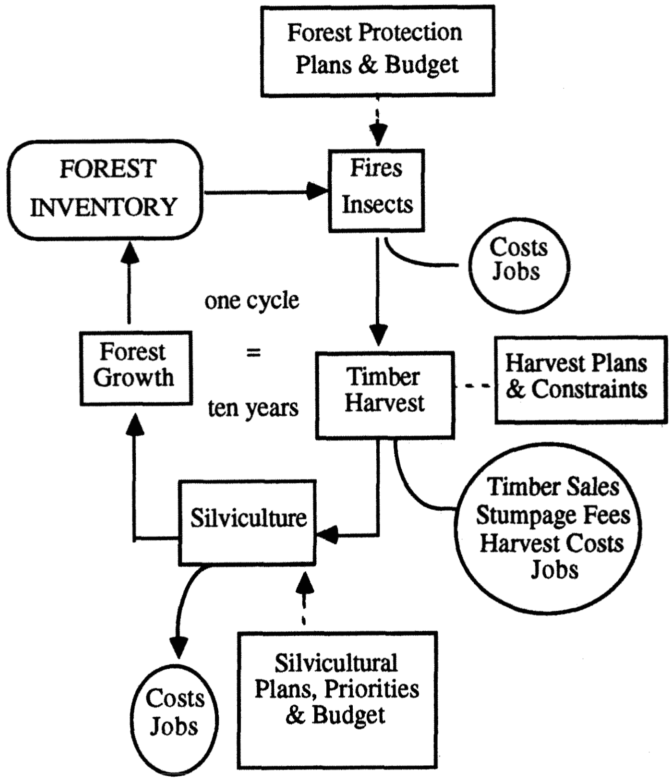
[a] Costs are for the BASE scenario. As the area to be treated with basic silviculture depends upon the harvest, the cost will differ between scenarios.
[b] Only for the first ten simulated years; 0 thereafter.

In the remaining sections we present a description of the simulation model used to project returns, and draw conclusions regarding silvicultural investment programs in British Columbia.

THE SIMULATION MODEL

The model structure is depicted in Figure 1. Its basic elements are briefly described here (for detailed information and data see Phelps *et al.* 1990a,b).

Figure 1.--Flowchart of the British Columbia Silviculture Planning model.



The forest inventory used in the model is that for the forest lands of British Columbia regulated and administered by the Ministry as Tree Farm Licenses (TFLs) and Timber Supply Areas (TSAs). Areas which are not commercially viable, including inaccessible areas, noncommercial tree species and problem forest types, have been excluded from the productive and available forest land base. The "potentially productive, available and suitable" area modelled is 64 percent of the available forest land (Ministry of Forests 1984). It covers 22.1 million hectares (excluding deciduous sites). It is classified by region, predominant tree species (known as 'growth type'), site quality, past silvicultural treatment, harvest cost class, and age class in our data base.

This land has been divided into three forest regions, aggregations of the Ministry's administrative regions. These are: *Coast*, which combines the Vancouver region and the small coastal part of the Prince Rupert region; *Northern Interior*, which includes the Prince George region, the interior part of the Prince Rupert region, and the small northern part of the Cariboo region; and *Southern Interior*, corresponding to the Kamloops, Nelson and the remainder of the Cariboo regions.

Within each region, forest types were aggregated into six *growth types*, designated by the dominant species. However, the "deciduous" type was excluded from this study because deciduous species have historically commanded little or no value and little is known about their silviculture. The remaining five growth types are: (Douglas) fir, cedar, hemlock, balsam (true firs) and spruce for the Coast region; and (Douglas) fir, cedar plus hemlock, pine, balsam (true firs) and spruce for each of the Interior regions.

Growth types were further subdivided into three *site qualities*: good, medium and poor. On better sites, volume growth is faster, and the timber sells for a higher price per cubic metre because of the larger dimensions of the trees. Differences in *harvest cost* arising from distance from forest lands to mills and difficulty of terrain were accounted for by further dividing lands into 'low' and 'high' harvest cost classes, with lower operating costs for 'low' lands.

The forest inventory is divided into 16 *age classes*. Twelve represent 10-year age classes, from 0-9 years to 110-119 years. All stands 120 years and older are included in a single "old-growth" class and are assumed to have ceased growing. Two other classes represent land on which forest regeneration has been delayed for such causes as insufficient seed, destruction by wildlife or competition from weeds. One of these categories is assumed to progress into the first real age class in one decade, the other category in two.

The final "age class" consists of the lands classified as backlog NSR. These lands have been deforested (either from timber harvest or natural disaster such as fire or insect pest) and have remained unsatisfactorily restocked for longer than the acceptable regeneration period; and they are expected to remain unsatisfactorily restocked for many years unless they are artificially rehabilitated.

The model projects the inventory by decades, calculating the changes due to timber harvests, natural losses, regeneration, and stand improvement. In addition, age classes are advanced. Forest growth is accounted for by volume-age relationships which are specific to each combination of region, growth type, site class and treatment category.

The model dynamics and outputs are determined by five program modules: protection, harvest, silviculture, economics, and growth.

<u>Forest Protection</u>

The protection submodel calculates losses of forest area caused by fire and insect pests. A fraction of the losses are available for salvage; the remainder is divided between the age-0, regeneration delay and NSR backlog classes. Some insect pests destroy the current decade's growth but do not kill the trees.

Fire and insect losses depend upon age, region and growth type. These are determined by baseline parameters, which were calculated from aggregated historic data for the Province's forest regions. These prospective, baseline loss rates are modified by regional budget allocations for monitoring and control. Annual losses from fire and insects are quite variable, differing by a factor up to 10 between years. While losses often exceed the timber cut, they are not distributed evenly over the province; over ninety percent are in the Interior.

<u>Timber Harvest</u>

The harvest submodel determines the classes of forest to cut based on the current state of the forest land base, a target volume to harvest (annual allowable cut, henceforth called AAC), and a user specified set of cutting priorities and constraints. Both clear cuts and selective cuts are available options. The latter is applied only to Douglas fir in the Southern Interior. Harvest priorities and constraints include: maximum fraction of cut to be taken from salvage (25%); minimum volume per hectare (150 m^3/ha for Coast and Northern Interior; 100 m^3/ha for Southern Interior); minimum age and cutting cycle for selective cut (age 100 every 20 years); and priority of cut within growth type (lowest cost first). The AAC target annual harvest was set to 70 million m^3, which is close to the current annual harvest from Provincially regulated lands.

Silviculture

The silviculture submodel provides the framework for exploring the implications of alternative silvicultural programs. Four silvicultural options are distinguished in the model: (1) 'No treatment' - harvested land is allowed to regenerate naturally without any intervention; (2) 'Basic' - appropriate treatment to ensure successful regeneration of commercial species on the site; (3) 'Incremental' - spacing and in some cases fertilizing and/or pruning of young stands (age 10-40 years); and (4) 'Backlog NSR' - clearing, site preparing and planting of backlog NSR lands. The 'No treatment' option (1) is unacceptable under current Ministry regulations, and is only included for comparison with 'Basic' silviculture. The latter (2) is defined by Ministry standards and must be implemented on all clearcut forest land regulated by the Ministry. The treatments which comprise 'Basic' silviculture vary with individual site conditions, but include site preparation, natural regeneration and planting. A mix of these treatments, distinct for each land class, is incorporated in the model . Like Basic silviculture, Incremental silviculture (3) and backlog NSR rehabilitation (4) are each defined in terms of a specific set of treatments, distinct for each land class.

For each silvicultural option we assumed an average mix of treatments in terms of their frequency, costs, effects on stand age-volume relationship, and effects on timber age-value relationship (Smith 1989). Costs were accounted in terms of both money and labour. Constraints were imposed by a limited silvicultural budget. Priorities for treatment of land classes were based upon silvicultural objective (see silviculture strategies, below). Consequences of silvicultural activities were changes in frequency of successful stand establishment, in growth rate (i.e., volume-age curve), in timber value (i.e., value-age relationship), and in recovery of backlog NSR land to productive status.

Economics

The economics submodel calculates the financial costs of and returns from the simulated management activities, employment levels, and value measures of the forest estate. The results of these calculations are used both to implement cost, net return and labour constraints on forest protection, harvest and silviculture, and to provide primary outputs of forest management performance.

Gross revenue from harvest for each land class is calculated as the volume of timber harvested times the specific price for that class of timber. Timber prices depend upon species and mix of log grades, which is modelled implicitly as a function of region, growth type, stand age, site quality and past silvicultural treatment. For a given log volume, price increases and delivered wood cost decreases with stand age, reflecting the larger average log size in older stands. Tables of log prices and wood costs for each forest land class were developed from Vancouver log market data and published reports (Nawitka 1987; Sterling Wood 1988, 1989; Williams 1987; Williams and Gasson 1986, 1987). For further details of log prices and harvest costs see Thompson *et al.* (1991). Stumpage values are calculated according to the Ministry's current practice. Regional 'permanent' employment was calculated as directly proportional to volume harvested, with different proportionality constants for the Coast and Interior reflecting differences in labour productivity between regions. Indirect and induced employment within British Columbia were calculated as 1.1 man-years per man-year of direct employment (Jacques and Fraser 1989). Inter-regional indirect or induced employment effects were ignored. Regional 'temporary' employment was direct employment in forest protection and silviculture during the period (e.g., fire fighting, tree planting).

Forest Growth

For each forest land class (region, growth type, site quality and silvicultural treatment class) the model has a volume-age relationship. These specify the average volumes of merchantable timber per hectare for each age category of the given forest land class. The relationships for naturally regenerated stands were developed by aggregating Provincial data for all the TSAs in B.C. Mean annual increments ranged from 1.2 cubic metres per year for Douglas fir on poor sites in the Southern Interior to 12.5 cubic metres per year for Sitka spruce on good coastal sites. These mean growth rates are realized if stands are harvested when the annual increment equals the mean annual increment. Volume-age relationships for planted and silviculturally enhanced stands were developed by the Ministry using the TASS and XENO computer models. These models forecast little increase in volume for planted stands compared with natural stands. However, log values were forecast to be higher and delivered wood costs lower than for natural stands. Implicit in this value projection is the assumption that any decline in wood quality of planted second-growth timber compared to old growth will be more than compensated by improved average log size and grade.

RESULTS AND DISCUSSION

Projected results for each of the four silviculture policies and four scenarios are presented in three tables, one for each provincial region (Tables 3, 4, and 5). We will briefly summarize them here. Results for the Coast, which differed significantly from those for the two Interior regions, will be discussed first.

Table 3.--Projected results for the Coast

	Silviculture Policy NOSILV	BASIC	INCREM	CURRENT
Baseline Scenario:				
Harvest	16.5	21	21	21
Old growth	0	0	0	0
NPV 2%	45.3	47.8	49.8	47.8
NPV 4%	17.9	17.3	17.4	17.3
NPV 6%	10.7	10.3	10.1	10.2
Diversity - age	89	96	96	96
Diversity - spec.	49	38	42	38
Employment	73.8	94.9	95.4	94.9
Constant Price Scenario:				
Harvest	12.2	13.8	17.5	13.9
Old growth	16	16	16	16
NPV 2%	16.9	16	16.8	16
NPV 4%	10.7	10	10	0
NPV 6%	7.8	7.4	7.2	7.3
Diversity - age	91	87	92	87
Diversity - spec.	69	74	73	4
Employment	54.6	62.3	79.5	62.6
Fire Scenario:				
Harvest	16.1	21	21	21
Old growth	0	0	0	0
NPV 2%	44.4	47.2	49.8	47.8
NPV 4%	17.8	17.1	17.4	17.3
NPV 6%	10.6	10.1	10.1	10.2
Diversity - age	89	95	96	96
Diversity - spec.	50	38	42	38
Employment	72.2	94.9	95.4	94.9
Old Growth Preservation Scenario:				
Harvest	11	15.9	16.9	16.1
Old growth	50	50	50	50
NPV 2%	28	29.4	34	29.6
NPV 4%	13.6	13.2	13.8	13.2
NPV 6%	9.1	8.6	8.6	8.6
Diversity - age	84	85	86	85
Diversity - spec.	52	41	39	42
Employment	49.3	72.3	76.9	73

On the Coast the FIRE scenario differed little from the BASE scenario. In both cases all three policies which included basic silviculture had higher harvest rate, age diversity and employment than the NOBASIC policy. The NOBASIC policy led to higher average species diversity. At the higher two discount rates of 4 percent and 6 percent, no policy which included silviculture gave a positive return; discounted costs exceed discounted benefits. However, at the low discount rate of 2 percent, all three policies with silvicultural activity gave higher returns than the NOBASIC policy. The highest NPV at 2 percent was that for incremental silviculture (INCREM policy). Finally, none of the policies led to any old growth preservation.

Both the constant price and old growth preservation scenarios resulted in a substantial decrease in all the measures of commercial timber production, i.e., harvest, employment and NPV. The incremental silviculture policy dominated the basic only and basic plus NSR (CURRENT) policies on all measures except NPV at 6 percent and species diversity, where it was marginally lower. Old growth preservation was higher under the constant price scenario and much higher under the old growth preservation scenario. Other results were similar to those for the BASE scenario except that species diversity was substantially higher under the constant price scenario. Under all scenarios, the incremental silviculture policy seems the best on all measures.

Table 4.-- Projected results for the Southern Interior

	Silviculture Policy NOSILV	BASIC	INCREM	CURRENT
Baseline Scenario:				
Harvest	13.9	15.7	15.6	15.9
Old growth	0	0	0	0
NPV 2%	33.9	17.9	17.7	17.8
NPV 4%	15.2	6.9	6.7	6.7
NPV 6%	9.8	4.1	4	3.9
Diversity - age	91	93	93	94
Diversity - spec.	25	48	47	48
Employment	28.8	38.7	38.9	39.2
Constant Price Scenario:				
Harvest	13.6	14.6	14.3	14.8
Old growth	0	0	0	0
NPV 2%	15.8	-0.6	-0.9	-0.9
NPV 4%	10.1	1.6	1.4	1.4
NPV 6%	7.5	1.7	1.6	1.5
Diversity - age	91	89	89	89
Diversity - spec.	41	57	56	57
Employment	28.2	35.7	35.6	36.1
Fire Scenario:				
Harvest	13.5	15.2	15.6	15.9
Old growth	0	0	0	0
NPV 2%	32.4	15.9	17.7	17.8
NPV 4%	14.7	6.1	6.7	6.7
NPV 6%	9.4	3.6	4	3.9
Diversity - age	91	94	93	94
Diversity - spec.	25	47	47	48
Employment	28	37.8	38.9	39.2
Old Growth Preservation Scenario:				
Harvest	11.2	12.8	12.7	12.9
Old growth	50	50	50	50
NPV 2%	24	9.7	9.7	9.5
NPV 4%	11.7	4	3.9	3.8
NPV 6%	8.1	2.8	2.7	2.6
Diversity - age	91	94	94	94
Diversity - spec.	20	43	43	44
Employment	23.1	31.7	31.9	32.2

In contrast with the Coast, the NOBASIC policy had the highest NPV at all three discount rates in the Interior. Neither incremental silviculture nor backlog NSR reforestation gave positive financial return at 2, 4, or 6 percent discount rate except under the FIRE scenario in the Southern Interior. On all other measures and for all four scenarios the three policies which included basic silviculture differed little from each other. Basic silviculture provided substantially higher average age diversity and employment than the NOBASIC policy. Timber harvest was also higher when basic silviculture was performed. As on the Coast, old growth preservation was not affected by silvicultural policy. Choice of silvicultural policy in the Interior is less clear than on the Coast. If financial considerations are paramount, then doing no silviculture may be preferred. However, this is politically and socially unacceptable. Of the remaining three policies, the backlog NSR reforestation policy was consistently a bit better on most measures than the incremental silviculture or basic silviculture only policies.

Table 5.-- Projected results for the Northern Interior

	Silviculture Policy			
	NOSILV	BASIC	INCREM	CURRENT
Baseline Scenario:				
Harvest	19.2	20.2	20.1	20.4
Old growth	5	5	5	5
NPV 2%	48.8	34.2	34.1	34.2
NPV 4%	22.2	15.2	15	14.9
NPV 6%	14.1	9.5	9.4	9.2
Diversity - age	89	91	91	91
Diversity - spec.	52	67	67	67
Employment	39.8	46.4	46.7	47.1
Constant Price Scenario:				
Harvest	18.1	18.3	18	18.4
Old growth	5	5	5	5
NPV 2%	23.1	9	8.7	8.7
NPV 4%	14.9	7.8	7.7	7.6
NPV 6%	10.9	6.3	6.2	6.1
Diversity - age	84	87	87	87
Diversity - spec.	51	66	66	66
Employment	37.4	41.7	41.6	42.1
Fire Scenario:				
Harvest	18.5	19.4	20.1	20.4
Old growth	5	5	5	5
NPV 2%	46.2	30.3	34.1	34.2
NPV 4%	21.3	13.6	15	14.9
NPV 6%	13.5	8.5	9.4	9.2
Diversity - age	89	91	91	91
Diversity - spec.	50	66	67	67
Employment	38.2	45.1	46.7	47.1
Old Growth Preservation Scenario:				
Harvest	15.2	15.8	15.8	16
Old growth	53	53	53	53
NPV 2%	34.2	20.3	20.5	20.1
NPV 4%	17.7	10.4	10.3	10.2
NPV 6%	12.2	7.3	7.2	7.1
Diversity - age	90	90	91	91
Diversity - spec.	43	60	60	60
Employment	31.4	36.6	37	37.1

CONCLUSIONS

It has been argued that a choice of high discount rate reflects a myopic approach to forest management. Our study confirmed that the choice of a high discount rate reduces the propensity to invest in the forest resource. Furthermore, even a choice of low discount rate may make a substantial difference to the kind of forest environment that results from silviculture. The impact of silviculture, however, depends upon the biophysical characteristics of a forest region. Our results showed a marked difference between the Coast and the two Interior regions of British Columbia. In the Coastal region, forest diversity over age classes was increased by silviculture, but diversity over species was decreased. However, silviculture in the Interior was forecast to substantially enhance forest species diversity. In the debate over public forest investments in British Columbia, it is important to be aware of regional differences. In our study investments aimed at improving the growth of standing forests (i.e., incremental silviculture) gave the greatest returns for the Coast region, while investments in reforesting backlog NSR lands gave the greatest returns for the two Interior regions.

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PROPAGATING UNCERTAINTY ESTIMATES FROM AN EXPERT SYSTEM THROUGH A FOREST GROWTH SIMULATION MODEL[1/]

H. Todd Mowrer and Timothy C. Haas[2/]

Abstract.--Of six probability distributions tested, the beta provided the best overall fit across the three discrete classes of regeneration density predicted by an expert system. The mean and the variance from the beta distribution provided initial values to a growth simulation model. Over a 100-year rotation period, first-order Taylor series variance propagation equations within the simulation model estimated a minimum of 51 percent and a maximum of 103 percent coefficient of variation in projected gross total volume per acre.

Keywords: Bayesian belief network, propagation of error, variance estimation, computer simulation, Populus tremuloides.

INTRODUCTION

The trend over the past 50 years has been to increasingly augment subjective forest management practices with quantitative prediction methods. The integration of statistical estimation techniques into digital computer models has allowed the prediction of growth and yield of trees or stands through a network of statistically derived equations. When faced with desired future stand conditions not adequately represented through local experience, resource managers have come to rely on these quantitative tools. Quantitative estimation techniques, however, generally fail to integrate useful qualitative information. This trend has changed somewhat over the past 10 years with the development of "expert systems" within the field of artificial intelligence (Schmoldt 1987). The overall goal of an expert system is to encapsulate qualitative information in a computer-based inference process that can aid less skilled individuals in making a decision within a very restricted realm of knowledge (Weiss and Kulikowski 1984). Numerous paradigms have been developed to represent this domain-specific expert knowledge in a form that is applicable to similar problems encountered by other practitioners in that field.

As opposed to strictly quantitative calculations within computer simulation models, expert systems incorporate the subjective or qualitative knowledge of one or more domain experts. Often these experts make decisions based on heuristics or "rules of thumb" developed over years of experience. Initially, expert systems attempted to reconstruct this heuristic process by incorporating a set of rules into a knowledge base. The sequence in which the rules "fired" was determined by a series of questions regarding specifications, characteristics, or qualities of the problem at hand. Thus, the resulting sequence in which rules "fired" would, ideally, reconstruct the chain of logical steps in the problem-solving process. Using this additional qualitative knowledge to augment traditional statistically based quantitative algorithms should, in theory, improve the predictions of computer simulation models for forest growth and yield.

In addition to rare or expensive expertise, successful implementation of an expert system requires that the subject area be limited enough to be manageable, but not so limited as to lose utility (Weiss and Kulikowski 1984). Prediction of initial regeneration establishment and subsequent stem survival (noncatastrophic mortality) has traditionally been subject to a large degree of uncertainty (Hamilton 1986). While resource managers need to know what to expect when a forest stand regenerates, quantitative regeneration data

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[2/]Research Forester, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, and Assistant Professor, School of Business Administration, University of Wisconsin, Milwaukee, Wisconsin, respectively.

for aspen (Populus tremuloides Michx.) in the central Rocky Mountains were not adequate for traditional statistical estimation techniques. Under these circumstances, applying the expert system paradigm to regeneration density estimation provided a reasonable alternative.

Almost since their inception, expert systems have attempted to measure the uncertainty inherent in their recommendations. Often, an expert system will not reach a specific answer, but will offer one or more options with associated estimates of uncertainty (Harmon et al. 1988). Thus, the term "advisory" system has been suggested, rather than "expert," since the user is expected to participate in selecting the best recommendation. In this paper, we will use the terms "expert" and "advisory" system interchangeably. While uncertainty measurement has been incorporated to some degree in many expert system paradigms, it has generally been overlooked in the complex computer programs developed to simulate forest growth and yield. Confidence intervals and variance estimates are easily calculated for the individual statistical estimators within these systems, but estimation of overall prediction uncertainty is more difficult when many of these equations are integrated in the computer simulation as a whole. To achieve estimates of growth over long simulation periods, projection sequences for fixed time periods are often repeated. Outputs or estimates from the previous period become inputs or initial values to the next. In this network of calculations, uncertainty estimation can be a complex and tedious process at best. In the past 5 years, error propagation techniques for uncertainty estimation in growth and yield simulation have been explored to remedy this problem. Mowrer and Frayer (1986) and Mowrer (1991) integrated variance estimation equations into the simulation model used in the current study to estimate the errors propagated through the prediction sequence.

This paper describes the results of a pilot project investigating the opportunity to improve the prediction of forest stand dynamics through combining expert system and computer simulation methodologies. The goals of this research were two-fold. The initial goal was to begin the integration of qualitative predictions from an expert system into the framework of an empirically based computer simulation model for forest growth and yield. A result of this process was the ability to measure the uncertainty associated with expert system recommendations for initial stand density as this error propagated through the forest growth simulation framework.

The relative uncertainty contributions from expert system recommendations were assessed by initializing growth simulations with regeneration density estimates predicted by the expert system. This process was repeated twice to propagate the minimum and maximum initial regeneration density errors (of 17 and 51 percent coefficient of variation, respectively) through the growth simulation model. At the end of a 100-year rotation period, errors ranged from a coefficient of variation (c.v.--the standard deviation as a percent of the mean) of 28 to 124 percent for stems per acre, and from 51 to 103 percent for gross total volume per acre.

METHODS

Bayesian belief network

A recently developed method of knowledge representation in expert systems is the Bayesian belief network (Pearl 1986). The Bayesian belief network represents expert knowledge as a network of discrete random variables. These random variables are related hierarchically by directed links defined as conditional probabilities. Hence, expert knowledge is represented in the belief network through the choice of variables, the hierarchy or dependency structure, and the conditional probabilities defining each variable. Expert knowledge that can be expressed as uncertain conditional statements is represented by conditional probabilities. For a given situation, represented by fixing the input variables, the network yields marginal distributions (interpreted as beliefs) for the output variables. Input variables represent environmental conditions and/or interventions, while output variables represent effects.

Haas (1991a) developed a Bayesian belief network advisory system to estimate the amount of aspen regeneration under various site conditions and management regimes. Conditional probabilities were determined for sets of forest stand characteristics (physiographic variables, nontree community variables, and tree community variables) and management options (clearcut, clearcut and fence, burn, or do nothing) (figure 1). Haas's original network produced a belief distribution for three discrete classes of aspen sucker density two years after regeneration. These ranges were: less than 10,000 stems per acre, between 10,000 and 50,000 stems per acre, and over 50,000 stems per acre.

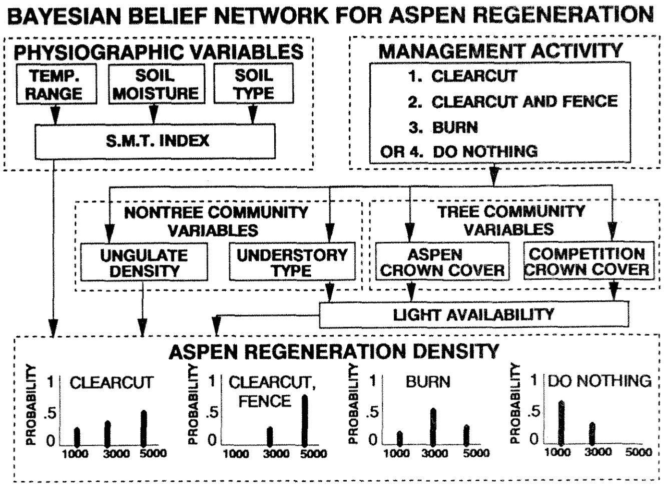

Figure 1.--Schematic diagram of the dependency structure in the Bayesian belief network for aspen regeneration.

The output of Haas's belief network needed to reflect juvenile tree density at 10 years breast height age in order to provide the required input for the simulation model. Since this extension to the belief network is not complete yet, for purposes of studying the ramifications of coupling the advisory system to the growth simulation, three juvenile tree density ranges were assigned as less than 2,000, 2,000 to 4,000, and over 4,000 stems per acre. These ranges attempt to reflect the usually high sucker mortality during the first 10 years, and are compatible with measured stand characteristics for aspen in the geographic region of the simulation model calibration data.

Fitting the probability distribution

The Bayesian belief network resulted in a distribution of probabilities across three discrete classes of stems per acre, as described above. In order to gauge the effect of integrating estimates from the Bayesian belief network into the growth simulation model, a single mean value and an associated variance or error were required. To obtain these statistics for the regeneration stem densities, the fit of continuous probability distributions to the three discrete probability classes was investigated. To assess the widest range of discrete probability class combinations that were possible from the Bayesian belief network, probabilities were systematically incremented from all probability in the lowest density class to all probability in the highest density class. A total of 175 possible combinations of three-class probability levels resulted. Six continuous probability distributions were fit to each of these 175 combinations: the normal, log normal, gamma, Weibull, Johnson's S_B, and beta. Though the last three distributions could assume bimodal shapes, and bimodal distributions could result from the Bayesian belief network, difficulties in computing the maximum likelihood parameter estimates prevented consideration of other than unimodal distributions.

Six criteria were used to evaluate the goodness-of-fit of these distributions: absolute deviations, weighted absolute deviations, chi-square, Kolmogorov-Smirnov, Cramer-Von Mises-Smirnov, and log likelihood. These goodness-of-fit tests and maximum likelihood estimates of parameters were derived using an updated version of a program initially developed by Schreuder et al. (1978). Results from these tests are given in Table 1.

Overall, the two bounded distributions, Johnson's S_B and the beta, ranked highest across the range of probability combinations. The beta distribution performed better than Johnson's S_B under four out of six goodness-of-fit criteria. However, a large difference in values from the log likelihood test caused the overall average rank to be lowest for the S_B. The deciding factor was that the mean and variance estimators for the S_B distribution are extremely complex. Thus, the beta distribution was selected for use in the current analysis.

Table 1.--Ordinal rankings of six goodness-of-fit tests averaged over 175 three-class discrete probability distributions fit to six probability distribution functions. Lower numbers indicate better fit.

Test Criteria	Probability Distribution Function Normal	Log Normal	Gamma	Weibull	S_B	Beta
	Averaged ordinal ranking					
Absolute Deviation	3.36	4.92	3.82	3.20	2.99	2.85
Weighted Absolute Deviation	3.52	4.52	3.73	3.38	3.10	2.89
Chi-square	3.18	5.31	4.11	3.12	2.76	2.66
Kolmogorov-Smirnov	3.63	5.17	3.89	2.89	2.78	2.79
Cramer-Von Mises-Smirnov	3.66	5.13	3.94	2.84	2.80	2.76
Log likeli-hood	4.38	4.57	4.27	3.49	1.66	2.77
Six-test Average	3.62	4.93	3.96	3.15	2.68	2.79

The mean and variance from the beta distribution were used to approximate normal distribution parameters. While there are statistical implications to ignoring higher order moments, such approximations are common practice in similar situations (Steele and Torrie 1980). The probability class combinations exhibiting the minimum and maximum coefficient of variation (displayed in figure 2) were selected to investigate the range of errors that could result from the Bayesian belief network. The distribution exhibiting the minimum c.v. of 17 percent is skewed to the left and results from the two probability density classes on the right of the figure. The maximum c.v. of 51 percent corresponds to the right-skewed beta distribution and the two probability classes on the left.

For each of these discrete belief distributions, the mean and variance of the fitted beta distribution were calculated. Stand growth and error estimation were initiated in the simulation model based on these two mean and variance pairs. Although bimodal belief distributions are possible for the density variable (see Haas 1991a), at least for the unimodal belief network outputs, these two distributions should cause the extremes of error propagation behavior to be exhibited.

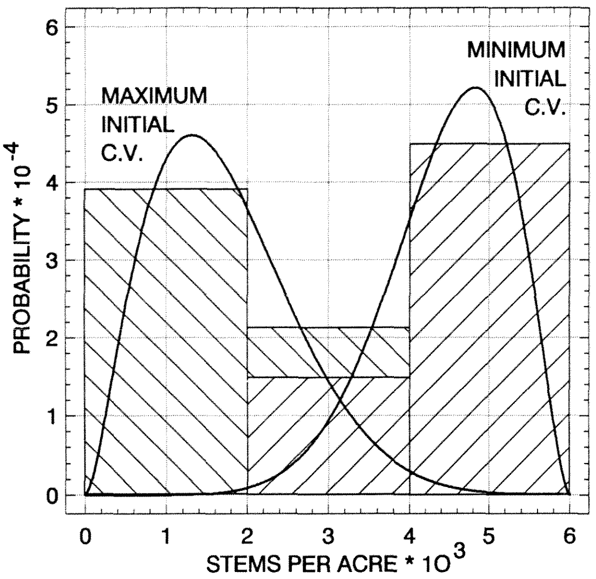

Figure 2. Probability classes and resulting beta probability distributions for the maximum initial c.v. (left, with negatively sloped cross-hatching) and the minimum initial c.v. (right, with positively sloped cross-hatching).

The computer simulation model

The computer model (Mowrer 1986) simulates the growth of pure, even-aged stands of aspen. Stand conditions are projected forward through time in 10-year increments based on ordinary least-squares estimation of the future value of three variables: stems per acre, and mean and variance of stand breast height diameter. In addition, site index (Edminster et al. 1985) and mean age must also be specified. Values for the latter four initialization variables (not specified by the belief network) were selected to correspond to similar juvenile stands in the calibration data with values as near as possible to each of the specified mean stem densities. These initialization values consisted of a 10-year breast height age, a site index of 64 feet, and mean breast height diameters of 1.7 inches for the denser (17 percent c.v.) stand and 2.0 inches for the less dense (51 percent c.v.) stand. Associated variances of diameter were 0.4438 and 0.3242 inches squared, respectively.

At each 10-year projection period in the simulation model, the mean and variance of breast height diameter determine a normal probability distribution. This normal probability distribution is used to allocate stems per acre across 1-inch diameter classes. Basal area per acre, height, and volume per acre are estimated within these 1-inch classes. Values of these derived variables are then aggregated across all diameter classes to calculate stand-level values at each 10-year projection period.

Variance estimation equations

To be useful, simulation models must be applicable over a range of stand conditions. To achieve this range, data must be collected at many different locations. When a simulation model is used to predict the growth and yield for a particular set of stand conditions, the range of variability in the calibration data leads to uncertainty in the predicted value, through the covariance matrix of the estimated regressor coefficients.

In addition, errors in the initial values of variables necessary to start model projections also contribute to uncertainty in model predictions. Normally, sources of this initial variance would accrue from sampling and measurement errors in forest inventories. Effects of these initial errors propagate through the estimation network within the model as variances in independent (or regressor) variables contribute to variances in the dependent (predicted) variable in each equation. In addition, the errors from the estimation of regressor coefficients (described above) are included as each predictive equation is used in the simulation sequence.

An error propagation technique had previously been applied to the growth and yield simulation model to estimate the uncertainty in variables projected over multiple periods (Mowrer and Frayer 1986, Mowrer 1991). In this technique, first-order Taylor series variance estimation equations integrate the errors in regressor variables with fixed contributions from estimated regressor coefficients. By calculating a variance estimate for each growth calculation in the model, accrued errors can be estimated in parallel to the growth and yield simulation sequence. Thus, at each step in the sequence, the error propagation technique estimates accumulated variance by combining propagated effects of uncertainties in model initialization values, with the accumulated uncertainties resulting from the calibration of each previously used predictive equation.

In summation form, the general formula for error propagation as applied to each equation in the growth and yield model is

$$\hat{Var}(\hat{Y}) = \sum_i^n \sum_j^n (\partial\hat{Y}/\partial X_i)(\partial\hat{Y}/\partial X_j) S_{X_i} S_{X_j} R_{X_i X_j} + \sum_k^p \sum_l^p (\partial\hat{Y}/\partial b_k)(\partial\hat{Y}/\partial b_l) S_{b_k} S_{b_l} R_{b_k b_l} + \sum_i^n \sum_k^p 2(\partial\hat{Y}/\partial X_i)(\partial\hat{Y}/\partial b_k) S_{X_i} S_{b_k} R_{X_i b_k}. \quad [1]$$

The first additive component propagates uncertainties from initialization variables through each successive calculation in the model, the second component accrues calibration errors from each predictive equation, and the third component adds the effects of correlation between regressor variables and coefficients as they accumulate over multiple projection periods. Note that summation occurs across all values of subscripts in the first two additive components, resulting in squares of terms for which the subscripts are equal, and in the doubling of cross-product terms.

Terms in the first additive component of equation [1] estimate the variance propagated through regressor variables and their cross-products. First-component parenthetic expressions refer to the partial derivatives of the regression equation with respect to each independent (regressor) variable. The standard deviations of the independent variables (S_{X_i}, S_{X_j}) are the path through which initial and estimation errors propagate through the model. Correlations between variables ($R_{X_iX_j}$)were estimated for each of the 10-year model projections, based on the calibration data set.

Second-component terms estimate variance contributions due to regressor coefficients. Parenthetic terms on the second line are partial derivatives of the regression equation with respect to each coefficient. The standard deviations (S_{b_k}, S_{b_l}) and correlation coefficients ($R_{b_kb_l}$) were obtained from the covariance matrix for the estimated regressor coefficients obtained from the growth model calibration process.

Third-component terms estimate variance contributions from correlations between regressor coefficients and regressor variables. These correlations develop as previously estimated dependent variables become regressor variables in subsequent equations or projection periods. Their effects have been explored by Mowrer (1991). Notation is the same as for the first two components. As noted in Mowrer (1991), higher order terms may be important for nonlinear estimators. These additional terms were not included in the current analysis. The analysis presented here is of sufficient complexity to provide an adequate lower bound variance approximation; however, additional terms or refinements may improve the variance estimation process.

In order to keep all other conditions constant for comparison between error propagation regimes for the minimum and maximum errors in initial stem density from the Bayesian belief network, the initial variances for the other four model initialization variables were set to a c.v. of 25 percent. This value is well within the range of most forest inventory errors.

RESULTS

Figure 3 shows errors propagated through the growth simulation model resulting from the minimum and maximum errors in initial stems per acre from the expert system. Propagated errors are tracked for two variables within the model, stems per acre (solid lines) and gross total cubic volume per acre (dashed lines). The error trajectories resulting from the minimum initial error in stem density from the Bayesian belief network are marked with asterisks, while the errors resulting from the maximum are marked with squares.

Errors propagated from the minimum initial error of 17 percent c.v. in stems per acre follow a low, concave trajectory for stems per acre and a generally downward trend for volume. The maximum c.v. of 87 percent for volume occurs at model initialization, while the maximum of 28 percent for stems per acre occurs at the end of the 10 projection periods. Propagated errors resulting from the 51 percent maximum initial c.v. in stems per acre maintain higher levels. Propagated errors in stems per acre increase continuously across projection periods to a maximum of 123 percent after 10 projections. Propagated errors for gross total volume per acre initially decrease and then increase to 103 percent, though they never exceed their initial level of 104 percent.

Assuming that an error of 50 percent c.v. or less is tolerable, results from the minimum error case would be generally acceptable. While the errors in volume are initially too high, both variables approach generally acceptable levels of error as projections progress. For the maximum error case, both variables maintain unacceptably high levels of error throughout the 100-year rotation, with continual increases in errors in estimated stems per acre. These errors are attenuated through the network of variance estimation equations within the model. Volume is an inherently more precise estimate than stem survival. Volume is estimated last in the model and reflects an overall lower level of propagated error.

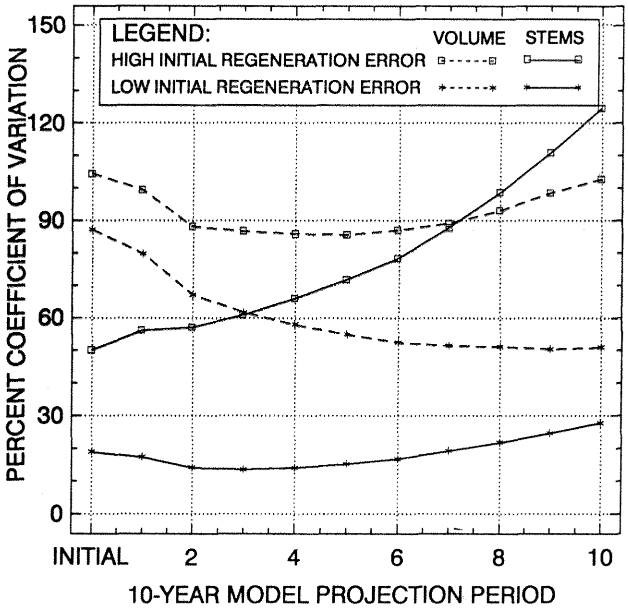

Figure 3. Errors propagated through the growth simulation model resulting from minimum and maximum initial c.v. levels for gross total cubic volume per acre and number of stems per acre.

CONCLUSIONS

As a result of this pilot study, we have become aware of opportunities to improve the integration of the Bayesian belief network and the simulation model. In the Bayesian belief network, the relative levels of the minimum and maximum c.v. were primarily determined by changes in the mean, rather than the variance. More predicted stem density classes are necessary to improve the estimation of the beta probability density function and the resulting sensitivity of initial error estimates to changes in variance. Also, levels of physiographic and community variables need to be related to specific ranges of values for all the initialization variables in the simulation model. One reason why the Bayesian belief network was developed was because information was inadequate to develop empirical predictions. This same dearth of information prevented empirical verification of the regeneration levels predicted by the Bayesian belief network. Haas (1991b) has developed a partial validation for the belief network, but demonstrated it with hypothetical data.

Mowrer (1991) compared the first-order Taylor series estimation technique for propagated errors applied here to a Monte Carlo-based approach. Differences between methods of estimating propagated error increased over lengthening sequences of equations within each projection period and over increasing numbers of periodic projections. These discrepancies were attributed to differences in the populations used to develop various covariance and correlation matrices. Populations used for covariance estimation in the first and third components of the error propagation equations were intentionally designed to allow the equations to be applicable to a wide range of stand conditions. The Monte Carlo comparison, however, was based on uncertainty in the initial values from a single stand. Thus, the mismatch in covariance populations.

This pilot project is part of a larger study to quantify the effects of propagated errors in decision support systems consisting of expert systems, computer simulation models, geographic information systems, and harvest optimization algorithms. In the current analysis, we do not attempt to address the question of what determines an acceptable level of error for management decisions, but maintain that precision requirements must surely be determined within the context of each decision. While the Bayesian belief network may propagate relatively high levels of error through the simulation model, the alternative of basing decisions on inadequate information or uninformed speculation is certainly less acceptable. When the level of precision is low, managers should have more latitude to use their professional judgment. In any regard, one is better off knowing the level of precision for an estimate than falling prey to the common misconception that each predicted value on a computer printout is absolutely correct.

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OPTIMIZING FOREST STAND MANAGEMENT

IN A STOCHASTIC ENVIRONMENT [1/]

Lauri T. Valsta [2/]

Abstract.--A stochastic optimization model is developed that can be used with single-tree stand simulators. Stochasticity is represented by a large set of scenarios, each of which is an outcome of stochastic processes. The optimization model is defined in control variable space and it includes planting density, the timing, intensity and type of thinning, and rotation length for an even-aged plantation. The stochastic environment is described by the yearly growth rate level, growth rate trend, and the probability of a catastrophe, such as wild fire or windthrow. Numerical results in a risk neutral case show that the optimum rotation is shortened and planting density is increased with an increasing probability of a catastrophe. Further, an increasing growth rate variation has mixed and weak effects that depend, in particular, on the tree mortality model.

Keywords: optimal harvesting, risk, even-aged stand, Norway spruce, *Picea Abies*.

INTRODUCTION

Stochasticity enters forest management from several sources, e. g., incorrect or inaccurate information concerning the forest at present, short term and long term variations in the biological or economic environment, disastrous events, the actual outcomes of forest operations, and incomplete knowledge about the goals of forest management now and in the future. Stochastic optimization models may be divided into two groups - adaptive and anticipatory models (Ermoliev and Wets 1988). In adaptive optimization, the state of the system is observed intermittently, at regular or irregular intervals. Observation results are used to adjust the (optimal) decision. This approach is also called feedback control or closed loop control. Lembersky and Johnson (1975), Lohmander (1987), Brazee and Mendelsohn (1988), and Haight (1990) use this approach to derive the optimal decision rule of whether or not to harvest a stand when the timber price at decision time is observed. Kao (1984) includes thinning (stocking level) into the optimization.

Anticipatory models are used for deriving optimal decisions for the whole period of time under planning. This is relevant when the state of the system is not observed or when a significant part of the time period is before the time of the first observation. In this case, the solution must take into account the uncertainties over time and, according to some criterion, be optimal overall. The optimum rotation problem can be modelled to be adaptive to the time-varying final harvest timber prices. However, if one wants to include alternative regeneration methods and detailed stand growth dynamics, the problem will also have a strong anticipatory component. Kao (1982) analyzes optimum thinning and rotation in an anticipatory setting when stand volume growth is probabilistic.

Several investigations have concerned the optimum rotation of a forest stand under the risk of a catastrophe, summarized in, e. g., Caulfield (1988). Fire risk studies have usually included some adaptation, such as regeneration following fire, or sometimes the salvaging of timber from a burned stand. However, because only the rotation length has been endogenously determined, adaptation has not played a full role.

In the present study, the effects of stochasticity on the optimum thinning program and rotation of an even-aged stand are analyzed using an optimization model based on the direct search method (Hooke and Jeeves 1961), as modified by Osyczka (1984). The optimization approach by Roise (1986a) is generalized to account for a probabilistic stand growth simula-

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[2/]Research Forester, Finnish Forest Research Institute, Unioninkatu 40 A, 00170 Helsinki, Finland

tor. The optimization model is anticipatory (not adaptive) and stochasticity is introduced in the form of scenarios. This results in a flexible and approachable model construction. The optimization model is applied to a single-tree, distance-independent growth model for Norway spruce (*Picea Abies* Karsten), by Mielikäinen (1985) and Hynynen (1990).

STOCHASTIC OPTIMIZATION USING SCENARIOS

The basic approach to stochastic stand level optimization problems has been the use of Markovian decision models (Hool 1966, Lembersky and Johnson 1975, Risvand 1976, Kao 1982 and 1984, Lohmander 1987). In Markov models, the process to be optimized is described by a state vector, the elements of which are the possible alternative states of the process. The dynamics of the process are given by a state transition matrix which indicates the probabilities of being in one state subject to being in another state one time step earlier. One or two stand characteristics, such as a stand density measure, are used to model stand development. However, modern models for stand development utilize single-tree simulators which incorporate tens or even hundreds of state variables. The use of transition matrices is no longer possible: if there are 10 state variables and each of them has 10 possible states, a very modest amount, the size of the transition matrix would be $10^{10} \times 10^{10}$. Although the transition matrix would be sparse, or the problem might have a more efficient form, there would still be severe computational problems. It should be noted that, in addition to Markov processes, a large selection of probabilistic modelling approaches have been developed which, so far, have remained largely unused in forest management research (Ross 1970, Moder and Elmaghraby 1978).

A recent development in deterministic stand level optimization studies is the use of nonlinear programming and the stand management control variables (Roise 1986b, Bare and Opalach 1987, Haight and Monserud 1990a, Haight and Monserud 1990b, Valsta 1990, Yoshimoto, et al. 1990). This nonlinear programming problem can be stated as

$$\max_{\{\mathbf{u} \in C \subset R^n\}} \quad g(\mathbf{u} \mid \mathbf{x}_0) \qquad (1)$$

where $g(\mathbf{u})$ is the objective function generated by the stand simulator, $\mathbf{u}$ is the vector of control variables, $\mathbf{x}_0$ is some initial condition for the stand simulator, and C is the set of feasible solutions. The control variables may be defined as times between silvicultural operations, their intensities, or the time of the final harvest.

Problem (1) has a stochastic counterpart. Assume a probability space $(\Xi,,P)$, where Ξ is the set of possible realizations and P is the associated probability measure. The corresponding vector of random variables is ξ. Suppose that the decision maker wishes to maximize the expected net return from stand management, given by a return function, $f(\mathbf{u},\xi \mid \mathbf{x}_0)$. The problem is then to

$$\max_{\{\mathbf{u} \in C \subset R^n\}} \quad \mathbf{E}\{f(\mathbf{u},\xi \mid \mathbf{x}_0)\} = \int_{\Xi} f(\mathbf{u},\xi \mid \mathbf{x}_0) dP(\xi) \qquad (2)$$

To solve equation (2) is not a simple undertaking. Possible approaches would be, e. g., to perform a multidimensional integration over Ξ – an extremely computing intensive, if not impossible, task – or to use stochastic quasigradients or their approximations (Ermoliev and Wets 1988).

A different design for the problem is to model the stochastic phenomena using scenarios. Define a set of scenarios, $S = \{\mathbf{s}^1,..., \mathbf{s}^L\}$, where each $\mathbf{s}^s$ is a joint realization of the stochastic processes over the planning horizon. Suppose that p_s, $s \in S$, are the probability weights associated with each scenario. These weights may have empirical or judicious bases. The maximization in (2) may be approximated by (3)

$$\max_{\{\mathbf{u} \in \cap_s C_s\}} \quad \sum_{s \in S} p_s \; f(\mathbf{u},\mathbf{s}^s \mid \mathbf{x}_0) \qquad (3)$$

where C_s is the feasible set for scenario s. The accuracy of the approximation depends, naturally, on the number of scenarios and the probability weights used. The problem is now one of deterministic nonlinear programming, for which a variety of numerical solution procedures are available.

In this modelling approach, the elements of $\mathbf{u}$ are quantitative measures that describe forest operations. The constraints imposed on them are, typically, just lower and upper bounds. Often, the sets C_s and their intersection $\cap_s C_s$ are convex, facilitating the maximization (3). The function $f()$, however, is likely to be nondifferentiable, or at least nonsmooth, and may be nonconcave, giving rise to local maxima that may mislead the optimization algorithm (these problems have been discussed in Roise (1986a, 1986b) and Haight and Monserud (1990a)).

THE PROBABILISTIC STAND SIMULATOR

Probabilistic stand optimization studies should be based on probabilistic simulation models where some of the physical or economic variables, or both, are random. As most of the simulators are based on deterministic relationships, stochasticity may have to be introduced to the models afterwards. In the present investigation, the starting point of the simulator is a deterministic, single-tree, distance independent growth model developed by Mielikäinen (1985). Only the models relating to Norway spruce are used. The biological part of the simulator consists of models of (1) d.b.h. growth, (2) height growth, (3) crown ratio, and (4) mortality rate. The models, which are described in detail in the Appendix, represent a common modelling strategy used in many single-tree simulators. Although these models cover a fairly small geographical area, their behavior may be thought to resemble that of several other models.

Randomness can be added into a simulator in various forms. In the first part of the present investigation, stochastic yearly levels of growth and a stochastic linear trend for the level of growth are included. The first source of stochasticity may be associated with annual growth variation and the second one with climatic change. Evidently, more realistic representations of growth variations could be constructed by employing the present knowledge on the subject, for example, by including autocorrelation between the growth levels of successive years (Jordan and Lockaby 1990). In the second part of the investigation, the effects of catastrophes are studied. Catastrophes are modelled as randomly occurring events which damage a part of the growing stock. The damaged trees have to be harvested immediately with a 25 % reduction in their stumpage value and a doubling of the logging costs.

When a scenario consists of yearly growth levels and a linear trend, the final level of growth is assumed to be a sum of the two processes. The random variables for yearly growth levels are assumed to be i.i.d. $N(0,\sigma)$ variates. Different values of the standard deviation of the yearly growth level were used in the computer runs, the base value being 17.8 %, which was obtained from the tree ring index values in Mielikäinen (1985). The same yearly growth levels are used for height growth and d.b.h. growth. In reality, the variation of height and d.b.h. growth may not necessarily coincide. Such refinements would be simple to include in the scenario descriptions.

All scenarios have the trend value equal to 0 at the beginning of simulation. Trend variation is defined as the growth level trend value in the last period and this value is a $U(-a/2,a/2)$ variate (uniform distribution) with the parameter a defining the range of values. Examples of the realization of the stochastic growth level for a period of 50 years are given in Figure 1. A significantly decreasing trend value is seen in scenario 2. Most of the time, growth is predicted for a period of 5 years, for which the variation is much smaller.

The catastrophes are modelled by using two random variables. The occurrence of a catastrophe is modelled as a *Bernoulli* random variable with the parameter *pcat*, e. g., 0.01. If a catastrophe takes place, a uniformly distributed random variate, U(0,1), gives the proportion of trees destroyed.

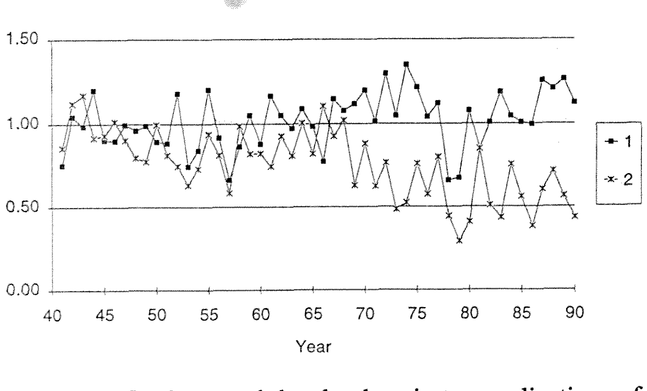

Figure 1.--Yearly growth level values in two realizations of the stochastic growth process.

The subroutines provided by the Numerical Recipes Scientific Subroutines (Press, et al. 1986) are used to obtain pseudorandom numbers and the deviates of the uniform and normal distributions (subroutines RAN2 and GASDEV).

The values of the stochastic variables that define the scenarios were generated randomly using uniform and normal distributions. The scenarios obtained in this fashion are hypothetical. The probability of the occurrence of a scenario was chosen to be $1/n$, where n is the number of scenarios in one analysis.

Different thinning types in the simulator are specified by thinning parameters, the number of which can be controlled. Thinning intensity is a function of tree diameter, relative to the smallest and the largest diameters in the stand. A piecewise linear function is used to describe thinning rates over the range of diameters. The thinning parameters define the thinning rates at the corner points of the piecewise linear function. At one extreme, there may be only one thinning parameter and the thinning rate is constant over tree diameters. At the other extreme, there may be a thinning parameter for each one-inch or one-centimeter diameter class. As an example, one which corresponds to the results of the present investigation, a thinning specification with 3 parameters is shown in Figure 2. The thinning specification used provides flexibility for simulating different types of thinning with only a few parameters per thinning.

Tree volumes and stumpage values are computed by diameter class, and logging costs are derived by using an equation based on the tariff tables used by the Finnish forest industries and logging contractors. These models are described in the Appendix.

RESULTS

A permanent plot in a long-term field experiment in Southern Finland (Heinola, Nynäs, 61° N - 26° E, elevation 300 ft) was used as the initial stand for simulations. The stand is a pure Norway spruce stand growing on mineral soils with

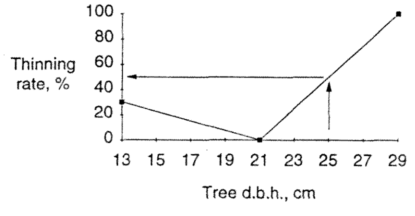

Figure 2.--Thinning intensities defined by a piecewise linear function with three parameters. The minimum and maximum diameters of the stand are 13 and 29 cm, respectively. The three parameters define thinning rates at minimum, midpoint, and maximum diameters; 30, 0, and 100 %; respectively. As an example, the thinning rate of the 25 cm diameter class is 50 %.

a predicted site index of 29 m or 95 ft (dominant height at 100 years). The stand was established with 4-year-old plants in 1926. The trees were 40 years old at the start of the simulation.

The simplest optimization problem, stand management with no thinnings, is analyzed first. The only control variable is rotation length, and it is convenient to conduct an exhaustive search over a reasonable range of rotation ages. The effect of including stochasticity in the analysis in the form of yearly growth level and trend variation was not significant (Fig. 3). Only a slight shift in favor of shorter rotations can be observed. Growth variation was symmetric about the expected value of growth, and the objective function was risk neutral. The graph shows smooth curves on the large scale, combined with small scale irregularities. The nonsmoothness results partly from using a growth simulator modelled for 5-year growth periods to predict shorter time steps. The values of the independent variables are updated when a full 5-year period is completed thereby creating small twists to the curves.

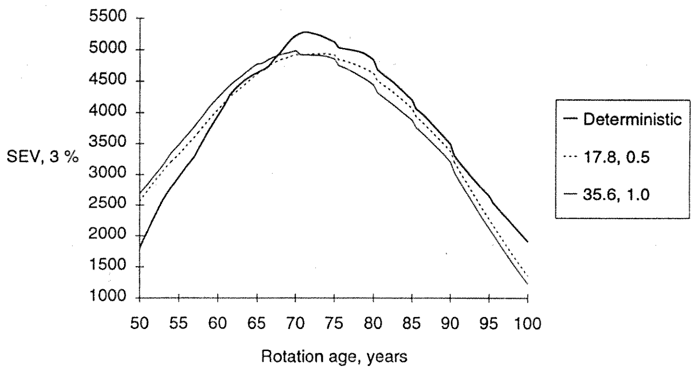

Figure 3.--Soil expectation value in relation to rotation length for the deterministic case and two magnitudes of stochasticity. Numbers refer to the standard deviation of yearly growth, %, and parameter *a* of the trend variation, respectively. The discount rate is 3 %.

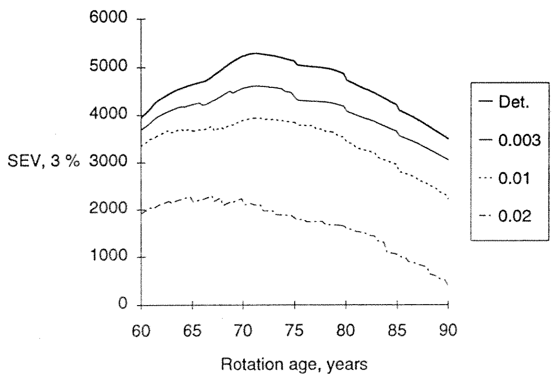

Figure 4.--The effect of the increasing risk of a catastrophe on soil expectation value for different rotations. Numbers refer to the annual probability of disaster. The discount rate is 3 %.

When the stand was subject to the risk of a catastrophe, the effect of increasing risk was a decrease of the optimum rotation. This is illustrated in Figure 4, where the deterministic case is compared with three levels of risk, represented by annual probabilities of a catastrophic event (e.g. wild fire or windthrow). No thinnings were made, but damaged trees are logged immediately after a catastrophe. Added to the final harvest stumpage revenue, bare land values were iteratively computed for each risk level, based on the corresponding soil expectation value of the optimum rotation.

Based on single tree growth models, the simulator used in this study is capable of predicting stand development for any thinning program. When there are several thinnings, the number of control variables is large and the results are difficult to comprehend. For this reason, only one thinning is considered in the following analysis. To permit the thinning type to vary, thinning intensities are defined by three parameters (as in Figure 2).

The optimum thinning schedule was derived for the deterministic case and four levels of yearly growth variation. With increasing stochasticity (Table 1), the rotation length was increased, thinning was scheduled sooner, and small trees mortality was captured. The results in Table 1 were computed with the seed number of the random number generator equal to 1. Seed numbers 2 and 3 were also examined and it was found that the numerical values varied by small amounts but the changes due to increasing stochasticity were similar.

TABLE 1.--Optimum thinning schedule for different levels of stochasticity, standard deviation (S. D.) of yearly growth variation. P1, P2 and P3 refer to thinning parameters. The discount rate is 3 %.

S. D. (%)	Rotation (years)	Thinning age (years)	P1 (%)	P2 (%)	P3 (%)	E[SEV] (FIM/ha)
0.0	82.2	69.8	0	0	100	5694
8.9	82.8	69.7	0	0	100	5669
17.8	86.0	68.4	0	0	100	5757
26.7	86.0	67.5	3.9	0	100	5948
35.6	86.0	67.2	45.0	0	100	6168

TABLE 2.--Effect of the increasing probability of a catastrophe (pcat) on the optimum thinning schedule. The discount rate is 3 %.

Pcat (%)	Rotation (years)	Thinning age (years)	P1 (%)	P2 (%)	P3 (%)	E[SEV] (FIM/ha)
0	82.2	69.8	0	0	100	5694
0.003	82.8	69.0	0	0	100	4936
0.01	78.0	63.8	0	0	100	4256
0.02†	70.0	62.9	0	0	100	2356
0.02†	82.0	64.6	0	11.4	100	2406

†Alternative optima.

The effect of an increasing probability of a catastrophe, manifested as a decreased rotation length, was also found when a thinning was included in the stand management (Table 2). Given a constant thinning rate, the optimum rotation was shortened from 82 years to 70 years when the probability increased from 0 to 0.02. Thinning was brought forward in higher risk cases. With 0.02 probability of a catastrophe, two optimum solutions were found: one was based on the same thinning rate (0, 0, 100) as the lower risk cases and had a shorter rotation, while the other one indicated a higher thinning rate (0, 11.43, 100) and a longer rotation.

DISCUSSION

The main purpose of the present study is to demonstrate a stand level optimization approach capable of working with probabilistic and complex growth simulators. When the stand production function is defined as a well behaved algebraic function, e. g., of the age of the stand, conclusive results concerning the effect of risk on optimal forest management can be inferred. Because the present investigation is based on a single set of growth models, the definite consequences of stochasticity are not revealed. Results may depend on the growth models, site characteristics, initial stand structure, and economic parameters. Obviously many more analyses are required to establish the general importance and effects of stochasticity.

The first form of stochasticity introduced into the simulator concerns yearly growth variation. The effect of this form of stochasticity is, in an interesting way, dependent on whether a thinning is available or not. Without a thinning, an increase in stochasticity results in a small decrease in the optimum rotation length. With a thinning included, the optimum rotation is increased by 2-4 years, depending on the seed number of the random number generator. Thinning intensity, too, increases with amplified growth variation. Given the initial stand and simulation parameters, the growing stock reaches its self thinning limit at about the age of 69 years. The self thinning limit is fixed with regard to growth level variation. Compared to other scenarios, those with many years of elevated growth lead to higher mortality at the end of the rotation. Such losses cause the optimum no-thinning rotation to shorten with increasing growth variation. When available, thinning is scheduled to coincide with the attainment of the limiting density. Limiting densities are not encountered after thinning, and increasing stochasticity leads to heavier thinnings and longer rotations. Overall, these observations point out that simulator parameter values and initial conditions may strongly influence the qualitative results of including stochasticity into stand level optimization.

The results concerning the effect of increasing risk on the optimum rotation length can be compared to some previous investigations as long as exact similarity in problem setup is not required. Lohmander (1987), and Brazee and Mendelsohn (1988) analyze numerically price fluctuations, whereas Kao (1982 and 1984) studies growth fluctuation. Lohmander (1987) states that "the expected optimal rotation age may be higher, lower or equal to the deterministic counterpart" and questions Kao's (1982) general conclusion that increasing stochasticity shortens the optimum rotation. Kao (1982, 1984) analyzes Mean Annual Increment (M.A.I.). Corresponding M. A. I. results from the non-adaptive model of the present investigation (Table 3) show a slight increase in the optimum rotation with increasing yearly growth variation. Brazee and Mendelsohn (1988) report that "in all the cases we examined, the expected harvest age increased slightly with increasing variance". Although not explicitly stated, Kao's (1982) model seems to incorporate risk aversion. He states: "When the future is less predictable, the expected return will be lower ...". This could be an explanation to the difference in results.

The stochastic optimization method applied in the present study requires a fair amount of computing resources. Unfortunately, this may be unavoidable in numerical stochastic optimization. For example, Kao (1984) reports that the computational load was 100 times larger in probabilistic optimization compared with the deterministic case. Because the approach of the present investigation is based on scenarios, their number is the main determinant of the amount of computing required. The number of scenarios should be large enough, so that optimization results are not markedly dependent on the set of scenarios in the analysis.

The dependence of soil expectation value on the rotation age for an unthinned stand was computed with the number of scenarios ranging from 10 to 500 (Fig. 5). The source of stochasticity was the probability of a catastrophe which was set to 0.01. To determine the optimum solution with confidence, approximately 100 scenarios were required - a smaller number would have created a significant risk of reporting an incorrect (local) optimum solution. Increasing the number of scenarios to as much as 500 still left some nonsmoothness in the response curve. As a result, only algorithms suitable for nonsmooth optimization can be applied in the present approach.

The response surface generated by the stand simulator is both nonsmooth and nonconcave, so the optimization algorithm may converge to a local rather than global optimum solution. The performance of the currently used version of the Hooke and Jeeves direct search algorithm (Osyczka 1984) is illustrated in Table 4 where the same problem was solved ten times, starting from randomly chosen initial solutions. Relying on a single solution would be risky. On the other hand, re-

TABLE 3.--Optimum mean annual increment (m^3/ha/v) at different rotation ages in relation to the yearly growth level variation (standard deviation, S. D.).

Rotation length	S. D., %			
(years)	8.9	17.8	26.7	35.6
70	8.74	8.73	8.73	8.74
75	8.82	8.81	8.83	8.84
80	8.88	8.88	8.91	8.93
85	8.86	8.89	8.94	8.96
90	8.79	8.81	8.82	8.83

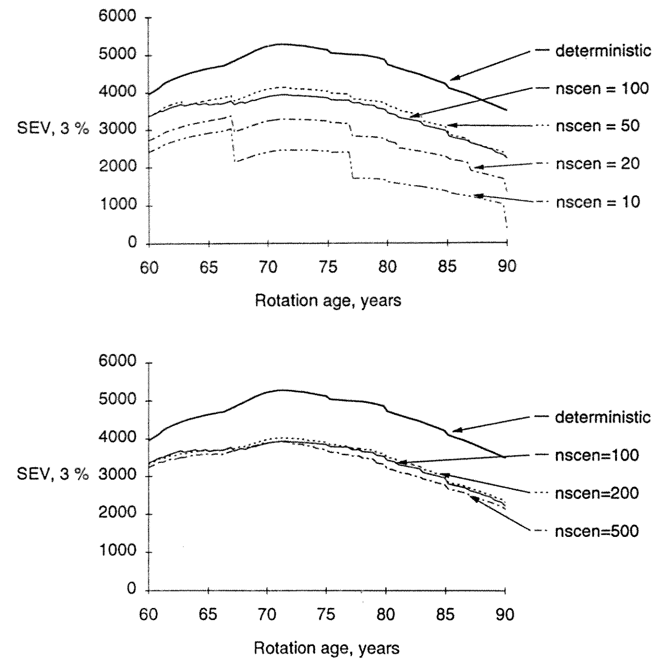

Figure 5.--Soil expectation value as a function of rotation age for different numbers of scenarios and in the deterministic case. The discount rate is 3 %.

running the optimization 3-5 times seems to provide adequate confidence. The results presented in Tables 1 and 2 are based on five replications of optimizations.

One of the strengths of the present scenario-based stochastic optimization method is that the distribution of the objective function values, by scenarios, is known and can be analyzed with respect to relevant variables. Furthermore, transformations of the distribution can be used to form other objectives based on the attractiveness of individual scenario outcomes. The scenario simulations produce large amounts of information all of which can be used to evaluate management strategies.

The scenario approach permits the simultaneous analysis of several stochastic phenomena. When including additional sources of risk, it is not necessary to increase the number of scenarios multiplicatively. For example, when producing Figure 4, it was found out that the number of scenarios (100) was sufficient, regardless of whether the growth trend variation was included or not. The approach is considered to have potential for, e. g., the joint optimization of regeneration and other silvicultural operations, or the analysis of the effects of stand inventory data inaccuracy.

The scenarios were formed by generating randomly outcomes of the defined stochastic process. Another alternative would be to form scenarios judiciously, so that they would be likely realizations of the future. Scenarios have been used extensively in econometrics and management science (see, for example, Makridakis (1983), Godet (1987)) where important

TABLE 4.--Ten optimum solutions for the same problem obtained from different random starting points of the optimization algorithm. The discount rate is 3 %.

N:o of run	Rotation (years)	Thinning age (years)	P1 (%)	P2 (%)	P3 (%)	E[SEV] (FIM/ha)
1	86.0	66.6	47.8	0.00	100.0	6172
2	86.0	66.6	47.8	0.00	100.0	6172
3	86.0	66.6	47.8	0.00	100.0	6172
4	86.0	67.5	44.3	0.01	99.9	6168
5	86.0	66.6	47.8	0.01	99.9	6172
6	85.8	65.0	31.7	0.00	99.9	6165
7	86.0	67.6	43.3	0.08	100.0	6168
8	86.0	66.6	47.9	0.01	100.0	6172
9	86.0	66.6	47.9	0.01	100.0	6172
10	85.8	64.7	29.8	0.00	100.0	6165

questions have been the determination of the most reliable forecast or the aggregating of scenarios to form "the best estimate". Such an approach differs markedly from that of the present investigation, in which scenarios are used to model probabilistic processes and represent the real world stochasticity in a manageable form.

In the present investigation, nonlinear programming is used to maximize the objective function - the expected soil expectation value. Most of the computing time is spent on evaluating the result of applying a decision variable vector to each of the scenarios. These scenario simulations are mutually independent. This approach is well suited for computers with parallel processing because the simulation computations are of the "single-instruction, multiple-data" type (Lootsma and Ragsdell 1988). Parallelism could be further extended by the use of scenario aggregation (Wets 1989) in which the optimization algorithm is also largely parallel.

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APPENDIX

The Appendix describes in more detail the simulator constructed for the present investigation, based on Mielikäinen (1985) and Hynynen (1990). The growth models were estimated for periods of 5 years. Shorter growth periods were needed in the present study however and they were linearly interpolated from full 5-year periods.

The simulation starts from a tree list containing data on tree d.b.h., height, age at breast height, and the number of trees per hectare represented by the tree. In the present application, trees can only be of single species, namely Norway spruce (*Picea Abies* Karsten). Before the growth projection, a set of stand variables is computed including stand basal area, basal area sum of trees larger than the subject tree, and dominant height. If not measured, the live crown ratio is computed for each tree. The models are listed below, and the respective coefficients are given in Table A1.

Tree basal area growth:

$$i_g = \beta_0 \, e^{\beta_1 d - \beta_2 d^2} \, cr^{\beta_3} \, (21 t_{1.3})^{-\beta_4} \, G^{-\beta_5} \, H_{100}^{\beta_6} \, (h/H_{dom})^{\beta_7} \cdot \varepsilon \qquad \text{(A.1)}$$

Height growth:

$$i_h = \beta_0 \, h^{-\beta_1} \, H_{100}^{\beta_2} \, (h/H_{dom})^{\beta_3} \cdot \varepsilon \qquad \text{(A.2)}$$

Live crown ratio:

$$cr = \beta_0 \; d^{\beta_1} \; t_{1.3}^{-\beta_2} \; e^{-\beta_3(h/d)} \; G^{-\beta_4} \cdot \varepsilon \qquad (A.3)$$

To predict mortality in a stand, a two-stage procedure is used. In stands with less than full stocking, equation (A.4) is applied. It is designed to predict the average mortality in managed stands when no major damages exist. In fully stocked stands, the number of trees is first checked against the stand level self-thinning curve (equation A.5). If it is above the curve, the number of trees is reduced to meet the limiting density. The excess number of trees is distributed into different diameter classes (or elements of the tree list) in such a way that the probabilities given by equation (A.4) for each diameter class are scaled to sum up to the excess number of trees.

Tree mortality:

$$P = \frac{1}{e^{\beta_0 + \beta_1 d - \beta_2 G - \beta_3 G_{above}}} + \varepsilon \qquad (A.4)$$

Self-thinning curve:

$$\ln D_g = \beta_0 + \beta_1 \ln H_{100} - \beta_2 \ln H_{100} \ln N + \varepsilon \qquad (A.5)$$

The symbols are:

- i_g = tree basal area growth in the coming 5-year period, cm^2
- i_h = tree height growth in the coming 5-year period, m
- cr = live crown ratio, %
- P = probability of death in the coming 5-year period
- β_i = coefficients (the signs are duplicated in the equations)
- d = tree d.b.h., cm
- g = tree basal area, cm^2
- h = tree height, m
- $t_{1.3}$ = tree age at breast height, years
- G = stand basal area, m^2/ha
- G_{above} = basal area sum of trees larger than the subject tree, m^2/ha
- H_{dom} = dominant height of stand (average height of the 100 thickest trees/ha)
- H_{100} = site index (dominant height at 100 years)
- D_g = basal area weighted average d.b.h., cm
- N = number of trees per hectare
- ε = error term of regression equation

TABLE A1. Coefficients of equations used to predict stand development.

Equation	β_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7
A.1	2.583	0.1142	0.001630	0.7742	-0.3772	0.03939	-0.2551	0.8393
A.2	2.942	-0.5298	1.174	0.04218				
A.3	173.6	0.1254	-0.1811	-0.1344	-0.2192			
A.4	4.396	0.09560	0.2042	-0.1990				
A.5	1.561	1.730	-0.1750					

Individual tree pulpwood and sawtimber volumes are based on the taper curve models by Laasasenaho (1982). Logging costs (*LC*) are computed as functions of the total volume removed, v_{tot}, and the average tree volume, $\overline{v}$. Separate functions for thinnings (A.6) and final harvests (A.7) were derived based on the Finnish logging and hauling work tariffs. Costs for logging after a disastrous event are doubled.

$$\ln LC_{TH} = 5.410 - .05217 \ln \overline{v} + .02429 \ln \overline{v}^2 - .4451 \ln v_{tot} + .03969 \ln v_{tot}^2 \qquad (A.6)$$

$$\ln LC_{FH} = 5.230 - .05976 \ln \overline{v} + .02076 \ln \overline{v}^2 - .3840 \ln v_{tot} + .03273 \ln v_{tot}^2 \qquad (A.7)$$

Roadside timber values were chosen as representative of Southern Finland. They amounted to 210 Finnish marks per cubic meter for spruce sawtimber and 180 Finnish marks per cubic meter for spruce pulpwood. Total regeneration costs, including young stand tending, were taken to be 4300 Finnish marks per hectare.

The soil expectation values for the deterministic analyses are computed as an infinite series of rotations equal to the first one. For stochastic analyses, a bare land value is added to the first rotation final harvest value. In cases where stochasticity does not significantly affect the profitability of timber growing, the optimum soil expectation value of a corresponding deterministic alternative is used as the bare land value. These cases include yearly and trend growth variation. When stochasticity enters the model as the probability of a catastrophe, the level of the discounted net present value is reduced with increasing stochasticity. The bare land value of a deterministic analysis is, therefore, an overestimate. To obtain scaled down bare land values, repeated optimization runs were made iteratively for each combination of catastrophe risk levels and thinning specifications. The initial diameter distribution used in all analyses is presented in Table A2.

TABLE A2.--Diameter distribution of a pure Norway spruce stand used as the initial stand.

Diam. class	D.b.h. (cm)	Height (m)	Live crown ratio (%)	Trees per ha
1	1.9	2.6	43.1	30
2	4.3	5.1	48.8	50
3	6.2	6.9	51.7	91
4	8.2	8.5	54.1	140
5	9.9	9.7	55.8	361
6	12.1	11	57.7	470
7	13.9	11.9	59.2	489
8	15.7	12.7	60.5	231
9	17.7	13.4	61.9	50

Buford, Marilyn A., comp. 1991. Proceedings of the 1991 symposium on systems analysis in forest resources; 1991 March 3–6; Charleston, SC. Gen. Tech. Rep. SE-74. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 423 pp.

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Keywords: Land management planning, systems analysis, forest management, modeling, natural resource economics.

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