AN ABSTRACT OF THE THESIS OF

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Title: A Comparison of Prediction Models for Cover Type Transitions and Their Effects on Harvest Schedules in Coastal Oregon

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There is considerable uncertainty associated with stand establishment in coastal Oregon. Several species can gain control of the site depending on stand conditions as well as management practices. In this study, three cover type transition models were developed using data from the Siuslaw National Forest to predict stand establishment patterns in aggregate forest planning.

Two discrete alternative probability models were analyzed. The full model included the cover type and age of the mature stand before harvest as well as vegetation management treatments. The reduced model included only the cover type of the mature stand. A third model, the naive model, consisted of assigning the old-stand cover type to the regenerated stand with probability one.

Discrete alternative probability models constitute a challenge in evaluation and validation. A residual-generating procedure developed in this study allowed graphic analysis of residual plots. Although specification bias in these models remains a potential concern, the full model

gave the best fit of the models analyzed in this study.

The different cover type transition models developed here resulted in substantially different forest plans in terms of harvest levels, financial return, and forest structure. The full model produced forest plans with lower harvest levels and financial returns, but greater biological diversity, than the other models investigated in this study. These results were achieved primarily through the type-conversion effects of vegetation management treatments.

The attractiveness of vegetation management depended on minimum rotation age requirements as well as cover type conversion policies in the forest planning formulation. Vegetation management was most effective at short minimum rotation ages. Type conversion policies requiring either constant or non-decreasing biological diversity over time resulted in forest plans in which vegetation management was consistently a marginal or unprofitable investment.

Given the substantial impact of different cover type transition models on forest plan results, and the indications of systematic bias in the models tested here, additional study on predicting cover type transition patterns is recommended. Recognition of the spatial configuration of hardwood seed sources surrounding the reforestation areas is likely to be an important area of research.

A Comparison of Prediction Models for Cover Type Transitions and Their Effects on Harvest Schedules in Coastal Oregon.

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Chapter 1

INTRODUCTION

Forest planning models often have planning horizons that span several generations of forest stands on any given site. The outcome of stand establishment in turn, is often subject to considerable uncertainty. Several species can gain control of the site, depending on physical site factors, characteristics of residual vegetation, and silvicultural treatments. It is therefore important that an accurate representation of stand establishment is included in forest planning analyses.

Stand establishment may be conceptualized as a transition between the cover type of the mature stand prior to harvest and the cover type of the regenerated stand at the end of the stand establishment phase. Stand establishment can then be represented by standard forest planning formulations with embedded matrices of transition probabilities between mature and regenerated stands, where each probability represents the relative frequency of a particular cover type transition. Examples of this forest planning approach includes Johnson and Stuart (1987) and Reed and Errico (1986).

Several approaches are possible for estimating the transition probabilities in this type of forest planning formulation. Knapp et al. (1984) and Alig and Wyant (1985) estimated transition probabilities for general forest cover types as frequency averages for different forest strata. Cleaves and Birch (1991) conducted a decision analysis of reforestation strategies using expert estimates of transition probabilities. Reed and Errico (1986), in a study of the effects of wildfire on harvest schedules, estimated transition probabilities from a hypothesized negative exponential distribution of fire occurrence with a scale parameter estimated by experts. In matrix-type growth models, transition probability matrices describe transitions between states of a forest. In these models, transition probabilities have sometimes been estimated with regression models. See for example Mengel and Roise (1990), Bonnor and Magnussen (1988), and Solomon et al. (1986).

The objective of the study reported here was threefold:

1. Develop a modeling strategy for predicting uncertain stand establishment patterns in a highly aggregated strategic forest planning context. Rather than point predictions for individual sites which are either right or wrong as compared to actual outcomes, this study aimed at providing a notion of the relative frequencies of

stands across the forest that follow different stand establishment patterns. To meet this objective different cover type transition models will be fit to available data from a representative National Forest, and evaluated on their predictive power and validity.

2. Analyze the consequences of different cover type transition model specifications on the results of forest plans. Two major issues are addressed. First, the study analyses whether different model specifications result in substantially different forest plans. Second, the study attempts to answer whether each of the fitted models results in forest plans that are substantially different from the traditional rule, which states that each harvested site regenerates in its entirety to a single new cover type.
3. Analyze the effects of different vegetation management strategies on forest plans under several different management situations, using a suitable cover type transition model. To meet this objective the forest plan effects of restrictions on chemical vegetation management as well as restrictions on all types of vegetation management will be assessed.

This study aims to produce both a methodological contribution to knowledge in the area of stand establishment modeling forest planning, as well as an understanding of the potential of such models to affect forest plan results. In addition, through the use of suitable cover type transition models, the study contributes to clarifying the role of different vegetation management treatments in shaping forest plan results.

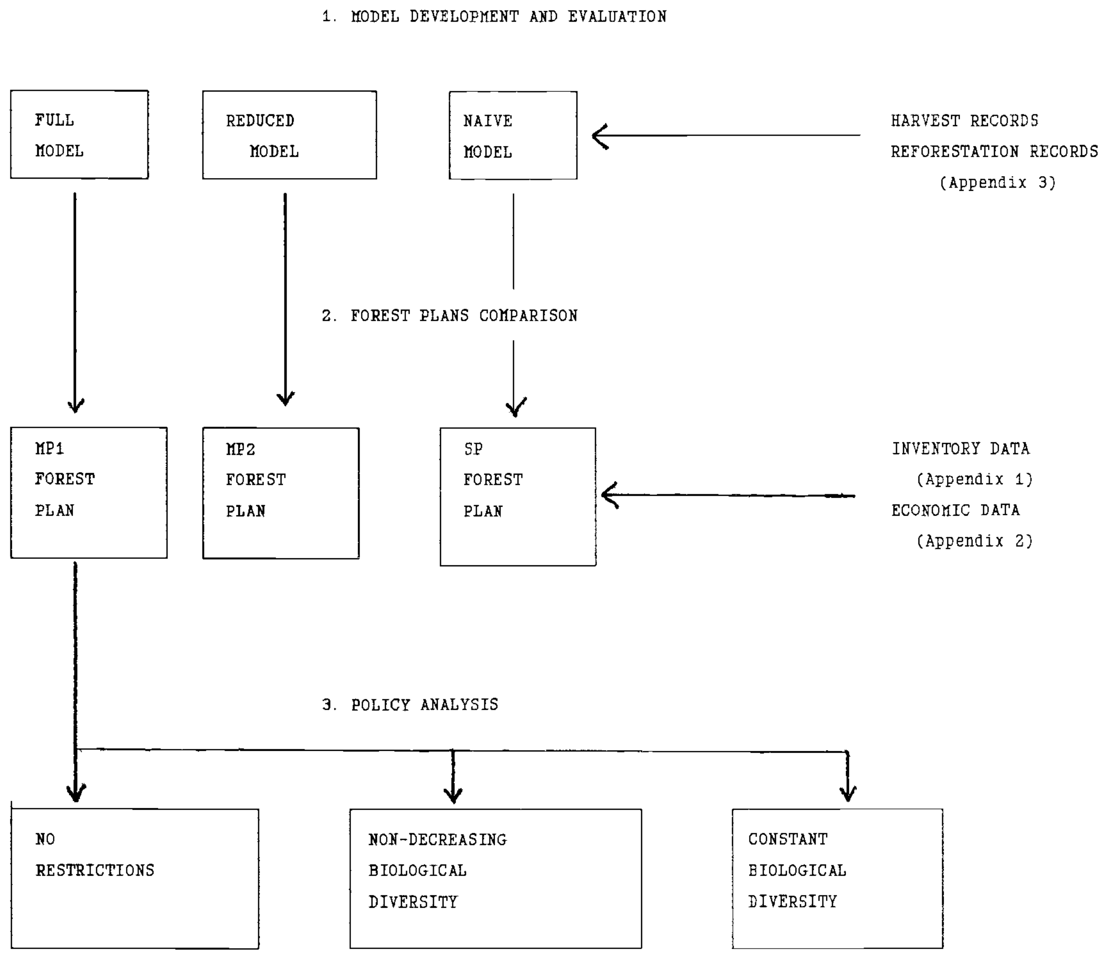
Chapter two addresses the first two objectives of the study. The first part of this chapter discusses the theoretical development and evaluation of three different cover type transition models. Then, a comparative forest planning analysis using the three models is conducted. The analysis compares the ways in which the three models affect the resulting forest plans and the differences in magnitudes of impacts.

Chapter three addresses the third objective of this study. It consists of a forest planning analysis of the Sisuslaw National Forest under different vegetation management strategies, using the cover type transition model in chapter two with the greatest predictive power. Eight different vegetation management strategies are analyzed, under management situations consisting of different minimum rotation ages and type conversion policies. Conclusions are drawn about the attractiveness of vegetation management in different situations.

Chapter 4 contains the combined literature reference section for both chapter two and chapter three. Three appendices describe the data and assumptions used in the analysis. Appendix one contains the starting parameters for existing and regenerated stands in the forest planning analyses. The data is summarized in the form in which it is used in the Siuslaw Forest Plan (USDA Forest Service, 1990). Appendix two describes the economic data used in this Forest Plan. Appendix three describes the data used to fit the cover type transition models. Appendix four documents the forest planning computer program developed for this study.

The overall structure of the analysis of this study is summarized by the flowchart in figure 1-1. In step one, three cover type transition models are developed and evaluated using the data in appendix three. In step two, the cover type transition models are incorporated into aggregate forest plans, using the inventory and economic data in appendix one and two, and the computer model described in appendix four, respectively. Finally, in step three, an analysis of different vegetation management strategies is conducted using the cover type transition model with the greatest predictive power from step two.

Figure 1-1. Flowchart of the analysis process.



Chapter 2

THE EFFECT OF DIFFERENT COVER TYPE TRANSITION MODELS ON THE RESULTS OF FOREST PLANS IN COASTAL OREGON

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ABSTRACT

There is considerable uncertainty associated with stand establishment in coastal Oregon. Several species can gain control of the site depending on stand conditions as well as management practices. In this study, cover type transition models were developed using data from the Siuslaw National Forest to predict stand establishment patterns in aggregate forest planning analyses.

Two discrete outcome probability models were analyzed. The full model included the cover type and age of the mature stand before harvest as well as vegetation management treatments. The reduced model included only the cover type of the mature stand. Finally, a decision rule termed the naive model was analyzed, which consisted of assigning the

old-stand cover type to the regenerated stand with probability one.

Discrete outcome probability models constitute a challenge in evaluation and validation. A residual-generating procedure developed in this study allowed graphic analysis of residual plots. Although specification bias in such models remains a potential concern, the full model gave the best fit of the models analyzed in this study.

Different cover type transition models resulted in substantially different forest plans, in terms of harvest levels, financial return, and forest structure. The full model produced forest plans with lower harvest levels and forest value but greater biological diversity, than the other models investigated in this study. These results were achieved primarily through the type conversion effects of vegetation management treatments.

Given the substantial impact of different cover type transition models on forest plan results, and the indications of systematic bias in the models tested here, additional study on predicting cover type transition patterns is recommended. Recognition of the spatial configuration of hardwood seed sources surrounding the reforestation areas is likely to be an important area of research.

INTRODUCTION

Stand establishment may be conceptualized as a transition in cover types between harvested and regenerated stands on the same site. The outcome of this process is subject to considerable uncertainty in the study area, located in Oregon's Coast Range (Knapp et al. 1984). Several species can conceivably gain control of the site, depending on the particular physical and environmental conditions which prevail on the site at the time of stand establishment. Silvicultural treatments such as vegetation management also affect the outcome (Walstad et al. 1987). The planning horizon in forest planning models usually spans several generations of stands on a site. An adequate representation of stand establishment is therefore essential to model accurately the structure of a forest over time in forest planning analysis this area.

The objective of this study was twofold:

1. Develop a modeling strategy for predicting uncertain stand establishment patterns in a highly aggregated strategic forest planning context. Rather than point predictions for individual sites which are either right or wrong as compared to actual outcomes, we aimed at providing a notion of the relative frequencies of stands across the forest that follow different stand establishment patterns. Meeting this part of the

objectives involved fitting different cover type transition models to available data from a representative National Forest, and evaluating their predictive power and validity.

2. Analyze the consequences of different cover type transition model specifications on the results of forest plans. Two major issues were addressed. First, we analyzed whether different model specifications result in substantially different forest plans. Second, we attempted to answer whether each of the fitted models resulted in forest plans that were substantially different from the traditional rule, which states that each harvested site regenerates in its entirety to a single new cover type.

STUDY AREA

The study area consisted of the Siuslaw National Forest, which lies primarily in the *Picea sitchensis* (Sitka Spruce) Zone of Franklin and Dyrness (1973). Two major early seral cover types are recognized in the zone: 1) coniferous, consisting of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and Sitka spruce (*Picea sitchensis* [Bong.] Carr.); and 2) hardwood, consisting of red alder (*Alnus rubra* Bong.).

Early forest development patterns in the study area reflect the competitive relationship between these two types. Red alder produces abundant seed crops every year, with bumper crops at approximately four year intervals. The light seed is easily disseminated by wind. It also regenerates through stump sprouts. As a result, there is nearly always enough seed or stump sprouts available on a site for red alder to regenerate naturally. Western hemlock is a prolific seeder, but Douglas-fir has less consistent seed production. At least one crop failure usually occurs between heavy crops (Fowells 1965).

Since moisture conditions seldom limit the development of red alder in the study area, its rapid initial height growth allows it to overtop conifers during early stand development. In typical young mixed stands of the two species groups, red alder is likely to dominate the stand.

In situations where alder seeds in heavily and no vegetation management treatments are applied, it can dominate the site to the exclusion of conifers (Hemstrom and Logan 1986). In mixed stands where conifer mortality is not excessive, alder is usually outgrown in height at age 20 to 40 years by conifers, which generally dominate the site after the first 50 years.

METHODS

Model Development

Detailed regeneration models have been developed which predict the establishment and early growth of new stands on cutover areas (Ferguson and Crookston 1991). If sufficiently detailed information existed for every stand on the forest, then predictions from such models, when accumulated over all stands, would give an accurate forest-wide picture of the cover type distribution of newly regenerated stands. When stands are aggregated into strata for planning purposes, however, much of the individual stand information is lost as a single set of average parameters is used to represent the stratum. Forest planning strata in this study, the largest of which was 26,000 acres, were based on the parameters of age, site index and cover type. Under these circumstances, a site-specific regeneration model is unlikely to provide satisfactory estimates of the different cover types that may occur and their relative frequencies.

The model reported here is designed to provide this information at the very aggregate level of detail typical of forest planning models. The response variable, which represented the cover type of regenerated stands at the end of the stand establishment phase, was divided into discrete outcome categories to facilitate prediction of the relative frequencies of each outcome. Based on past management practices and reforestation performance across the forest, the model estimates what percentage of forest strata will regenerate to each of several cover types after harvest.

Model choices for predicting the relative frequencies of several discrete alternatives includes OLS (ordinary least squares) regression, logit and probit models. The problems with using OLS regression models to predict event probabilities are well known (Judge 1985). Meaningless predictions can result since there is no guarantee that the predicted probability will lie in the interval between zero and one. The linear model is also very sensitive to the values of the explanatory variables.

Multinomial extensions of the logit and probit models, which are based on the logistic and normal distributions respectively, have been used frequently to model multiple outcome situations. The multinomial logit model (Greene 1990) is based on the assumption that error distributions are independent between outcomes. This may be an untenable assumption when modeling natural systems, where the outcome categories often are ranked in some way. In this study, the forest cover type outcome categories were intervals along a continuum of number of trees per acre by species, and as such were likely to be correlated. A test (Hausman and McFadden, 1984) of the multinomial logit model as fitted to the data in this study verified that the assumption of independent errors between outcomes is violated in this study. We concluded therefore that this model was unsuitable for analysis of the data in our study.

An ordered probit model (Zavoina and McKelvey 1975), which was used in this study to predict the cover type categories of regenerated stands, does not involve the assumption of independent errors between alternatives, and is therefore better suited for this type of analysis. Its form here is:

$$\begin{aligned} p_1 &= \Phi(\underline{x}'\underline{\beta}) \\ p_2 &= \Phi(a+\underline{x}'\underline{\beta}) - \Phi(\underline{x}'\underline{\beta}) \\ p_3 &= 1 - \Phi(a+\underline{x}'\underline{\beta}) \end{aligned} \qquad (1)$$

where

Φ denotes the normal cumulative distribution function.

P_1, P_2, P_3 are the predicted probabilities of obtaining regenerated cover type outcomes one (CONIFER), two (MIXED), and three (HARDWOOD) in plantations. Reforestation units in which between 20 percent and 49 percent of the number of trees per acre were hardwoods were classified as MIXED. Stands that fell below and above this range were classified as CONIFER and HARDWOOD stands, respectively (Turpin, 1990).

a is the second intercept parameter.

$\underline{\beta}$ is the vector of model parameters.

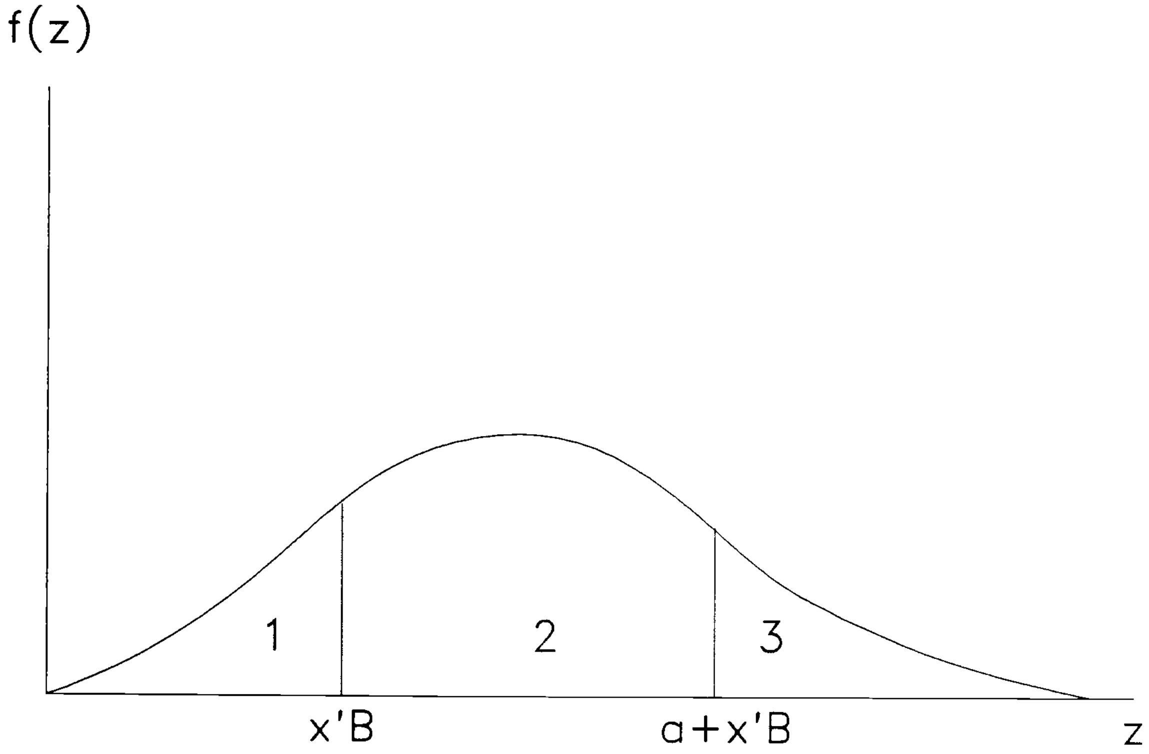
$\underline{x}$ is the vector of explanatory variables.

The structure of this model is described graphically in figure 2-1. The quantity $\underline{x}'\underline{\beta}$, the product of model parameters and explanatory variables, is measured on the horizontal axis. It separates areas under the normal probability density function, each of which represents the probabilities of occurrence for each outcome. Two features of this model specification are worth noting: 1) unlike OLS regression, in which predicted and observed responses are measured in the same units, predicted responses in the ordered probit model are outcome probabilities and observed responses are actual outcomes. 2) Unlike OLS regression, in which a predicted response is a single value, a prediction in the ordered probit model consists of the entire probability distribution of the response variable. The predicted probabilities therefore sum to one.

The following explanatory variables were used in the model:

SPOLD1, SPOLD2 are indicator variables which denote the cover type of the old stand on the site before harvest. The cover type of the old stand on the site before harvest was divided into three categories: CONIFER (SPOLD1=1, SPOLD2=0), MIXED (SPOLD1=0, SPOLD2=1), and HARDWOOD (SPOLD1=0, SPOLD2=0). If a single explanatory variable were used to explain this source of variation, a specific (in this case, linear) relationship would be assumed between that variable and the response. Rather than imposing this hypothesized

Figure 2-1. A graphical illustration of the structure of the ordered probit model.The normal probability density function is portrayed on the vertical axis as a function of the product of explanatory variables and model parameters on the horizontal axis. Numbers under the curve denote cover type outcomes 1 (CONIFER), 2 (MIXED), and 3 (HARDWOOD).



relationship on the model structure, indicator variables were used, allowing the data to suggest the underlying parametric relationship.

The cover type of the old stand on a site before harvest can influence the type of new stand that will develop after harvest through its effect on the type and amount of seeds, the characteristics of the residual understory vegetation after harvest, and the abundance of red alder stump sprouts. The cover types were given on timber sale examination records by Siuslaw National Forest personnel. They were defined by Forest personnel in the same way as for the response variable (Turpin, 1990): CONIFER stands consisted of less than 20 percent hardwoods by trees per acre. MIXED stands had between 20 and 49 percent hardwoods, and HARDWOOD stands contained more than 50 percent hardwoods.

This definition did not necessarily imply a spatially even distribution of both species groups throughout the stand. Stands could consist of conifers throughout with localized clumps of red alder (Turpin 1980). The cover type definitions did not take into account the relative canopy position of the two species groups. Since most of the stands measured were even-aged, however, the number of trees per acre was considered a suitable criterion for distinguishing between species categories in the study area.

AGEOLD: the age in years of the stand component with the largest number of trees per acre in the overstory. As the age of the stand increases, it is likely to be increasingly dominated by the longer-lived conifers as the shorter-lived hardwoods die. Most of the stands in the data set were less than 120 years old.

MNLVEG: manual vegetation management treatments applied to the new stand after harvest. Silvicultural treatments applied to the regenerated stand during the stand establishment phase by design influence the cover types that result. Manual methods denote the removal or neutralization of unwanted species with hand or power tools. The high cost of this treatment often prohibited treating the entire unit at each entry. Many units were treated more than once during the stand establishment phase.

In order to capture the variation in both the number of stand entries and the fraction of the area treated at each entry, this variable was measured as a ratio of the total area treated after all stand entries, divided by the area of the reforestation unit. The units of measure of this variable can thus be thought of as the number of equivalent whole area treatments that have been administered by the end of the five-year stand establishment phase. The data were obtained from reforestation records that specified the number of entries and area treated at each entry. The model was fitted to data describing values of this variable of up to 3.0.

CHMVEG: Chemical vegetation management treatments applied to the new stand, measured in the same way as MNLVEG. Chemical methods denote the elimination of unwanted species with herbicides, and includes aerial spraying and manual application. The greatest value of this variable in the data set used to fit the model was 2.0.

Both variables MNLVEG and CHMVEG were broadly defined to include all site preparation and stand release treatments up to the end of the stand establishment phase. Although site preparation and stand release from a silvicultural point of view are distinctly different treatments, it appeared that in this study the benefits achieved in terms of a smaller number of model parameters warranted this aggregation. In addition to the treatments represented by these variables, two default site treatments were assumed in all cases: initial soil scarification to expose mineral soil and slash burning. During the period of time described by the data in this study, these two treatments were established silvicultural practices on the Siuslaw National Forest to the extent that most reforestation units had received some form of site disturbance, either from the logging operation or from subsequent treatment, and some form of slash burning.

The data for the model were collected from treatment records on 172 different stands throughout the Siuslaw National Forest and from research data. The treatment record data consisted of observations on a site at two points in time. Timber sale preparation surveys provided information about cover type and age of the old stand on a site before harvest. Reforestation surveys at age five years provided the cover type of the new stand on the same site after harvest, along with records of the amount and type of vegetation management treatments applied. The end of the stand establishment phase was defined to occur at age five years. This definition was designed to restrict the scope of the model to the beginning of the forest development sequence when stand establishment occurs. Future treatments that may influence the cover type of the new stand, such as precommercial thinning, can be represented in the forest planning models for which this model was developed.

The model was not intended for detailed site-specific silvicultural predictions. Rather, it was developed for prediction of large-scale cover type transition patterns in a highly aggregate strategic forest planning context. The model is therefore only a gross approximation of the complex nature of forest stand establishment. Processes such as seed dispersal, herbaceous vegetation development, reforestation, early growth and mortality, and physical site factors were only considered indirectly through their influence on the explanatory variables in the model.

Maximum likelihood estimates of the model parameters (SAS Institute Inc. 1989) for the full model and the reduced model with old-stand cover type as the only explanatory variables are given in table 2-1. The reduced model, containing only the cover type of the old stand, is equivalent to the cover type transition probability matrix of Johnson and Stuart (1987). It was fitted in this study for comparison with the full model. The table also shows the maximized value of the log-likelihood functions for both models, as well as for the model with all parameters but the constant term set to zero. The likelihood ratio index ρ^2 (Judge 1985), which is an analogous statistic to R^2 in OLS regression, is shown for both models.

A third model, termed the naive model, was also investigated in this study. Under this model, the same species was perpetuated over all harvests. Mathematically, this model can be described as

$$\begin{aligned} P_j &= 1 \text{ if cover type before harvest } = j \\ &= 0 \text{ else} \end{aligned}$$

where $j = 1,2,3$ denotes the cover type.

Table 2-1. Maximum likelihood estimates of the model parameters for the full model and the reduced model. Explanatory variables are cover type of the old stand (SPOLD1, SPOLD2), age of the old stand (AGEOLD), manual vegetation management (MNLVEG), and chemical vegetation management (CHMVEG). Estimated standard errors and p-values for the t-statistic testing significance of the coefficients are shown in parentheses.

	Full Model			Reduced Model		
Explanatory Variables	Coefficient	Standard Error	P-value	Coefficient	Standard Error	P-value
CONSTANT	-5.4009	0.690	0.0001	-1.0405	0.266	0.0001
SPOLD1	1.8251	0.434	0.0001	2.0730	0.300	0.0001
SPOLD2	1.1071	0.402	0.006	1.1517	0.301	0.0001
AGEOLD	0.04129	0.0057	0.0001			
MNLVEG	0.8340	0.201	0.0001			
CHMVEG	1.4855	0.420	0.0004			
INTERCEPT 2	1.7165	0.254		0.9950	0.147	

Full Model: Log likelihood = -73.7 $\rho^2 = 0.496$

Reduced Model: Log likelihood = -119.1 $\rho^2 = 0.185$

CONSTANT: Log likelihood = -146.2

Number of observations: 172

Model Validation

Model validation usually involves some type of comparison between predicted and observed responses. In the case of the discrete event probability model used in this study however, a direct comparison is not meaningful because observations consist of actual outcomes whereas predictions consist of a vector of probabilities. Although various rules-of-thumb defining proxies for predicted outcomes have been devised, these rules are inherently inaccurate since the rules themselves introduce an unknown amount of error.

A frequently used decision rule prescribes defining the predicted outcome as that associated with the highest predicted probability (Greene 1990). This rule is always biased except in the special case where the maximum probability is one. The bias is greatest when the outcomes have equal or nearly equal predicted probabilities. For example, in a three-outcome case in which predicted probabilities are P_1 - 0.333, P_2 - 0.332, and P_3 - 0.334, the predicted outcome will be outcome three. Residuals (the discrepancy between predicted and observed values) based on this predicted outcome however, will have little meaning.

Alternative criteria for model evaluation and validation, which we used in this study included: goodness-of-fit statistics, prediction success tables, graphical analysis of residuals from subsamples, and evaluation of the stability of parameter estimates over subsamples. The scarcity of data available to fit the models in this study precluded setting aside a separate validation data set. Instead, residuals and parameters were estimated from subsets of the data used to fit the model.

Goodness-of-fit: a likelihood ratio test (Mendenhall et al. 1981) of the full model in table 2-1 versus the model containing only the constant term showed that the full model explained a significant amount of the variation in the response variable. The reduced model, containing only the cover type of the old stand, is equivalent to the cover type transition probability matrix of Johnson and Stuart (1987). A likelihood ratio test showed that the variables AGEOLD, MNLVEG, and CHMVEG in the full model added significant explanatory power to the reduced model. This result, as well as the large difference in likelihood ratio index (ρ^2) values between the full and reduced model, supports the hypothesis that the reduced model does not explain all the variation in forest stand establishment in the study area.

The structure of discrete event probability models results in goodness-of-fit statistics that are usually less impressive than those often found in for example ordinary least squares models. A prediction from a discrete event probability model must exhibit a complete normal probability density function of outcomes, with all outcomes assigned a non-zero probability, regardless of the actual outcome.

Hensher and Johnson (1981) warned about comparing the likelihood ratio index to its OLS equivalent:

> "values of ρ^2 between 0.2 and 0.4 are considered extremely good fits so that the analyst should not be looking for values in excess of 0.9 as is often the case when using R^2 in ordinary regression".

Prediction success: prediction success tables (Hensher and Johnson 1981) involve comparing the expected number of observations, given a particular model, in each outcome category with the observed numbers in each outcome category, for an entire sample data set.

Define $N_{ij} = \sum_{t=1}^{T} f_{ti} \, P_{tj}$

where N_{ij} is the sum, over all observations in the sample data set, of predicted probabilities of outcome j for observations on which the observed outcome was i. Given the prediction model, this is the expected number of observations for which the observed outcome is i and the predicted outcome is j.

f_{ti} is an indicator variable which equals one if the observed outcome for observation t is i , and zero otherwise.

T is the number of observations in the sample data set.

P_{tj} is the predicted probability of outcome j for observation t.

Table 2-2 shows a prediction success table for the full model, the reduced model and the naive model, based on the

Table 2-2. Prediction success table for the full, reduced and naive models. Table entries represent the expected number, given the particular model, of sample observations for which the observed outcome is i (row) and the predicted outcome is j (column). Percent correct is the diagonal table entry divided by the corresponding column total.

FULL MODEL:

Observed Outcomes	Predicted outcomes 1 CONIFER	 2 MIXED	 3 HARDWOOD	Total
1 CONIFER	101.150	12.978	.872	115.000
2 MIXED	12.282	16.670	8.048	37.000
3 HARDWOOD	2.812	4.992	12.196	20.000
Total	116.244	34.639	21.116	172.000
% Correct	.870	.481	.578	.756

REDUCED MODEL:

Observed Outcomes	Predicted outcomes 1 CONIFER	 2 MIXED	 3 HARDWOOD	Total
1 CONIFER	87.224	20.513	7.263	115.000
2 MIXED	20.815	10.042	6.143	37.000
3 HARDWOOD	7.362	5.798	6.840	20.000
Total	115.401	36.353	20.246	172.000
% Correct	.756	.276	.338	.605

Table 2-2. (Continued).

NAIVE MODEL:

Observed Outcomes	1 CONIFER	2 MIXED	3 HARDWOOD	Total
	Predicted outcomes			
1 CONIFER	86.000	25.000	4.000	115.000
2 MIXED	10.000	21.000	6.000	37.000
3 HARDWOOD	4.000	4.000	12.000	20.000
Total	100.000	50.000	22.000	172.000
% Correct	.860	.420	.545	.692

172 observations in the data set. Each table entry represents a value of the variable N_{ij} . Each diagonal table entry, representing the sample sum of predicted probabilities for a particular outcome given the identical observed outcome, can be interpreted as the expected number of correct predictions in the sample. Conversely, off-diagonal table entries, which represent the sample sum of predicted probabilities for a particular outcome given a different observed outcome, can be interpreted as the expected number of incorrect predictions.

Row totals represent the observed number in each outcome category in the data set. Similarly, column totals represent the expected number in each outcome category in the sample, given a particular prediction model. The percentage of correct predictions was defined as the expected number of correct predictions divided by the total expected number in each outcome category, or the ratio between each diagonal table entry and the corresponding column total. It follows that in a model with perfect fit all off-diagonal table entries must be zero.

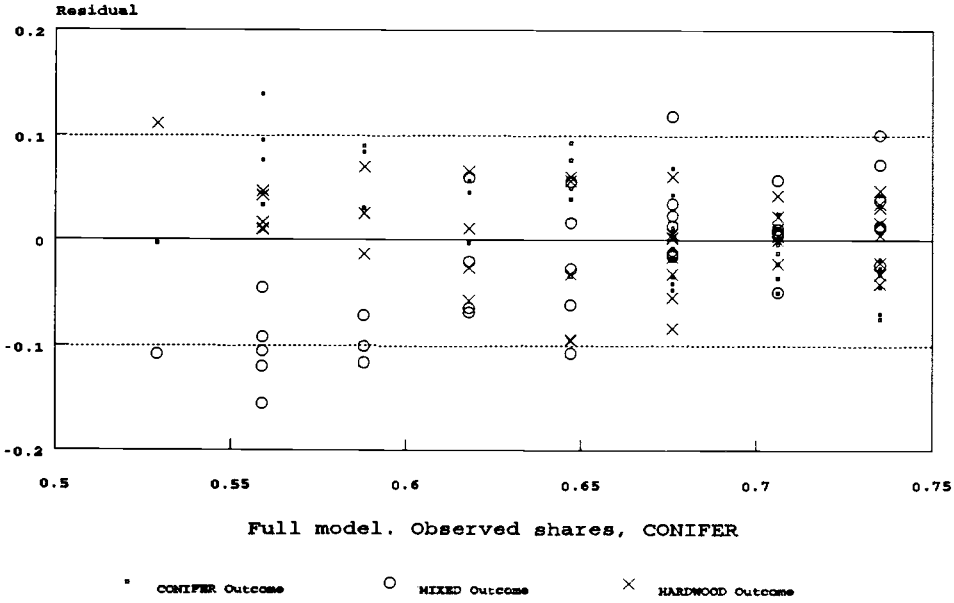
The table shows that the full model has the highest percentage of correct predictions both overall and for the individual outcomes. The naive model had a greater percentage of correct predictions than the reduced model, for all outcomes as well as overall. This part of the model evaluation therefore suggested that the reduced model explained less of the variation in the response than both the full model and the naive model. This result demonstrates the problem of omitted variable bias in regression analysis.

Residual analysis: because residual plots for individual observations are not meaningful, we used a subsampling procedure to obtain repeat observations of overall subsample residuals. Forty validation data subsets of 20 percent (34 observations) and estimation data subsets of 80 percent (138 observations) were drawn from the complete data set of 172 observations used to fit the full and reduced models. Random sampling without replacement was used in order to enable an evaluation of model performance over randomly drawn subsets of the data, and to avoid drawing the same observation twice in the same data subset. The random number generator DRAND (Law and Kelton 1982) was used to sample observations for the validation data set, leaving the remaining 138 observations for the estimation data set.

One residual was obtained for each validation data set by fitting a model to the estimation set and then using the fitted model to predict the observations in the validation set. Predicted shares in the validation set were defined according to the above prediction success tables as the expected number of observations with a given outcome (column totals) divided by the sample size. Equivalently, observed shares were defined as the observed number of observations with a given outcome (row totals) divided by the sample size. The difference between the predicted and observed shares was interpreted as an overall residual for that validation data set.

Figure 2-2 shows plots of these subsample residuals for the full model. Each graph portrays residuals for the outcomes CONIFER, MIXED and HARDWOOD versus observed shares for one of the three outcomes. The figures indicate some degree of specification bias in all models, as measured by the trend in the residual plots. For low values of the observed share of the CONIFER outcome, as shown in the top graph in figure 2-2, the models tended to overpredict CONIFER results. As the observed share increased, the residual values decreased, and eventually became negative. The residuals for the MIXED outcome showed an opposite compensating trend. The residual plots from the reduced model, shown in figure 2-3, exhibited similar but more prevalent trends. Also, the residuals under the reduced model were generally greater than under the full model. The residuals from the naive model, shown in figure 2-4, exhibited systematic trends which were more severe than those in either the full model or the reduced model. In addition, residuals for a given outcome from the naive model tended to lie exclusively either above or below zero.

Figure 2-2. Full model residuals (predicted minus observed sample shares) for outcome 1 (CONIFER), 2 (MIXED), and 3 (HARDWOOD), versus observed shares. Each graph represents observed shares for one cover type outcome.



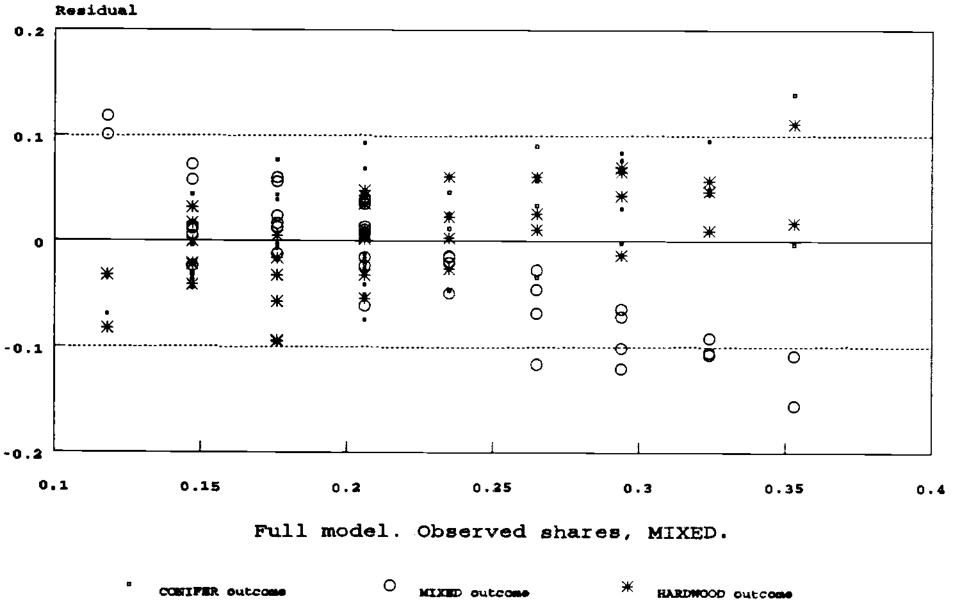


Figure 2-2. (Continued).

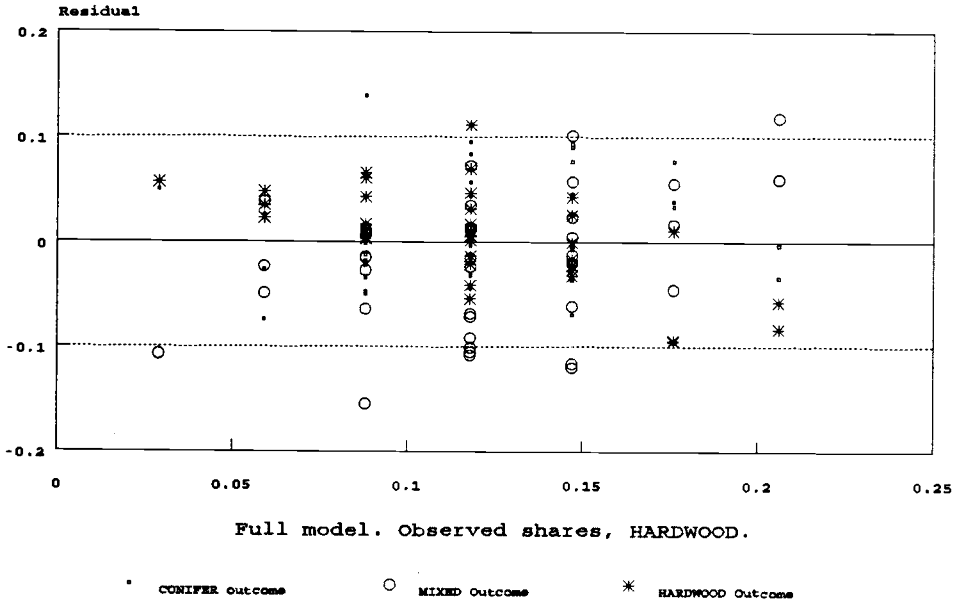
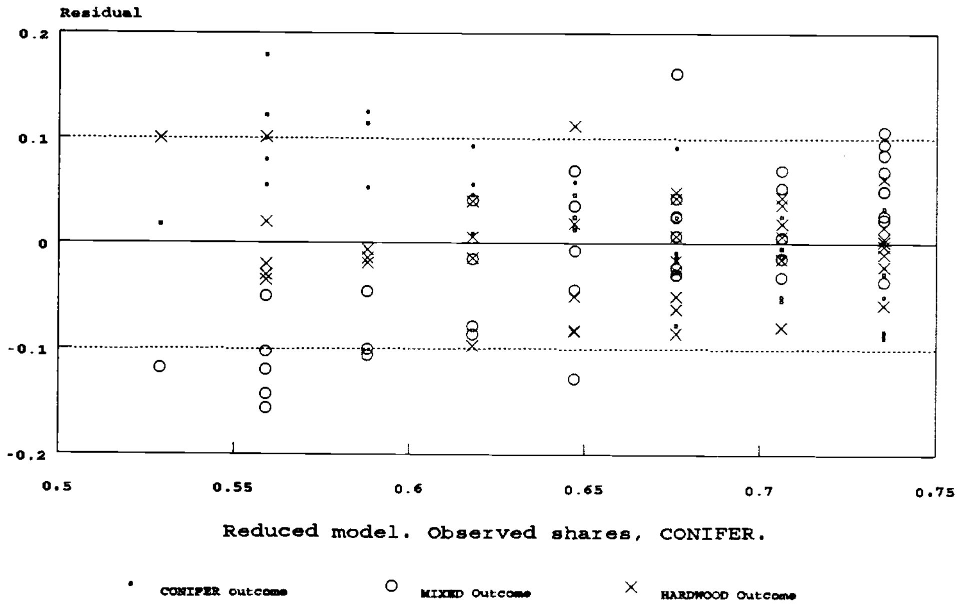


Figure 2-3. Reduced model residuals (predicted minus observed sample shares) for outcome 1 (CONIFER), 2 (MIXED), and 3 (HARDWOOD), versus observed shares. Each graph represents observed shares for one cover type outcome.



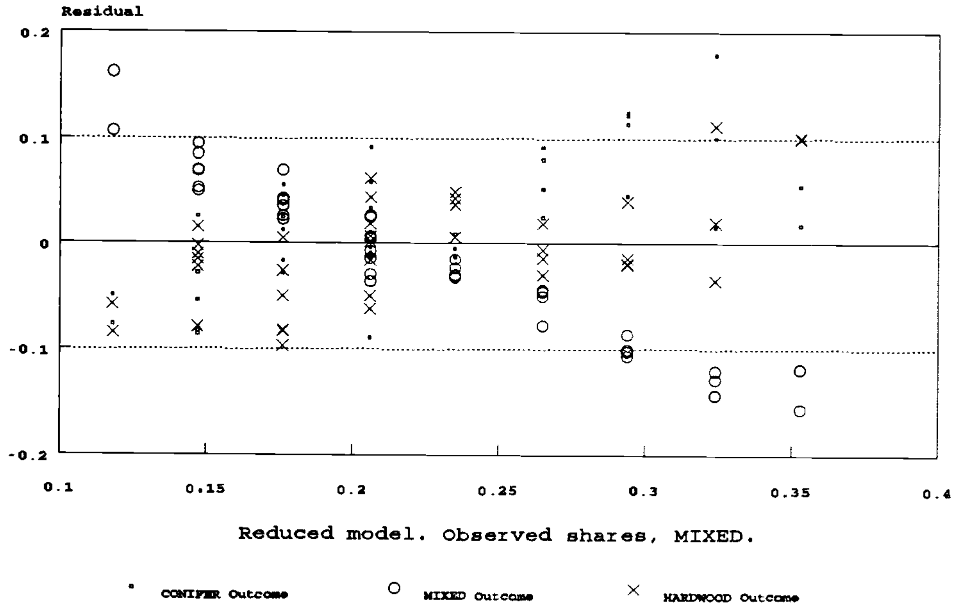


Figure 2-3. (Continued).

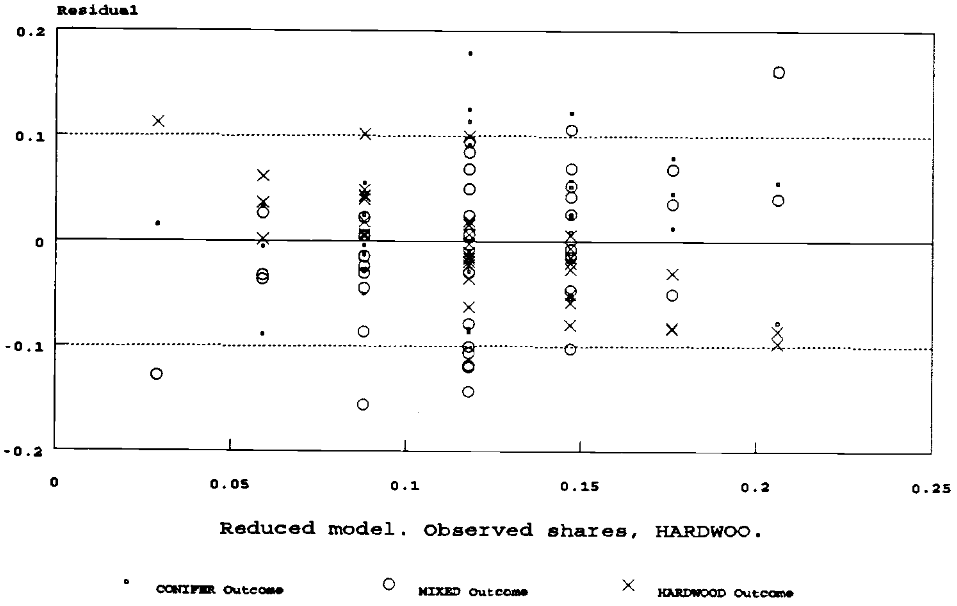
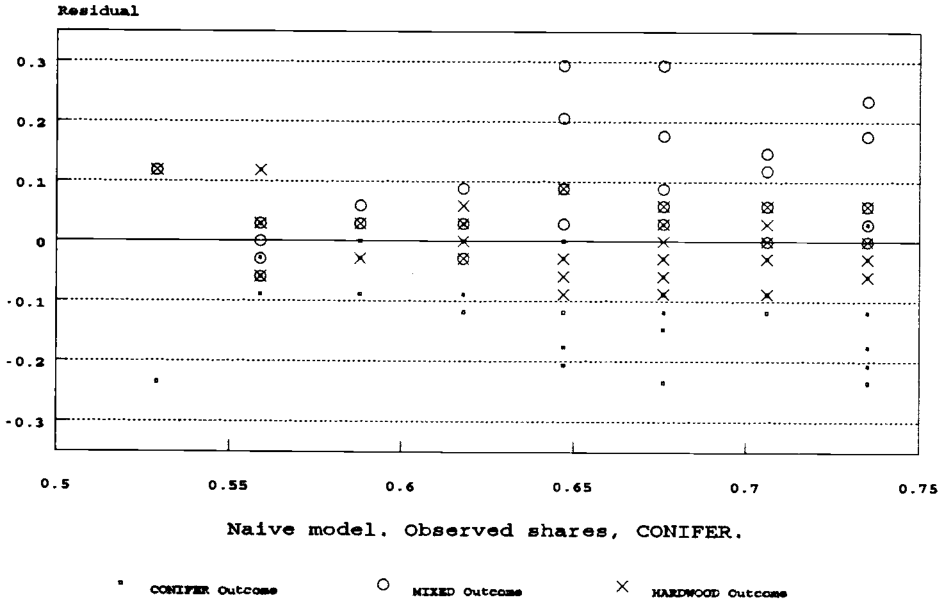


Figure 2-4. Naive model residuals (predicted minus observed sample shares) for outcome 1 (CONIFER), 2 (MIXED), and 3 (HARDWOOD), versus observed shares. Each graph represents observed shares for one cover type outcome.



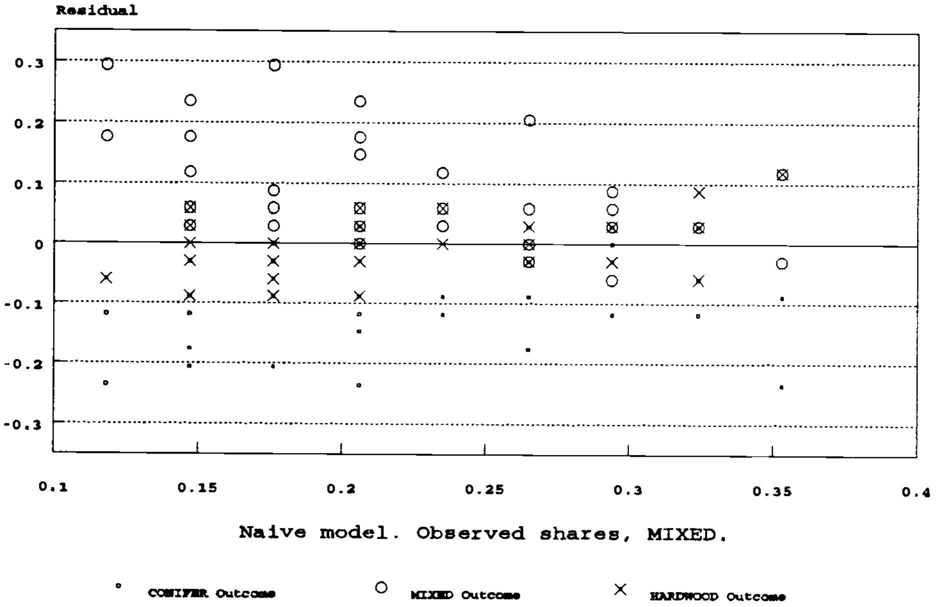
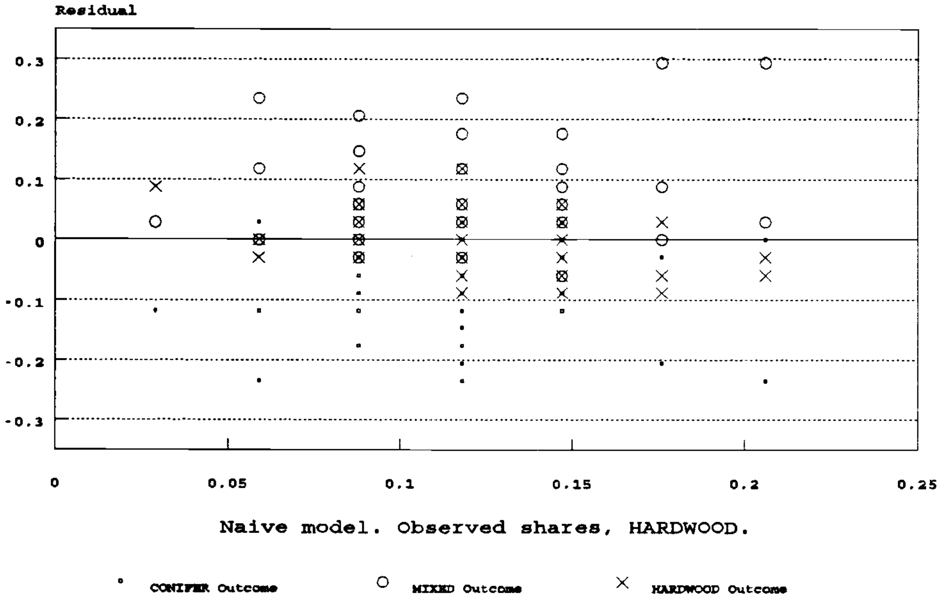


Figure 2-4. (Continued).



Parameter stability: table 2-3 shows a summary of the mean and ranges of parameters for the full model and the reduced model, fitted to the estimation data sets of 40 random subsamples consisting of 80 percent of the observations in the complete data set. None of the parameter estimates appeared excessively unstable. The spread in most parameter estimates was 30 percent of the mean or less in either direction.

In summary, the full model had less systematic bias and gave better goodness-of-fit statistics than the reduced and naive models. It was therefore judged to be the most suitable for cover type prediction of the three models analyzed here. The naive model had better goodness-of-fit scores than the reduced model as measured by the prediction success table, but had more systematic bias than did the reduced model.

It is not obvious what degree of systematic trends in residual plots should be considered acceptable when using these models in a strategic forest planning analysis. Interpretation of validation results is inherently subjective, and is often carried out with reference to an implicit standard of acceptability based on results from previous similar studies. Comprehensive validation of discrete event probability models is rare however, possibly due to the methodological difficulties involved. Literature review did not reveal any other applied studies of discrete

Table 2-3. Summary of parameter estimates for the full model and the reduced model based on 40 random subsamples of 80 percent of the complete data set. The mean as well as the standard error, minimum and maximum value of each parameter is given.

	Full Model				Reduced Model			
	Mean	Standard Error	Minimum	Maximum	Mean	Standard Error	Minimum	Maximum
CONSTANT	-5.562	0.077	-7.265	-4.904	-1.023	0.023	-1.339	-.788
SPOLD1	1.879	0.041	1.344	2.678	2.062	0.026	1.776	2.472
SPOLD2	1.167	0.036	0.798	1.673	1.147	0.025	0.873	1.480
AGEOLD	0.042	0.000	0.036	0.055				
MNLVEG	0.880	0.018	0.675	1.097				
CHMVEG	1.567	0.042	1.241	2.341				
INTERCEPT 2	1.769	0.038	1.500	2.631	0.996	0.015	0.847	1.260

alternative probability models in which graphical analysis of residuals had been used for validation: this effort appears to be the first attempt to do so. Also, residuals as defined in this study represent a measure of model fit for each subsample. As shown, goodness-of-fit statistics for discrete alternative probability models are usually less impressive than those of traditional OLS models.

Although systematic trends exist in the residual plots for all the models analyzed in this study, the trends in the residuals tended to counterbalance across outcomes. Also, the estimated parameters of the full model and the reduced model were fairly stable over the sample space.

Possible improvements to the full model developed in this study might include increasing the number of possible cover type outcomes for the response variable. This would give a more detailed notion of the possible stand establishment patterns. Additional explanatory variables could be investigated, including site quality, aspect, elevation, and the type of harvest, site preparation, and reforestation methods. Red alder often becomes established in the study area by seeding in from adjacent areas. Thus, a representation of the spatial configuration of different cover types would allow recognition of the seed sources surrounding each reforestation area.

Reaction Profiles

Figure 2-5 shows the results of model simulations of the full model for different values of the variable MNLVEG. This variable was evaluated across its sample range with AGEOLD set to 60 years and CHMVEG set to zero. Each graph represents one of the three possible values of the cover type of the old stand before harvest. Figure 2-6 shows the same simulations for chemical vegetation management methods. The figures show that on the average reforestation unit with an old-stand cover type of either CONIFER or MIXED, the probability of achieving a new stand of a non-HARDWOOD type was close to one when the reforestation unit was given two whole-area treatments with either manual or chemical vegetation management methods. When the old-stand cover type was HARDWOOD, the probability of obtaining a non-HARDWOOD cover type was still greater than 0.5 if the reforestation unit was treated twice with either manual or chemical vegetation management methods. Chemical vegetation management methods were somewhat more effective than manual methods.

Figure 2-7 demonstrates that the explanatory variable AGEOLD had the same effect as vegetation management. Increasing values of this variable resulted in an increasing probability of obtaining a non-HARDWOOD outcome.

Figure 2-5. The effect of manual vegetation management on regenerated cover type outcome probabilities. Age of the mature stand at harvest is 60 years. No chemical vegetation management. A) Old-stand cover type = CONIFER. B) Old-stand cover type = MIXED. C) Old-stand cover type = HARDWOOD.

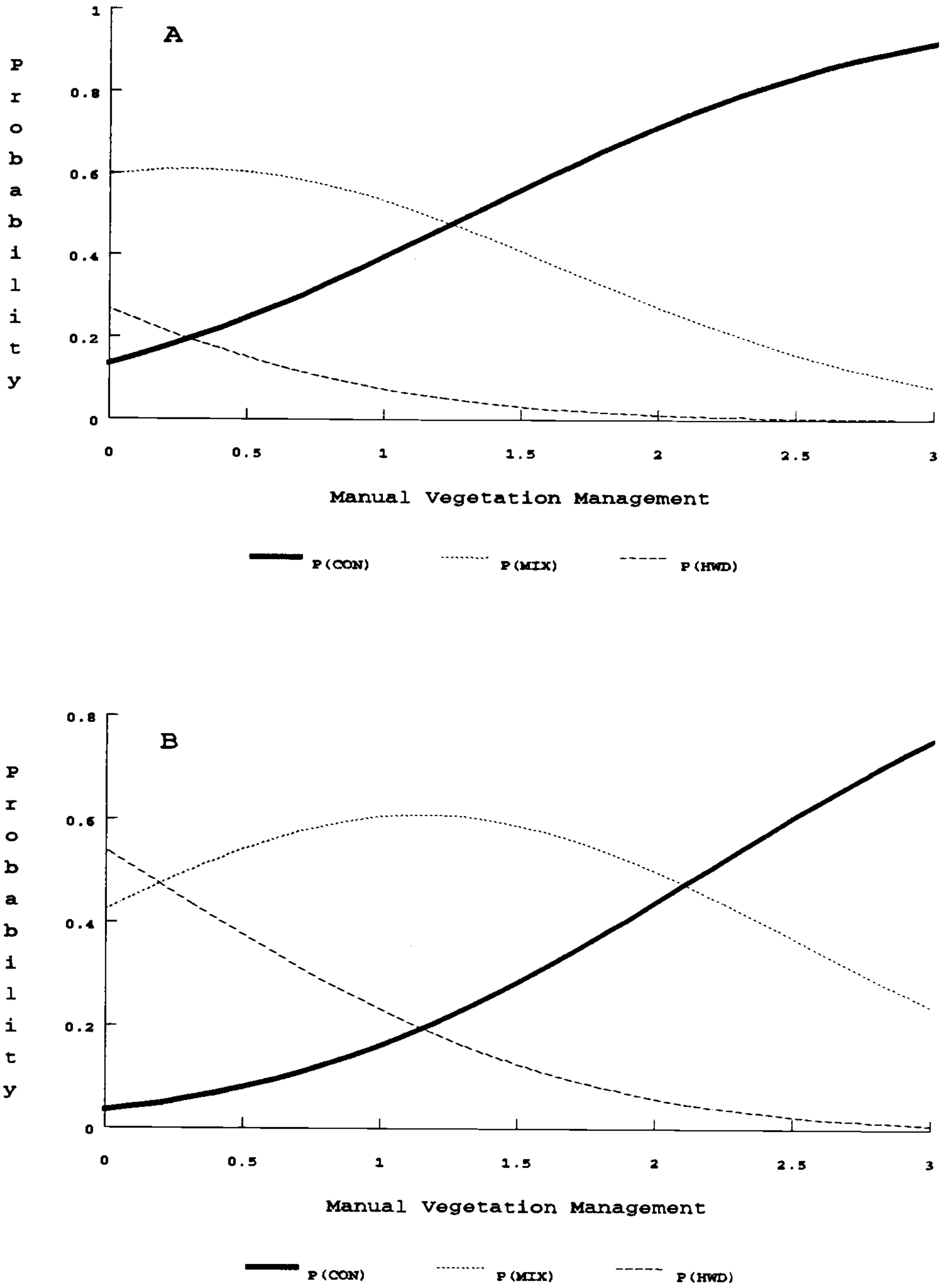


Figure 2-5. (Continued).

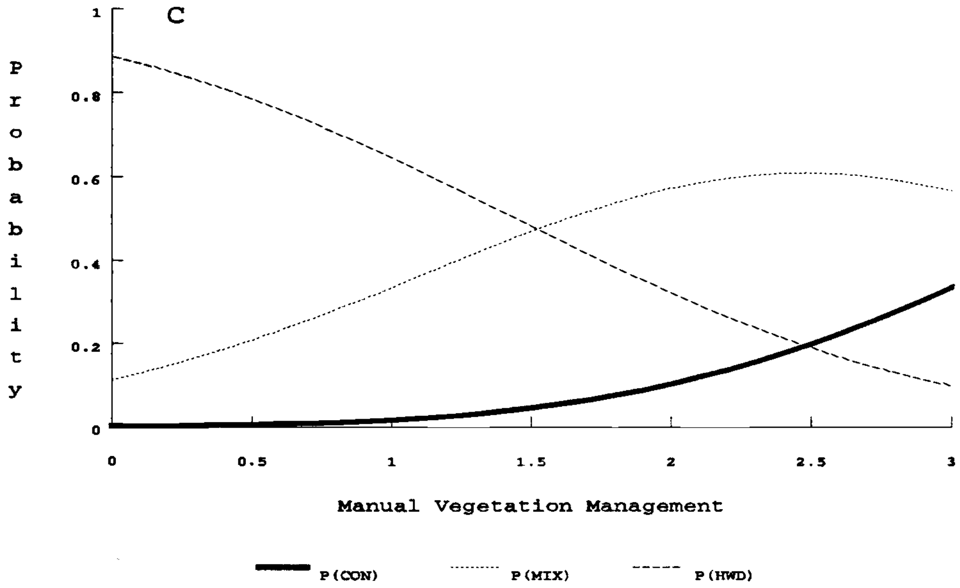


Figure 2-6. The effect of chemical vegetation management on regenerated cover type outcome probabilities. Age of the mature stand at harvest is 60 years. No manual vegetation management. A) Old-stand cover type = CONIFER. B) Old-stand cover type = MIXED. C) Old-stand cover type = HARDWOOD.

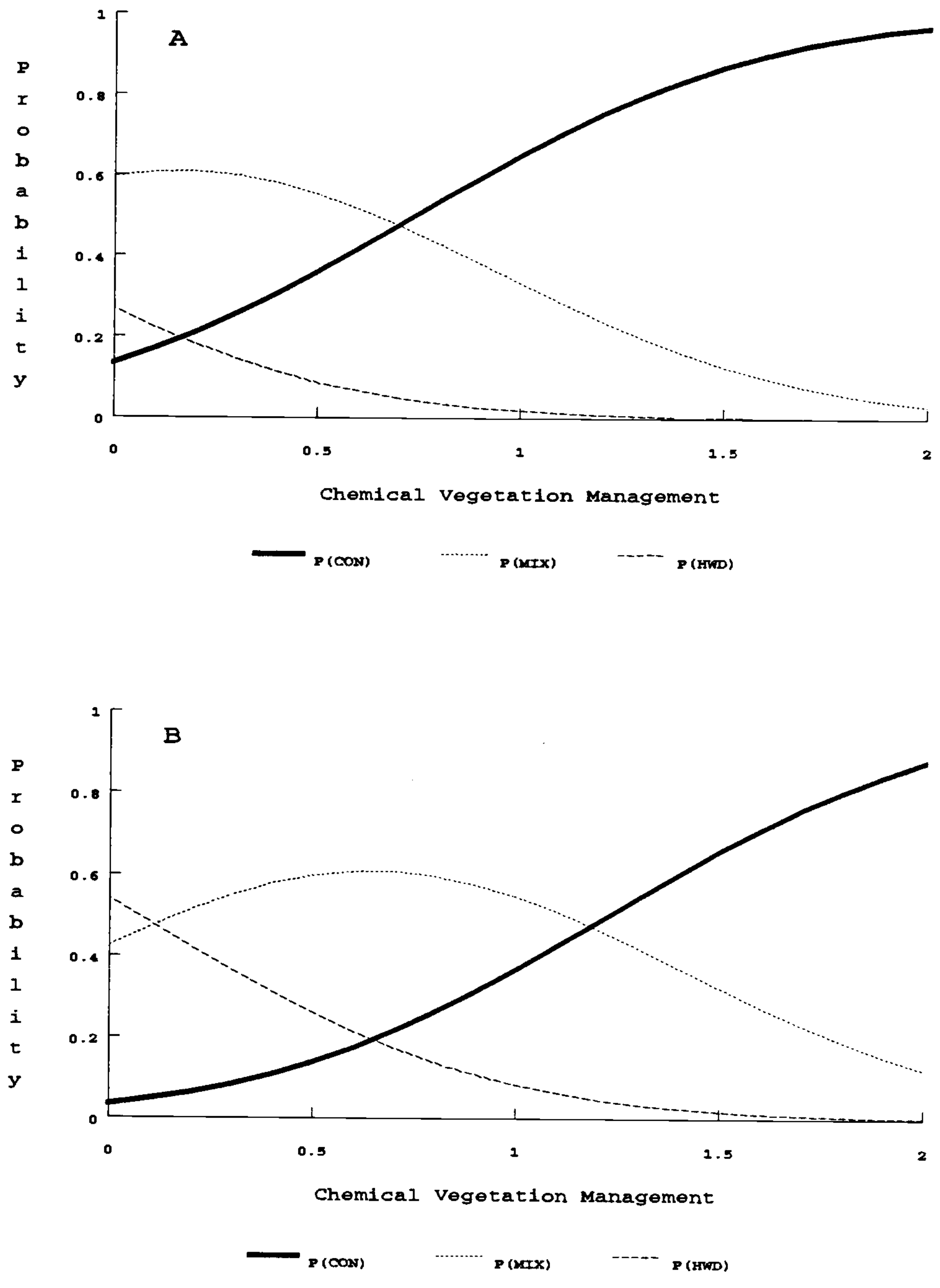


Figure 2-6. (Continued).

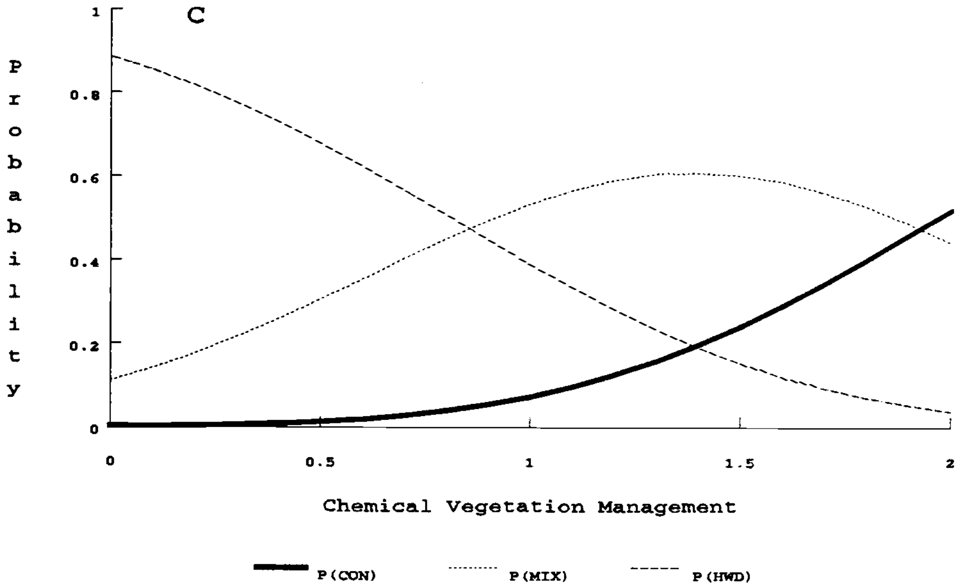


Figure 2-7. The effect of old-stand age on regenerated cover type outcome probabilities. No manual or chemical vegetation management. A) Old-stand cover type = CONIFER. B) Old-stand cover type = MIXED. C) Old-stand cover type = HARDWOOD.

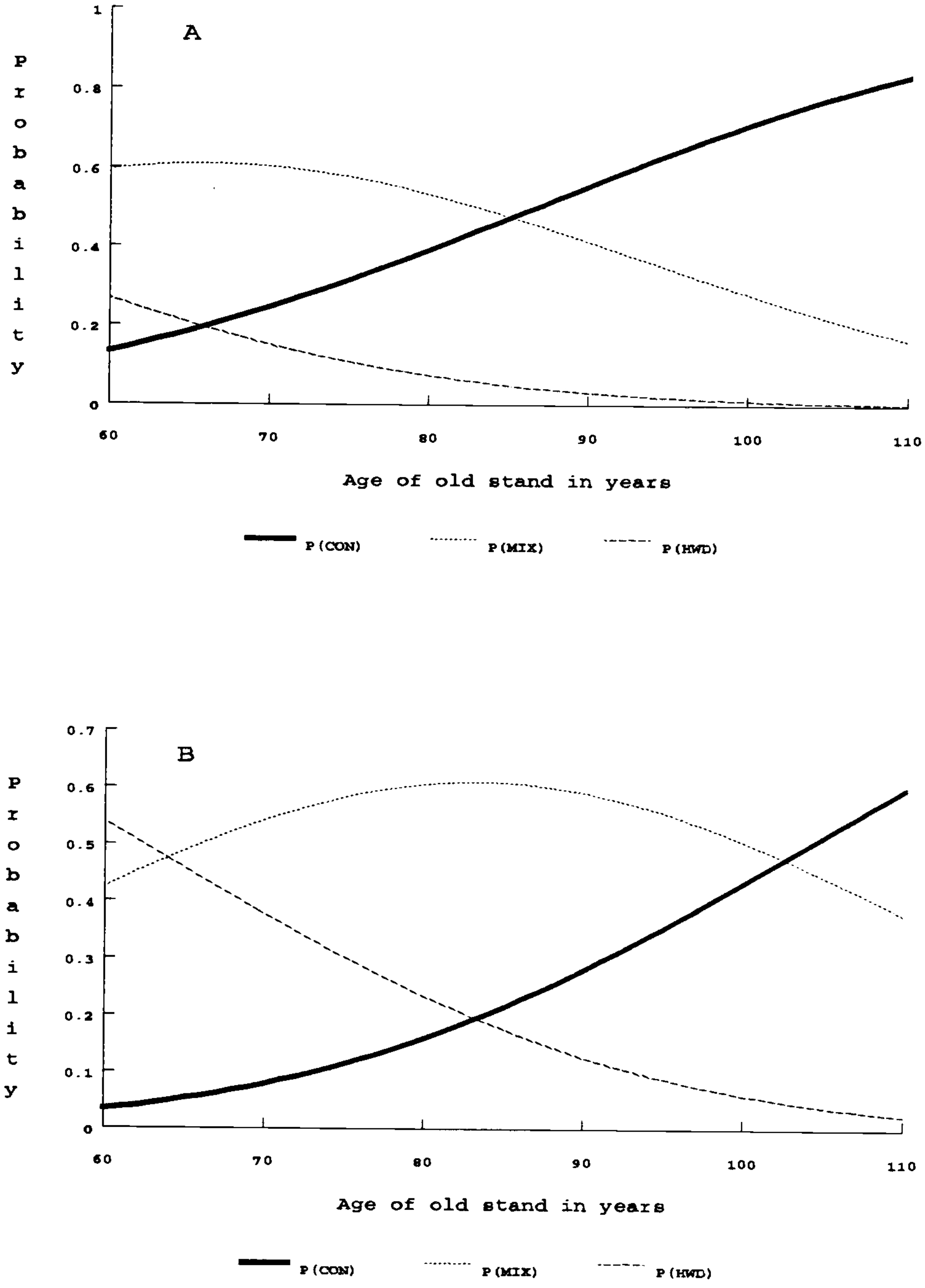
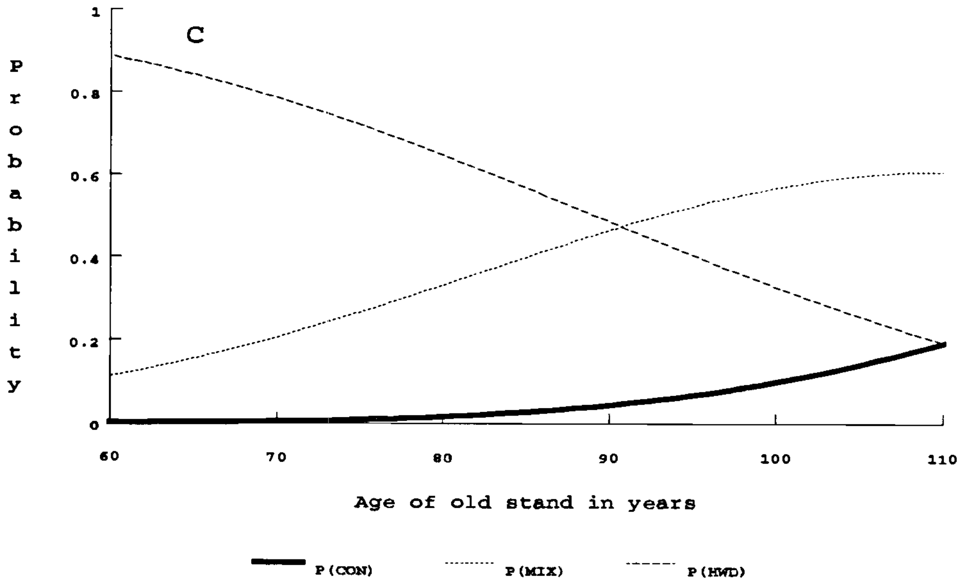


Figure 2-7. (Continued).



In summary, the figures indicated that increasing values of the variables MNLVEG, CHMVEG and AGEOLD unambiguously resulted in an increasing probability of the CONIFER type and a decreasing probability of the HARDWOOD type. The probability of obtaining the MIXED cover type initially remained constant or increased, then decreased.

The cover type transition probability matrix resulting from the reduced model in table 2-1 is shown in table 2-4. A comparison of the figures in this table with the graphs in figure 2-5 demonstrates that the difference in predictions between the full model and the reduced model can be substantial. For example, the reduced model predicted that the probability of obtaining a CONIFER regenerated cover type when the old stand before harvest was of type CONIFER was 0.85. The full model in figure 2-5 predicted the same probability to be approximately 0.4, assuming one whole-area treatment of manual vegetation management and an old-stand age of 60 years.

Comparison of Forest plans

Recent developments in forest planning models include ways to represent the uncertain nature of forest development. Different development patterns, each with an associated probability of occurrence, are embedded as transition probability matrices in forest planning

Table 2-4. Cover type transition probability matrix resulting from the reduced model in table 2-1.

	After Harvest		
Before Harvest	CONIFER	MIXED	HARDWOOD
CONIFER	0.85	0.13	0.02
MIXED	0.54	0.32	0.14
HARDWOOD	0.15	0.33	0.52

formulations (Reed and Errico 1986, Johnson and Stuart 1987). This type of formulation was used in this study to develop three different forest planning formulations, each incorporating a different cover type transition model (full, reduced and naive).

In the full model in table 2-1, the probability of a given regenerated cover type was a function of the cover type and age of the old stand before harvest along with manual and chemical vegetation management treatments applied to the new stand after harvest:

$P_j = f(SPPOLD, AGEOLD, MNLVEG, CHMVEG)$

The forest plan incorporating the predictions from the full model will hereafter be referred to as the MP1 (multiple path 1) formulation:

$$\text{Maximize} \quad \sum_{s=1}^{S} \sum_{i=1}^{3} \sum_{m=1}^{M} \sum_{h=1}^{H+1} \sum_{r=b}^{h-g} c_{simrh}^{t_h} \, x_{simrh}^{t_h} \qquad (3)$$

subject to

$$\sum_{i=1}^{3} \sum_{m=1}^{M} \sum_{h=1}^{H+1} \sum_{r=b}^{h-g} x_{simrh}^{t_h} = A_s \qquad s=1,\ldots,S \qquad (4)$$

(Existing stands acreage accounting constraints)

$$\sum_{m=1}^{M} \sum_{r=b}^{h-g} \sum_{i=1}^{3} (p_j \mid m, r, h, t_h) \; x_{simrh}^{t_h} = \sum_{m=1}^{M} \sum_{q=h+g}^{H+1} x_{sjmhq}^{j_h} \qquad (5)$$

$$j=1,\ldots,3, \quad h=1,\ldots,H, \quad s=1,\ldots,S$$

(Regenerated stands acreage accounting constraints)

$$\sum_{s=1}^{S}\sum_{i=1}^{3}\sum_{m=1}^{M}\sum_{h=1}^{H+1}\sum_{r=b}^{h-g} y_{simrh}^{k} x_{simrh}^{t_h} \leq$$

$$\sum_{s=1}^{S}\sum_{i=1}^{3}\sum_{m=1}^{M}\sum_{h=1}^{H+1}\sum_{r=b}^{h-g} y_{simrh}^{k+1} x_{simrh}^{t_h} \qquad (6)$$

$$k=1,..,H-1$$

(Non-declining yield constraints)

where

$x_{simrh}^{t_h}$ is the number of acres of existing or regenerated stands in physical stratum s , initial cover type i , management prescription m , that belong to cover type t_h in period h . All constraints keyed on the cover type of each stratum in the current period instead of the initial cover type, because the cover type designation of a stand can change over its life as a result of stand development processes. The decision variable was defined from the end of the stand establishment phase in period r , through final harvest to the end of the stand establishment phase of the new stand in period h . Each planning period was 10 years long. The end of the stand establishment phase occurred at age five years (the middle of the period). This definition accounted for cover type transitions between harvested stands and subsequent regenerated stands.

y_{simrh}^{k} is the per-acre yield associated with each unit of the decision variable $x_{simrh}^{t_h}$ in period k .

$c_{simrh}^{t_h}$ is the objective function coefficient corresponding to variable $x_{simrh}^{t_h}$. In this study, $c_{simrh}^{t_h}$ was either the contribution to first-period harvest volume or the contribution to forest present net worth (PNW) of each unit of $x_{simrh}^{t_h}$.

$p_j \mid m, r, h, t_h$ is the relative frequency of acres that transfer to cover type j after harvest, given the vegetation management strategy included in management prescription m , the age at harvest given by r and h , and the cover type at harvest given by t_h . It was estimated from the full model in table 2-1.

b is the period of birth (negative) of the oldest existing stand on the forest.

A_s is the number of acres on the forest in physical stratum s .

g is the minimum rotation age.

H is the number of periods in the planning horizon.

H+1 denotes ending inventory.

The reduced model follows Johnson and Stuart (1987), in which the transitions between cover types at harvest were described as a species to species transition probability matrix, where the probability that a regenerated forest stratum will be a given cover type is a function of the cover type of the same forest stratum before harvest:

$P_j = f(SPPOLD)$

This is equivalent to the reduced model in table 2-1. The forest planning formulation that uses the reduced model will hereafter be referred to as the MP2 (multiple path 2) formulation. It is similar to the MP1 formulation above except for the acreage accounting constraints for regenerated stands:

$$\sum_{m=1}^{M}\sum_{r=b}^{h-g}\sum_{i=1}^{3} (p_j \mid t_h)\ x_{simrh}^{t_h} = \sum_{m=1}^{M}\sum_{q=h+g}^{H+1} x_{sjmhq}^{j_h} \qquad j=1,\ldots,3,\quad h=1,\ldots,H,\quad s=1,\ldots,S \tag{7}$$

where

$p_j \mid t_h$ is the relative frequency of acres that transfer to cover type j after harvest, given that the cover type at harvest was t_h . It was estimated from the reduced model in table 2-1.

The naive model follows the traditional Model II (Davis and Johnson 1987) forest planning formulation in which there is a one-to-one transfer between cover types at harvest. All acres in a harvested stratum regenerate to a single new cover type, and no formal rule exists for which regenerated cover type will result. In this study it was assumed that each harvested stratum regenerated to its own cover type throughout the planning horizon.

The forest planning formulation incorporating the naive cover type transition model will hereafter be referred to as the SP (single path) formulation. The acreage accounting constraints for regenerated stands under this formulation can be written as:

$$\sum_{m=1}^{M}\sum_{r=b}^{h-g}\sum_{i=1}^{3} X_{simrh}^{j_h} = \sum_{m=1}^{M}\sum_{q=h+g}^{H+1} X_{sjmhq}^{j_h} \tag{8}$$

$$j=1,\ldots,3, \quad h=1,\ldots,H, \quad s=1,\ldots,S$$

The forest land base was 569,000 acres, of which 357,000 acres were managed for timber production and the rest was withdrawn from timber production in order to meet non-timber management objectives. A strict non-declining yield policy was imposed on all forest plans. Each formulation was optimized with a maximum present net worth (PNW) objective as well as an objective of maximizing first-period harvest.

No ending inventory conditions were imposed on the forest plans. These conditions are usually aimed at specifying a required steady-state target forest at the planning horizon. Defining these target conditions is problematic under the multiple outcome formulations used in this study because it is unlikely that the forest will ever reach a steady-state distribution of cover types. Transition probabilities are non-stationary in the MP1 formulation, in that they change with old-stand age, old-stand cover type and vegetation management regime. The same is true for the MP2 formulation in which transition probabilities change with old-stand cover type.

Instead of using explicit ending inventory regulation constraints, a 400-year planning horizon was used to approximate an infinite horizon model. Under the PNW objective function, all decision variables in the forest plans were represented in the objective function by their PNW. Decision variables representing ending inventory were valued at the hypothetical PNW that would result from harvesting the stand at an age as close to 90 years as possible as well as the soil expectation value (SEV) resulting from subsequently managing the land in perpetuity with a 90-year rotation age. The equation used for residual value of ending inventory was:

$$PNW = \frac{R_n + SEV_{90}}{(1+r)^n}$$

where

R_n is the net return from harvesting the stand in year n .

r is the rate of return.

SEV_{90} is the soil expectation value resulting from managing the stand in perpetuity under a 90-year rotation.

The 90-year rotation was representative of harvest ages in the data set used to fit the cover type transition model. Since discounting ending inventory values, including SEV, over 400 years will yield a vanishingly small objective function value, the hypothetical rotation age used for ending inventory will have little effect on the optimal forest plan in this study.

Vegetation management strategies consisted exclusively of either manual or chemical methods, with treatment intensity measured by the number of whole-area treatments. Vegetation management was applied only to plantations on which the old stand before harvest was a MIXED or HARDWOOD cover type.

Forest planning formulations were generated with a matrix generator and report writer written by the author (Eng 1991b). Formulations ranged from 300 to 500 rows and 7,000 to 12,000 columns, depending on the minimum rotation age and type of formulation. Matrix densities ranged from two to three percent for the SP formulation to four to five percent for the MP1 and MP2 formulations. Each forest planning formulation was generated and solved using a 486/33 IBM-compatible personal computer and the MPSIII/pc mathematical programming software.

The matrix generator included an integrated yield module consisting of the SPS growth and yield simulator (Arney 1985), which provided unique yield projections for each stratum in the forest planning formulation. The 1987 Siuslaw National Forest vegetative resource survey (USDA Forest Service 1986) provided the starting yield parameters and acreages by strata for existing stands (appendix one), and Siuslaw National Forest reforestation records used to fit the cover type transition models provided starting yield parameters for regenerated stands (appendix one).

RESULTS

The different forest planning formulations resulted in substantially different forest structures over time. Figures 2-8 through 2-10 show the standing acres of each cover type by planning period for the optimal solutions to the MP1, MP2, and SP formulations. The formulations reflect a policy of no vegetation management, a minimum rotation age of 60 years, and an objective function of maximizing first period harvest volume subject to a non-declining yield constraint.

Under the MP2 formulation, the proportion of the forest in the CONIFER cover type increased throughout the planning horizon, at the expense of the MIXED and HARDWOOD type. Under this formulation, the acreage in the CONIFER cover type was greater than that in the MP1 formulation, and the acreage in the MIXED and HARDWOOD type was less than that of the MP1 formulation.

Under the SP formulation the initial distribution of cover types was unchanged throughout the planning horizon. The SP formulation as defined in this study did not account for cover type changes over time. Management strategies such as vegetation management and minimum rotation age had no direct effect on forest structure in these formulations.

In this study, under the MP1 formulation and a 60-year minimum rotation age, harvesting existing stands resulted in a higher percentage of acres regenerating to the CONIFER

Figure 2-8. Acres of standing inventory by cover type over time for the MP1 formulation. Minimum rotation age is 60 years. A strategy of no vegetation management is used.

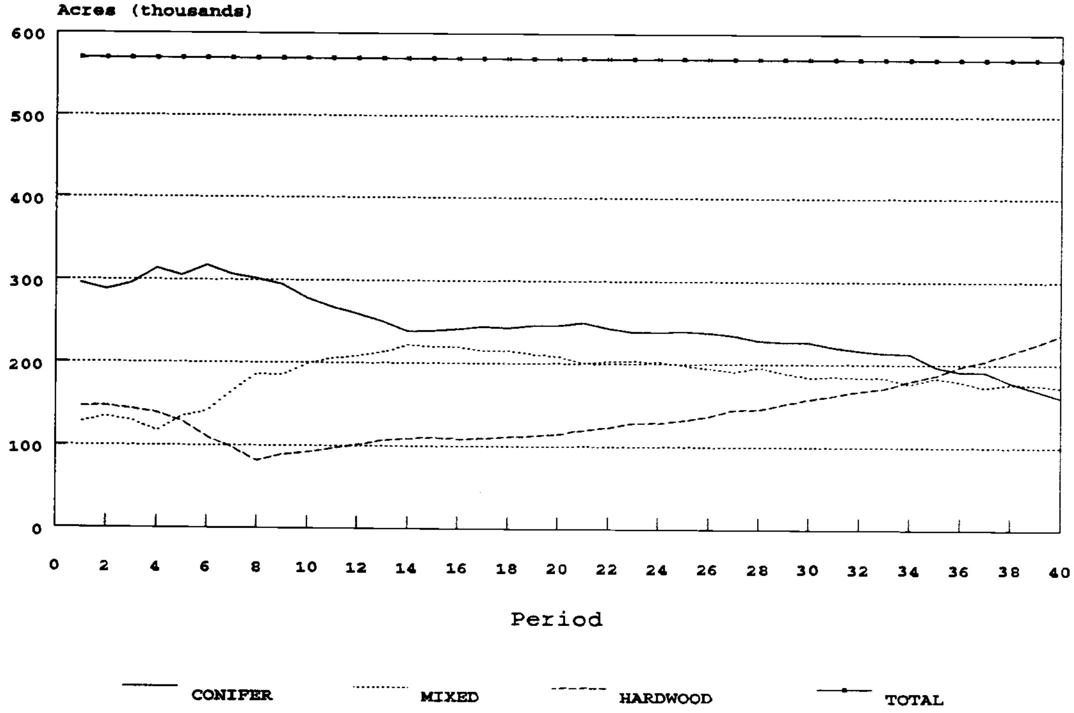


Figure 2-9. Acres of standing inventory by cover type over time for the MP2 formulation. Minimum rotation age is 60 years. A strategy of no vegetation management is used.

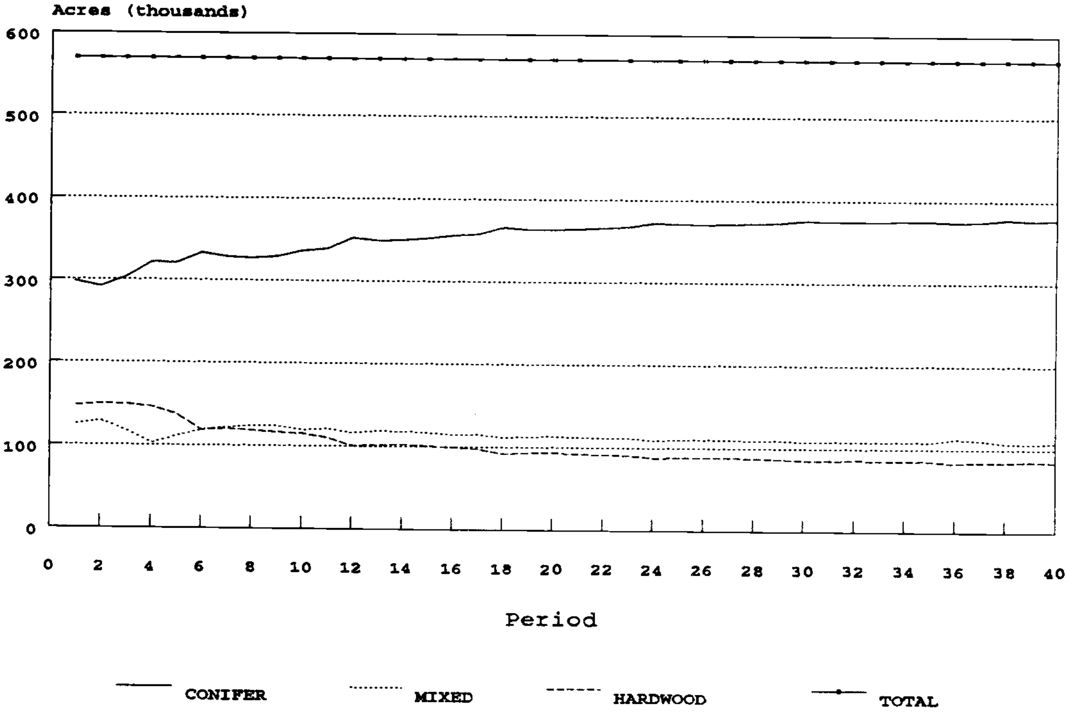
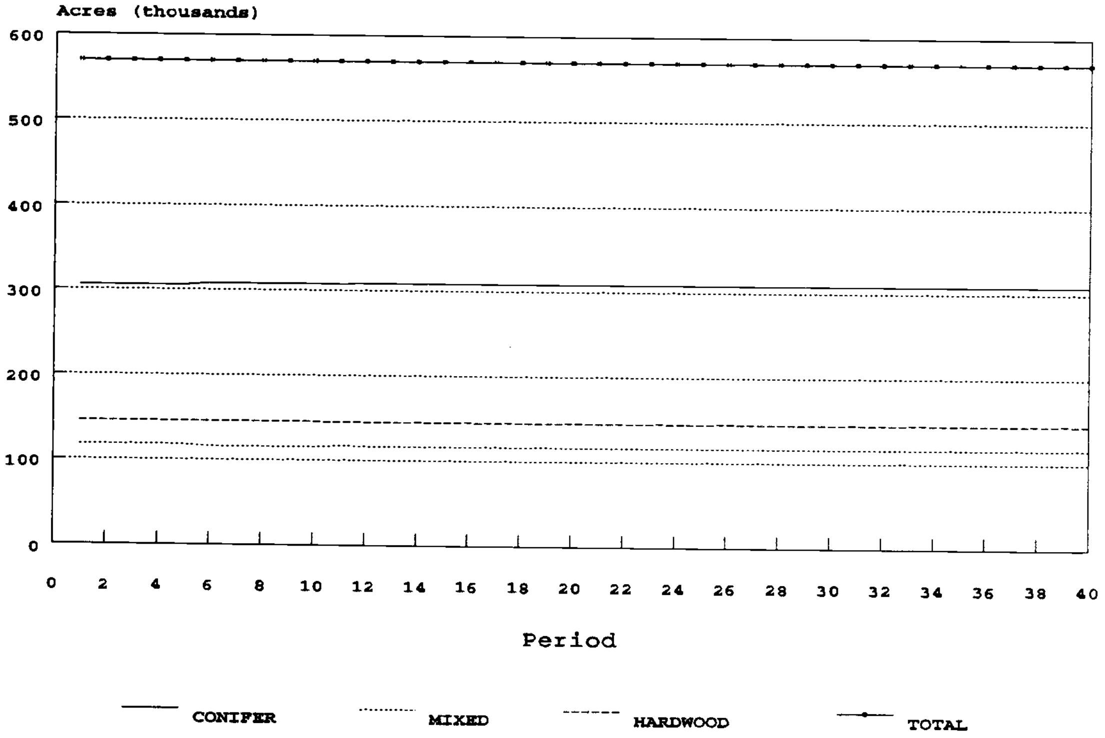


Figure 2-10. Acres of standing inventory by cover type over time for the SP formulation. Minimum rotation age is 60 years. A strategy of no vegetation management is used.



cover type than when harvesting regenerated stands. This was a result of the effect of the variable AGEOLD in the cover type transition model (as shown in figure 2-7, increasing values of this variable unambiguously caused an increase in the probability of the CONIFER outcome). Harvesting the comparatively mature existing stands resulted in high values of AGEOLD, whereas regenerated stands, which were usually harvested near the minimum rotation age, produced low values of AGEOLD. Thus, because the majority of harvests in the first 10 periods came from existing stands, the number of acres in the CONIFER cover type remained at the initial high level during this interval.

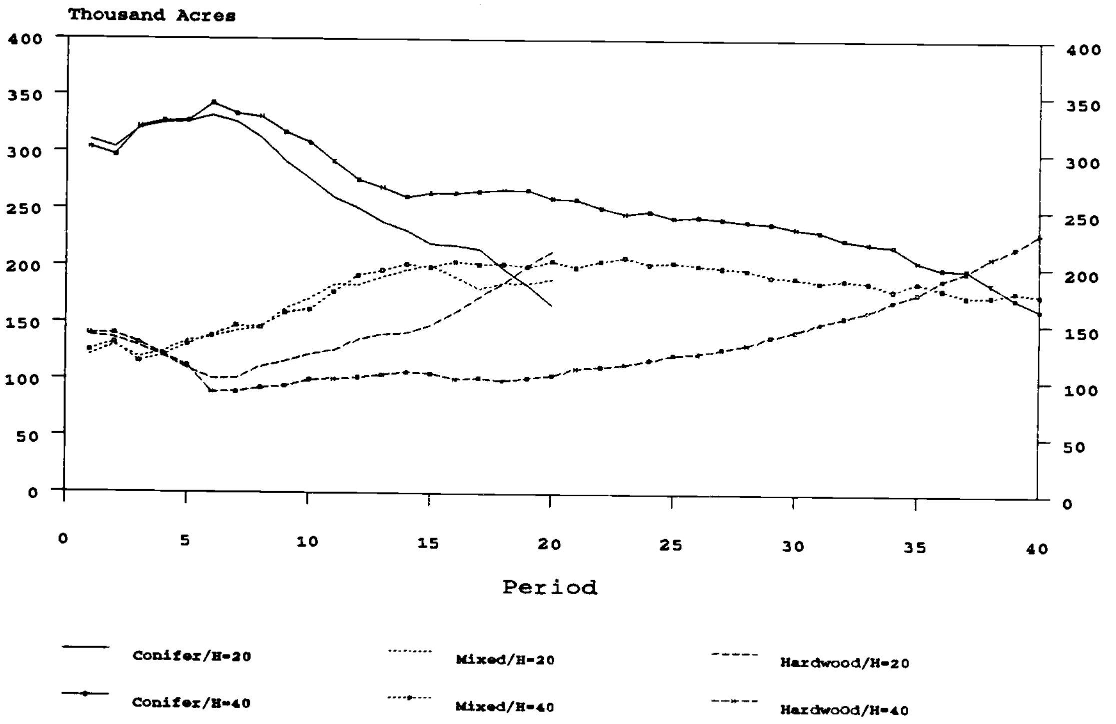
Conversely, after the first 10 periods, when harvest occurred primarily in regenerated stands with shorter rotation ages, the cover types began to merge and eventually cross towards the end of the planning horizon.

The intersecting cover types, with the number of acres in the CONIFER type decreasing and the number of acres in the MIXED and HARDWOOD types increasing, illustrate the cover type transitions resulting from large-scale harvest near the end of the planning horizon, in the absence of ending inventory regulation constraints. This pattern follows from an allowable cut effect which is a function of the forest planning model specification. To maximize the objective function (either first period harvest or PNW) the optimization algorithm schedules as many stands as possible for harvest before the planning horizon. The contribution to increasing early periods' harvest levels under non-declining yield makes profitable the harvesting of any standing inventory above the minimum rotation age at the planning horizon.

One of the purposes of using a 400-year planning horizon in this study was to minimize the effect of ending inventory bias on forest plans. Under a 400-year horizon, the crossing of cover types that takes place near the planning horizon occurs so late that the effect on early periods harvest levels are likely to be small enough that early periods' harvest levels can be considered sustainable. Furthermore, the early periods' cover type conversion patterns can be considered reflective of the underlying biology.

This argument is supported by the results in figure 2-11, which shows optimal forest plans under a PNW-maximizing objective, no vegetation management, a minimum rotation age of 60 years, and planning horizons of 200 years as well as 400 years. A 200 years planning horizon resulted in a higher harvest level than a 400 years planning horizon. Under the 200 years horizon, a more aggressive forest plan was followed, with shorter rotations, than under the 400-year horizon. This resulted in a more rapid drop in CONIFER acres and increase in MIXED and HARDWOOD acres than under a 400 year horizon. The comparatively low per-acre yields of the

Figure 2-11. Acres of standing inventory by cover type for the MP1 formulation with a planning horizon of 200 years and 400 years, respectively.



MIXED and HARDWOOD cover types were compensated for by harvesting a greater number of acres in periods 15 to 20. As a result, a non-declining yield level could be maintained through the 200 year horizon.

Under the longer planning horizon, however, the increased harvest acreage could not be sustained up to 400 years. This forced a less aggressive harvest regime with lower harvest levels and correspondingly longer rotations. Longer rotations under the MP1 formulation resulted in a higher probability of the CONIFER type as well as a lower probability of the HARDWOOD type in regenerated stands, and generally a slower convergence of cover types than under the 200 year planning horizon.

The results from the 200-year horizon forest plan indicate that ending inventory valuation alone is not sufficient to ensure that the forest plan will leave an ending forest that is capable of supporting the non-declining yield level from then on. Under an objective of maximizing harvest volume subject to non-declining yield, valuation of ending inventory will not affect the optimal forest plan. Under a PNW-maximization objective, valuation of ending inventory by itself was not sufficient to avoid liquidation of harvestable inventory toward the end of the horizon. This suggests that ending inventory regulation constraints or a long planning horizon is necessary in order to achieve forest plans for which the non-declining yield level will be sustainable in perpetuity. Due to the difficulties in defining a steady-state ending forest structure under multiple outcome formulations, we used a 400-year horizon in this study to approximate an infinite horizon.

The cover type distribution over time under the MP1 formulation could be changed by management strategies such as vegetation management as well as the minimum rotation age, to resemble that of the MP2 and the SP formulations. Increasing the minimum rotation age resulted in a higher value of the variable AGEOLD in the cover type transition model, which in turn resulted in an increased proportion of the CONIFER type and a decreased proportion of the HARDWOOD type in the resulting regenerated stands. This effect is illustrated in figure 2-12, which shows the distribution of cover types for two forest plans with minimum rotation ages of 60 years and 80 years, respectively. In this case, the increase in the minimum rotation age also resulted in an increase in the acreage of the MIXED type over most of the planning horizon.

Table 2-5 shows first period harvest levels for the MP1, MP2 and SP formulations, for minimum rotation ages ranging from 60 to 100 years. Each entry in the table represents a forest plan with an objective of maximizing first period harvest volume subject to a non-declining yield policy, and a unique minimum rotation age.

Figure 2-12. Acres of standing inventory by cover type for two MP1 forest plans with minimum rotation ages of 60 years and 80 years and no vegetation management.

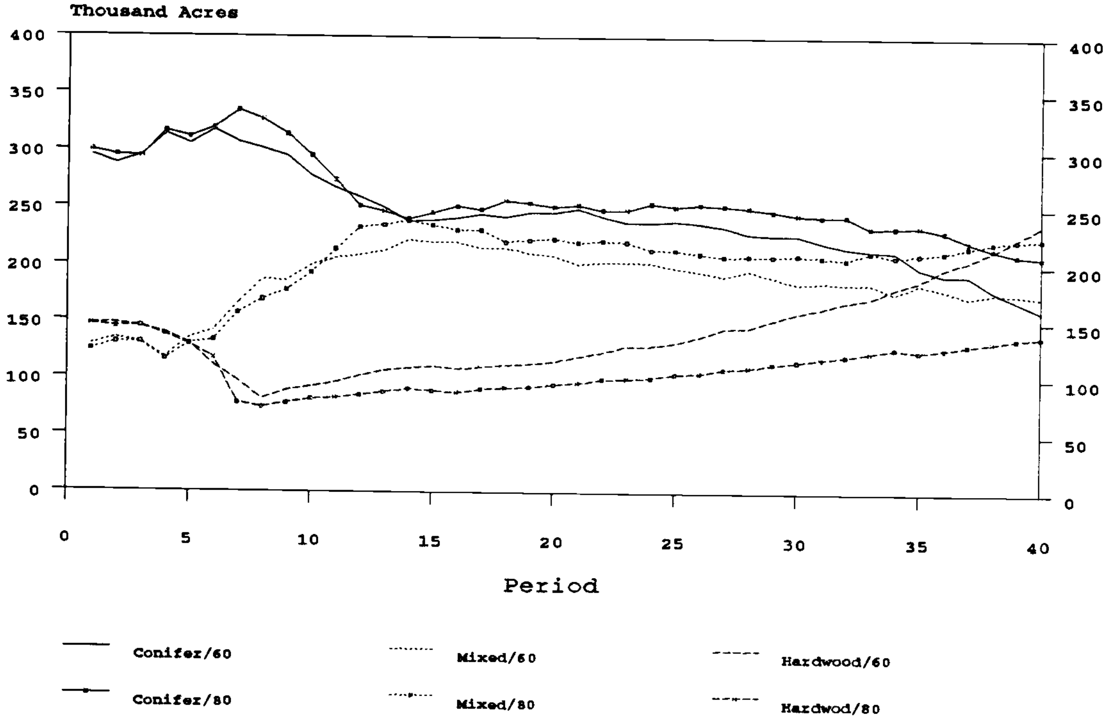


TABLE 2-5.

First period annual harvest levels, in million cubic feet, for the MP1, MP2 and SP formulations under a volume maximization objective. Planning horizon is 400 years. Minimum rotation ages range from 60 to 100 years. Five manual (MVT) and four chemical (CVT) vegetation management treatment strategies are shown for the MP1 formulation, ranging from 0.0 to 3.0 whole-area treatments.

Minimum Rotation Age	MP1			MP2	SP
	Treat-ments	MVT	CVT		
60	0.0	61.0	61.0	69.5	64.3
	0.5	62.7	64.1		
	1.0	64.4	66.7		
	2.0	67.2	69.5		
	3.0	69.0			
70	0.0	60.7	60.7	66.7	63.2
	0.5	62.4	63.8		
	1.0	64.1	66.2		
	2.0	66.6	68.4		
	3.0	68.0			
80	0.0	60.1	60.1	60.9	60.6
	0.5	61.3	61.6		
	1.0	61.7	62.3		
	2.0	62.5	63.2		
	3.0	63.0			
90	0.0	55.9	55.9	55.5	56.0
	0.5	56.0	56.1		
	1.0	56.2	56.5		
	2.0	56.5	57.1		
	3.0	57.0			
100	0.0	52.1	52.1	51.6	51.7
	0.5	52.4	52.6		
	1.0	52.6	53.0		
	2.0	53.0	53.5		
	3.0	53.4			

Under the MP1 formulation, harvest levels are shown for each of several manual or chemical vegetation management strategies, consisting of none to three whole-area treatments with manual methods and none to two whole-area treatments for chemical methods. Each vegetation management strategy consisted exclusively of either manual or chemical treatment methods.

The harvest levels projected by the MP2 and SP formulations at short minimum rotation ages exceeded those of the MP1 formulation by up to 14 percent and five percent, respectively. At a minimum rotation age of 60 years, the harvest level under the MP2 formulation was as high as the MP1 harvest level with a policy of two whole-area applications of chemical vegetation management. The difference is due to the different cover type transition models underlying each formulation.

Because each formulation is optimized separately, the exact relationships are confounded, but a clue can be found in the prediction success table in table 2-3. For the reduced model used in the MP2 formulation, a total of 92 percent of the observations where the actual outcome was MIXED or HARDWOOD were incorrectly predicted as CONIFER (20.815/37 plus 7.362/20), as opposed to 47 percent for the full model (MP1 formulation) and the naive model (SP formulation). The inflated estimates of the high-yielding

CONIFER cover type were reflected in higher overall harvest levels.

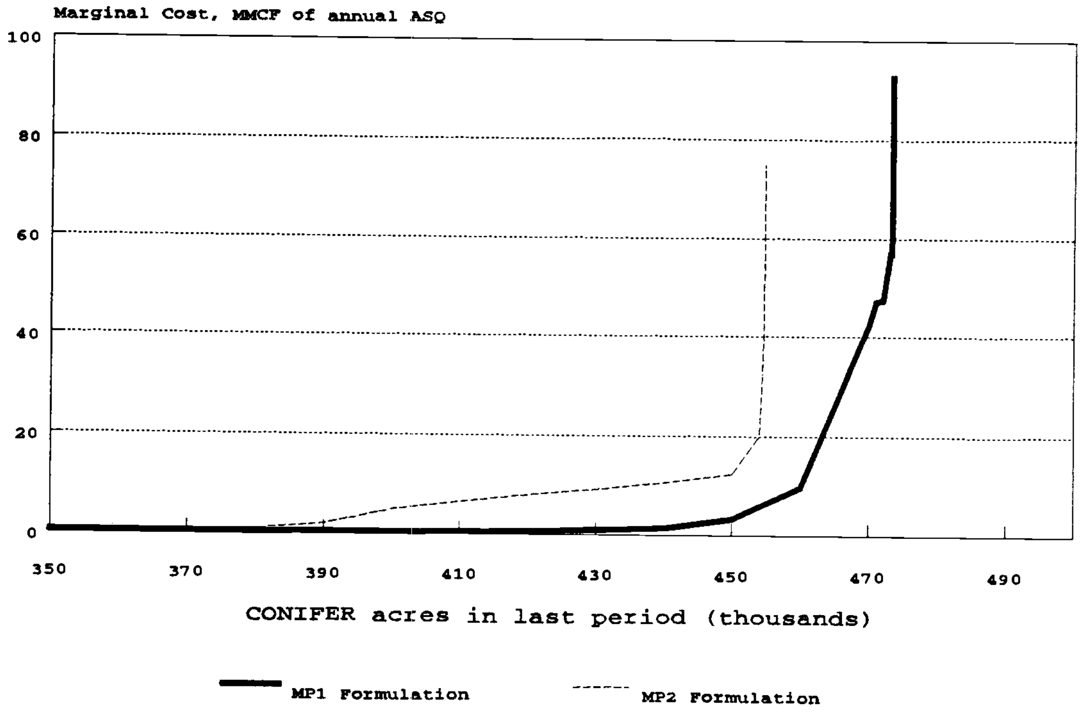
Harvest levels decreased as the minimum rotation age increased in all the forest planning formulations in table 2-5. A high minimum rotation age resulted in a smaller number of rotations within the fixed planning horizon and therefore a lower harvest level than with a short minimum rotation age. Under the MP1 formulation, the minimum rotation age had a second counteracting effect by virtue of affecting the value of the variable AGEOLD in the cover type transition model for stands harvested at minimum rotation age. Increasing values of AGEOLD were associated with an increasing probability of obtaining the CONIFER cover type, which generally produced the highest yields.

As a result of this second yield-increasing effect, harvest levels decreased less with increasing minimum rotation age under the MP1 formulation than under the MP2 and SP formulations: harvest levels under the MP1 formulation decreased by about one percent as the minimum rotation age changed from 60 to 80 years. The harvest level decreased by about twelve percent and six percent under the MP2 and SP formulations respectively, over the same interval.

Manual and chemical vegetation management treatments influenced harvest levels in the MP1 formulation, through their effect on the distribution of forest acreage by cover type. Vegetation management increased harvest levels by up to 14 percent. The effect of vegetation management decreased with increasing minimum rotation age: the increasing value of the variable AGEOLD resulting from increasing minimum rotation age shifted the cover type distribution towards the CONIFER type to the extent that vegetation management had little additional effect on the distribution of cover types.

Parametric analysis is sometimes done on the right hand side of constraints in order to derive supply responses for outputs and determine economically efficient constraint levels (Teeguarden 1990). To compare the results of a parametric analysis for the MP1 and MP2 formulations, a forest plan was implemented for each formulation, with an objective of maximizing first period harvest volume subject to non-declining yield. Both forest plans included a constraint on the minimum amount of standing CONIFER acres in the last planning period, as well as manual vegetation management treatment policies ranging from no treatment to one complete treatment of every reforestation unit. A parametric analysis was then performed on the right hand side of this constraint in both the MP1 and MP2 formulations. The resulting derived supply responses for standing inventory of the CONIFER cover type in the last period are shown in figure 2-13. The marginal cost on the vertical axis is measured in units of million cubic feet of

Figure 2-13. Derived supply curves based on a last-period constraint on the minimum number of acres in the CONIFER cover type, for the MP1 and MP2 formulations. Formulations were identical except for the cover type transition models. Objective was to maximize first period harvest volume subject to non-declining yield. Marginal cost (shadow price) was measured in units of million cubic feet decrease in annual harvest levels as a result of a unit increase in the right hand side of the minimum CONIFER acreage constraint.



annual harvest level. This marginal cost is the shadow price of the constraint on standing CONIFER acres in the last period, and it represents the marginal decrease in the objective function of maximum harvest volume with an increase in the minimum CONIFER acreage requirement.

The shape of the curves is due to the characteristics of the optimization problem. At low values of the constraint right hand side, only a small decrease in the objective function results from an increase in the right hand side. For example, increasing the number of standing CONIFER acres from 400 to 450 acres lowers the objective by approximately seven million cubic feet. As the right hand side value of the constraint approaches the limits of available resources, it becomes prohibitively expensive to meet the constraint requirement. The MP1 formulation was capable of producing approximately 18,000 more CONIFER acres than the MP2 formulation in the last planning period because in the MP1 formulation some of the acres of the CONIFER cover type arose from type conversion caused by vegetation management. This management option was not recognized in the MP2 formulation where transition probabilities did not depend on vegetation management treatments.

CONCLUSIONS

The analysis demonstrated that the results of a forest plan, including estimated harvest levels, forest structure, and derived supply responses to name a few, depends on the type of cover type transition model used. Thus, assumptions about cover type transitions can have a profound influence on forest plan results.

The full model which included old-stand cover type and age as well as vegetation management treatments as explanatory variables, had the best performance of the cover type transition models analyzed in this study. The results of the analysis also indicated that the naive model performed somewhat better than the reduced model.

The performance of the cover type transition models were consistently reflected in forest plan results: the cover type transition models that performed the best gave lower harvest levels and more evenly distributed cover type distributions over time. The MP1 forest plans, based on the full cover type transition model, gave the lowest harvest levels and the most evenly distributed cover type distributions over time.

The MP2 formulation produced considerably higher harvest levels than the other formulations, and a cover type distribution that diverged throughout the planning horizon.

The results of the validation analysis indicated that the reduced cover type transition model underlying the MP2 formulation tended to inflate the relative frequencies of the high-yielding CONIFER cover type.

The SP formulation, as formulated in this study, generally produced harvest levels intermediate between the MP1 and MP2 formulations, reflecting the intermediate performance of the naive cover type transition model. These results suggest that in terms of accurate portrayal of harvest levels in a strategic forest planning context, the classical single-outcome model as embodied in the SP formulation may be preferable to the species-to-species transition matrix embodied in the MP2 formulation.

Specification bias remains a concern for all the cover type transition models analyzed in this study. The full model, however, had less systematic bias than the other two models. Furthermore, the amount of specification bias that may be considered acceptable for this type of models in forest planning is not well known. Because the goal of discrete event probability models such as the ones analyzed in this study is not point prediction but rather prediction of the entire probability distribution of the response variable, the answer will probably at least in part consist of carefully defining the required accuracy of these models as used in a strategic forest planning analysis. Comprehensive evaluation of discrete event probability models including residual analysis is scarce in the received literature, possibly due to methodological difficulties posed by a model structure in which predicted and observed values are measured in different units. The residual-generating procedure developed in this study constitutes a practicable method for overcoming the difficulties inherent in residual analysis of discrete event probability models.

The modeling strategy represented by the cover type transition models developed in this study is a useful vehicle for modeling stand establishment in a strategic forest planning context. This modeling approach is likely to be useful for describing other elements of forest development as well, such as the response to fire, pest and disease attacks.

Chapter 3

THE EFFECT OF VEGETATION MANAGEMENT STRATEGIES ON FOREST PLANS IN COASTAL OREGON

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ABSTRACT

Stand establishment was modeled, in a strategic forest planning context, with a cover type transition model that predicted the relative frequencies of different cover types resulting in regenerated stands after harvesting the mature stands. Explanatory variables in the model included the cover type and age of the mature stands prior to harvest, as well as vegetation management treatments applied to the regenerated stands. Predictions from the cover type transition model were then included in a forest planning formulation with embedded matrices of transition probabilities, in which each transition probability

represented the relative frequency of a particular cover type transition at harvest.

Vegetation management had a significant effect on the results of forest plans on the Siuslaw National Forest in coastal Oregon. Chemical vegetation management methods were somewhat more effective than manual methods. Both chemical and manual treatments were most effective at low minimum rotation ages.

The potentially higher cost of manual vegetation management combined with budget constraints may force lower intensities of treatments with manual methods than with chemical methods, thereby increasing the practical difference in effectiveness between the two methods.

When no restrictions were placed on cover type conversions, vegetation management was always profitable, in terms of harvest levels and forest value. The yield reductions resulting from no vegetation management, though, should be interpreted in the context of a highly aggregated forest planning analysis. Yield reductions on individual sites may differ substantially from those found in this study.

Vegetation management treatments, which are designed to cultivate certain tree species at the expense of others, produced little or no improvement in harvest levels or forest value in forest plans that contained constraints aimed at preserving or enhancing tree species diversity. In forest plans with no diversity constraints, diversity decreased moderately initially and then consistently increased during the remainder of the planning horizon. If some reduction in biological diversity is accepted in early periods, higher harvest levels can be produced than if a strict adherence to non-declining diversity is enforced.

INTRODUCTION

The forest stand establishment phase in the area of Oregon's Coast Range covered by the Siuslaw National Forest is characterized by competition between conifers such as Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and Sitka spruce (*Picea sitchensis* [Bong.] Carr.); and hardwoods, primarily red alder (*Alnus rubra* Bong.) Because the juvenile growth rate of red alder is faster than that of the conifers, it can dominate the site under favorable conditions to the near exclusion of conifers (Franklin and Dyrness 1973). There is, however, considerable uncertainty associated with the stand type that will be established. In addition to characteristics of the vegetation and the physical environment, silvicultural treatments such as vegetation management also affect the stand type that results at the end of the stand establishment phase.

In forest planning formulations, the stand establishment phase is usually represented only implicitly through the link between decision variables representing the harvested stand and decision variables representing the subsequent regenerated stands. The variation in cover type outcomes can be represented by forest planning formulations that incorporate multiple regenerated cover types, each with an estimated relative frequency (Reed and Errico 1986, Johnson and Stuart 1987). Although vegetation management treatments have the potential to affect the results of forest plans through their impact on regenerated forest cover types, their effect in a forest planning context in the study area is not well known. A prediction model has been developed for the study area (Eng 1992a) which estimates the relative frequencies of each regenerated cover type given variables describing the vegetation prior to harvest as well as vegetation management treatments.

The objective of the study reported here was to evaluate the effects of different vegetation management strategies on forest plans in coastal Oregon, using forest planning formulations that recognize multiple regenerated cover types as affected by vegetation management. This study also shows ways in which legislatively mandated considerations of biological diversity in forest planning can be integrated into forest plans, and how vegetation management can affect biological diversity.

METHODS

The analysis in this study was done using a Model II strata-based forest planning formulation (Davis and Johnson 1987) with embedded matrices of transition probabilities in regenerated stands acreage accounting constraints, representing the relative frequencies of different cover type transitions at harvest:

Maximize $\sum_{s=1}^{S} \sum_{i=1}^{3} \sum_{m=1}^{M} \sum_{h=1}^{H+1} \sum_{r=b}^{h-g} c_{simrh}^{t_h} \, x_{simrh}^{t_h}$

subject to

$$\sum_{i=1}^{3} \sum_{m=1}^{M} \sum_{h=1}^{H+1} \sum_{r=b}^{h-g} x_{simrh}^{t_h} = A_s \qquad s=1,\dots,S \tag{1}$$

(Existing stands acreage accounting constraints)

$$\sum_{m=1}^{M} \sum_{r=b}^{h-g} \sum_{i=1}^{3} (p_j \mid m, r, h, t_h) \; x_{simrh}^{t_h} = \sum_{m=1}^{M} \sum_{q=h+g}^{H+1} x_{sjmhq}^{j_h} \qquad j=1,\dots,3, \quad h=1,..,H, \quad s=1,\dots,S \tag{2}$$

(Regenerated stands acreage accounting constraints)

$$\sum_{s=1}^{S} \sum_{i=1}^{3} \sum_{m=1}^{M} \sum_{h=1}^{H+1} \sum_{r=b}^{h-g} y_{simrh}^{k} x_{simrh}^{t_h} \le \sum_{s=1}^{S} \sum_{i=1}^{3} \sum_{m=1}^{M} \sum_{h=1}^{H+1} \sum_{r=b}^{h-g} y_{simrh}^{k+1} x_{simrh}^{t_h} \qquad k=1,..,H-1 \tag{3}$$

(Non-declining yield constraints)

where

$x_{simrh}^{t_h}$ is the number of acres of existing or regenerated stands in physical stratum s , initial cover type i , management prescription m , that belong to cover type t_h in period h . All constraints keyed on the cover type of each stratum in the current period instead of the initial cover type, because the cover type designation of a stand can change over its life as a result of stand development processes. The decision variable is defined from the end of the stand establishment phase in period r , through final harvest to the end of the stand establishment phase of the new stand in period h . Each planning period was 10 years long. The end of the stand establishment phase occurred at age five years, in the middle of the period. This definition accounted for cover type transitions between harvested stands and subsequent regenerated stands.

y_{simrh}^{k} is the per-acre yield associated with each unit of the decision variable $x_{simrh}^{t_h}$ in period k .

$c_{simrh}^{t_h}$ is the objective function coefficient corresponding to variable $x_{simrh}^{t_h}$. In this study, $c_{simrh}^{t_h}$ was either the contribution to first-period harvest volume or the contribution to forest present net worth (PNW) of each unit of $x_{simrh}^{t_h}$.

$p_j \mid m,r,h,t_h$ is the relative frequency of acres that transfer to cover type j after harvest, given the vegetation management strategy included in management prescription m , the age at harvest given by r and h , and the cover type at harvest given by t_h .

b is the period of birth (negative) of the oldest existing stand on the forest.

A_s is the number of acres on the forest in physical stratum s .

g is the minimum rotation age.

H is the number of periods in the planning horizon.

H+1 denotes ending inventory.

The relative frequency coefficients in this forest planning formulation were estimated with the following probabilistic cover type transition model (Zavoina and McKelvey 1975):

$$\begin{aligned} p_1 &= \Phi(\mathbf{x}'\boldsymbol{\beta}) \\ p_2 &= \Phi(a+\mathbf{x}'\boldsymbol{\beta}) - \Phi(\mathbf{x}'\boldsymbol{\beta}) \qquad (4) \\ p_3 &= 1 - \Phi(a+\mathbf{x}'\boldsymbol{\beta}) \end{aligned}$$

where

Φ denotes the normal cumulative distribution function.

P_1, P_2, P_3 are the predicted probabilities of obtaining regenerated cover type outcomes one (CONIFER), two (MIXED) and three (HARDWOOD). Stands in which between 20 percent and 49 percent of the total number of trees per acre were hardwoods were classified as MIXED. Stands that fell below and above this range were classified as CONIFER and HARDWOOD stands, respectively.

a is the second intercept parameter.

$\boldsymbol{\beta}$ is the vector of model parameters.

$\boldsymbol{x}$ is the vector of explanatory variables, which described the old stand before harvest as well as vegetation management treatments applied to the new stand after harvest:

SPOLD1, SPOLD2 are indicator variables which denote the cover type of the old stand on the site before harvest. The cover type of the old stand on the site before harvest was divided into three categories: CONIFER (SPOLD1=1, SPOLD2=0), MIXED (SPOLD1=0, SPOLD2=1), and HARDWOOD (SPOLD1=0, SPOLD2=0).

AGEOLD is the age of the old stand before harvest, in years.

MNLVEG is the amount of manual vegetation management treatments applied to the regenerated stand.

CHMVEG is the amount of chemical vegetation management treatments applied to the regenerated stand.

The variables MNLVEG and CHMVEG were measured as the fraction of the total area that was treated after all stand entries up to the end of the stand establishment phase at age five were completed. The value of these variables often exceeded one, because many reforestation units in the study area were treated several times. Due to the high cost of manual treatment methods, however, often only a part of the reforestation unit was treated at each entry. The units of measure of these variables can be described as the number of equivalent whole area treatments.

The average cost of chemical vegetation management in the study area, as compiled from reforestation records on the Siuslaw National Forest, was $90 per acre. Because manual vegetation management was not a traditional treatment method in the study area at the time of this study, reliable cost estimates were hard to find. Cost figures from the reforestation records used as data in this study were often five to 10 years old and were not considered representative of current costs. Fiddler and McDonald (1990) quoted evidence that winning contract bids in coastal areas of southern Oregon and northern California had often been too low, in the sense that operators frequently went out of business with periods of insufficient supply of release services. They claimed that a more realistic equilibrium market price may be more than three times the historic average bidding level. Their estimated cost of $350 per acre for manual vegetation management for coastal southern Oregon was used in this study. Sensitivity analysis showed that forest plan results were not appreciably different for costs of this treatment ranging from $100 to $400.

This cover type transition model was fitted to data from the Siuslaw National Forest (Eng 1991a). Estimated coefficients for the model are shown in table 3-1. Specification bias remains a potential concern for the

Table 3-1. Maximum likelihood estimates of model parameters for the cover type transition model which contains explanatory variables cover type of the old stand (SPOLD1, SPOLD2), age of the old stand (AGEOLD), manual vegetation management (MNLVEG), and chemical vegetation management (CHMVEG). Estimated standard errors and p-values for the t-statistic testing significance of the coefficients are shown in parentheses. Source: Eng (1991a).

Explanatory Variable	Coefficient	Standard Error	P-value
CONSTANT	-5.4009	0.690	0.0001
SPOLD1	1.8251	0.434	0.0001
SPOLD2	1.1071	0.402	0.006
AGEOLD	0.04129	0.0057	0.0001
MNLVEG	0.8340	0.201	0.0001
CHMVEG	1.4855	0.420	0.0004
INTERCEPT 2	1.7165	0.254	

Log likelihood, full model = -73.7

Log likelihood, constant only = -146.2

Likelihood ratio index, $\rho^2 = 0.496$

Number of observations: 172

cover type transition models that have been developed so far (Eng 1991a). The model described here, however, had less systematic bias and a better fit than other models examined. Therefore, even though this model is not the final answer in cover type transition modeling in the study area, it was deemed the most suitable for forest planning cover type prediction in the study area at the present time.

The forest was divided into 51 physical strata according to site index class, stand age and cover type. Acreage allocations were similar to that of the Preferred Alternative in the Siuslaw National Forest Plan (USDA Forest Service 1990). The total land base was 569,000 acres, of which 357,000 acres were managed for timber production. The remaining 212,000 acres were designated as reserved lands and were withdrawn from timber production in order to meet non-timber management objectives. Although withdrawn from timber production, these areas affected the results of the forest plans, such as forest structure and biological diversity. The reserved land was therefore included in all the analyses in this study.

Starting yield information for existing natural stands strata recognized in the forest plans was compiled from data in the 1987 Siuslaw National Forest Vegetative Resources Survey (USDA Forest Service 1986). Reforestation records from the Forest provided initial yield parameters for regenerated stands strata, by site index class and cover type. This information is given for existing as well as regenerated stands in appendix one.

Instead of accessing external yield tables, the matrix generator was linked to a yield module consisting of the growth-and-yield model SPS (Arney 1985), which provided unique yield estimates for each stand stratum. For the purposes of yield estimation, Douglas-fir and red alder was used to represent the conifer and hardwood species contingent, respectively, in the cover type definitions used in this study. Possible yield bias resulting from this assumption was expected to be negligible, because Douglas-fir and red alder are the dominant conifer and hardwood species on the Siuslaw National Forest (USDA Forest Service 1990).

Figure 3-1 shows SPS yield predictions based on the starting parameters for regenerated stands (appendix one). Total per-acre yields in cubic feet are shown for each of the three cover types CONIFER, MIXED and HARDWOOD, for the 50-year site index class of 119. The total yields shown in this figure are given by species components in table 3-2.

Figure 3-1. Total per-acre cubic foot volume yield curves based on the starting conditions for regenerated stands on 50-year site index 119, given in appendix one. Each yield curve represents one of the three cover types CONIFER, MIXED or HARDWOOD. Yield projections were generated with SPS (Arney 1985).

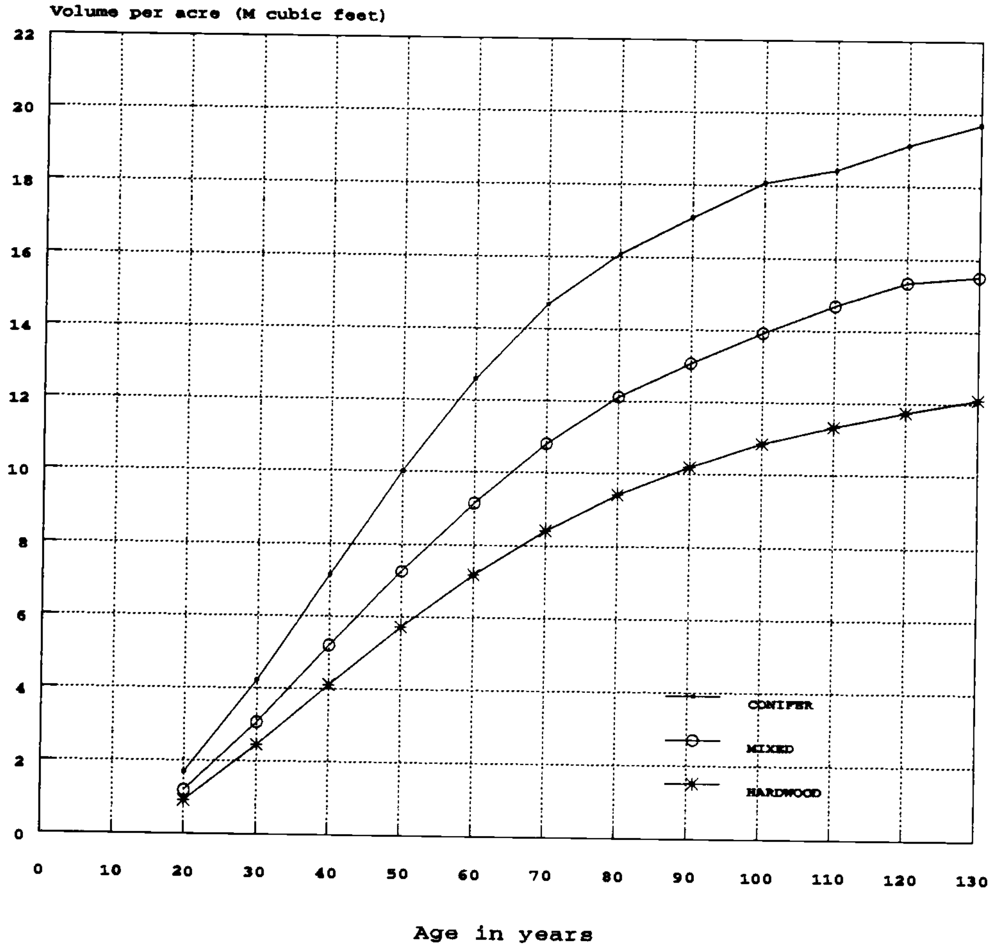


TABLE 3-2. Total cubic foot volume per acre, total and by species component, for cover types CONIFER, MIXED, and HARDWOOD. DF = Douglas-fir. RA = red alder. Source: SPS yield predictions (Arney 1985) based on regenerated stands starting parameters for fifty-year site index 119 (appendix one).

	CONIFER			MIXED			HARDWOOD		
Age	DF	RA	TOTAL	DF	RA	TOTAL	DF	RA	TOTAL
20	1550	130	1690	570	610	1180	260	640	900
30	3950	280	4230	1610	1460	3070	840	1590	2440
40	6760	390	7150	2920	2300	5210	1570	2550	4120
50	9520	500	10020	4310	2960	7260	2370	3360	5720
60	12040	570	12600	5680	3480	916	3180	3990	7180
70	14190	490	14670	6980	3830	10800	3970	4450	8420
80	15680	400	16080	8070	4050	12130	4670	4730	9410
90	16850	270	17110	8970	4110	13080	5270	4920	10190
100	17810	270	18080	9750	4180	13930	5810	5030	10850
110	18430	0	18430	10430	4250	14690	6270	5060	11330
120	19130	0	19130	11030	4300	15330	6660	5090	11750
130	19690	0	19690	11280	4220	15500	6960	5140	12100

Figures 3-2 and 3-3 show total cubic foot per-acre yields weighted by the transition probabilities from (4) above resulting from different chemical (CVT) and manual (MVT) vegetation management applications, respectively, at a rotation age (AGEOLD) of 60 years and an old cover type (SPOLD1, SPOLD2) of CONIFER. The yield curve for each vegetation management intensity consisted of the sum of the yields for each cover type multiplied by the fraction of each harvested acre transferring to that cover type, given the cover type transition model. These figures illustrate the pure yield impacts of different vegetation management strategies in the absence of forest-wide constraints such as non-declining yield, which in this study applied to all cover types.

The term vegetation management strategy as used here denotes the combination of method of treatment, manual or chemical, and intensity of treatment, measured by the number of whole-area treatments applied during the stand establishment phase. Vegetation management was not subject to optimization within individual forest plans; the same strategy was applied to all stands in which the old stand cover type was MIXED or HARDWOOD. It was assumed that reforestation units were treated exclusively with either manual or chemical methods. Treatment intensities ranging from no treatment to three whole-area treatments were used for manual methods while a range of no treatment to two

Figure 3-2. Total per-acre cubic foot volume yield curves as affected by chemical vegetation management treatments. No manual vegetation management. Rotation age was 60 years. Old-stand cover type was CONIFER. For each treatment intensity, the fraction of each harvested acre that transferred to each regenerated cover type was estimated with the cover type transition model in (4) above and multiplied by the yields for that cover type (table 3-2). Yields were then added across cover types.

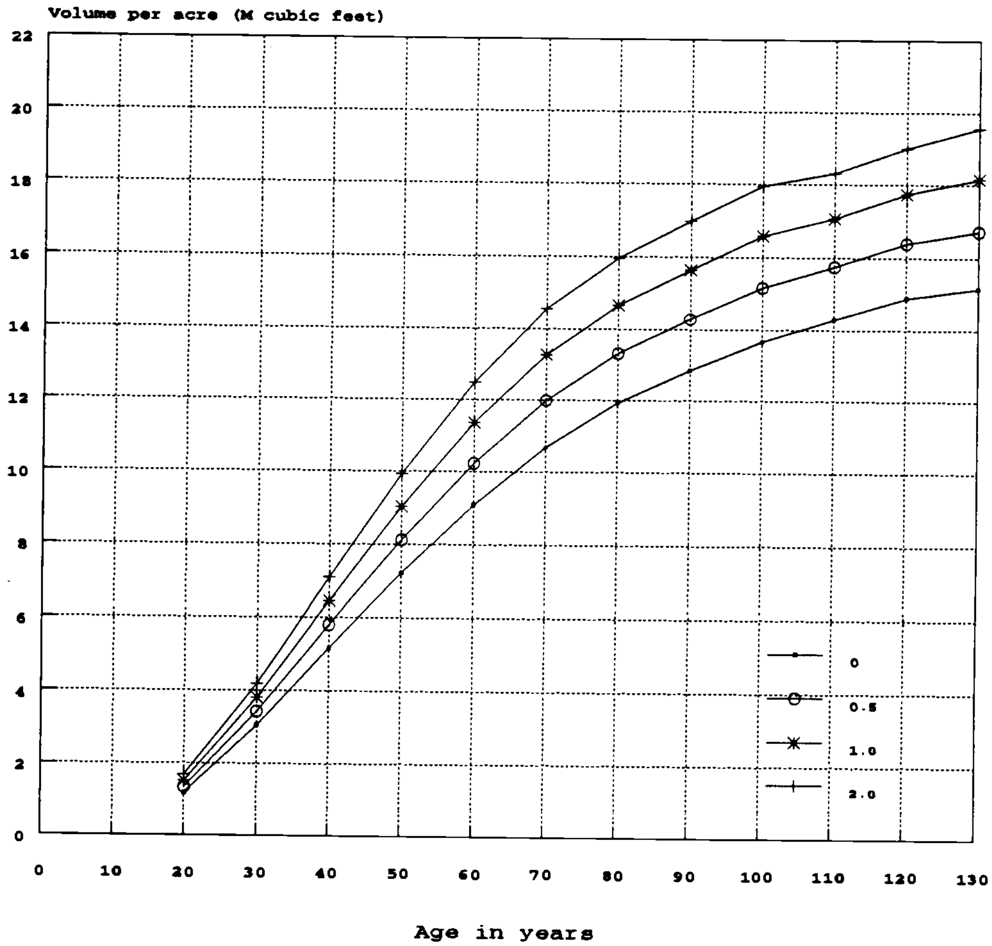
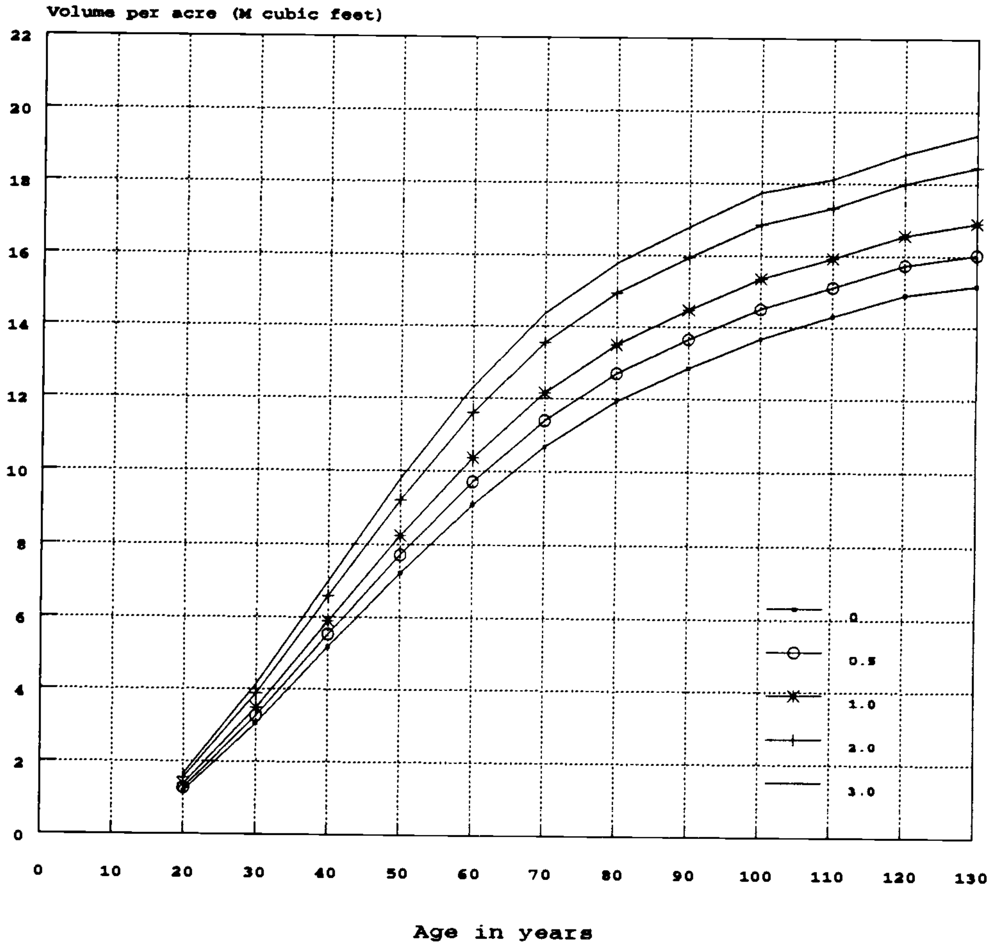


Figure 3-3. Total per-acre cubic foot volume yield curves as affected by manual vegetation management treatments. No chemical vegetation management. Rotation age was 60 years. Old-stand cover type was CONIFER.For each treatment intensity, the fraction of each harvested acre that transferred to each regenerated cover type was estimated with the cover type transition model in (4) above and multiplied by the yields for that cover type (table 3-2). Yields were then added across cover types.



whole-area applications was used for chemical methods. This reflects historical application rates in the study area.

Biological Diversity

Among the guidelines for forest planning contained in The National Forest Management Act (NFMA) are several sections that pertain to biological diversity. The NFMA regulations state:

> "Management prescriptions, where appropriate and to the extent practicable, shall preserve and enhance the diversity of plant and animal communities, ..., so that it is at least as great as that which would be expected in a natural forest and the diversity of tree species similar to that existing in the planning area" (Federal Register 47(190), 219.27(g), 1982).
>
> ... "diversity shall be considered throughout the planning process. Inventories shall include quantitative data making possible the evaluation of diversity in terms of its prior and present condition. For each planning alternative, the interdisciplinary team shall consider how diversity will be affected by various mixes of resource outputs and uses, including proposed management practices" (Federal Register 47(190), 219.26, 1982).

In this study we addressed this mandate by attempting to quantitatively measure and evaluate biological diversity in our strategic forest planning analysis. Quantitative measures of biological diversity traditionally have incorporated elements of both species richness (the number of species present) and evenness (the distribution of the individuals among the species) (Elliott 1990). Species richness was assumed constant in the forest planning analysis done in this study. Preliminary analyses showed that given the initial cover type distribution on the forest as well as the historical early stand treatment patterns reflected in the cover type transition model in (4) above, it would be difficult to eliminate a cover type entirely in any planning period. Diversity as it is used in this study, therefore, refers only to the evenness concept.

To accommodate this narrower definition of diversity, a biological diversity index was developed which consisted of the complement of the sum of squared deviations from a uniform distribution of cover types:

$$1 - \sum_{i=1}^{S} (1/S - a_i/A)^2 \qquad (5)$$

where

a_i is the total number of acres in cover type category i on the forest.

A is the total number of acres on the forest.

$1/S$ is the fraction of acres in each of the S possible cover type categories in a forest of maximum diversity. In this analysis, the value of S is three because three cover type categories are recognized.

Most quantitative indices of biological diversity are based on the notion that under constant species richness, a convergence in abundance of cover types is associated with increased diversity, and vice versa. This implies that a forest of maximum diversity is one in which the S different cover types follow a uniform distribution, with 1/S acres in each cover type (Patil and Taillie 1982). The diversity index used in this study satisfies these criteria. The function is strictly concave throughout its range, which guarantees that cover types converging in abundance result in increased diversity. The diversity index function has its maximum value of one when the forest acreage is uniformly distributed among the different cover types, and its minimum value of 0.5 when the entire forest consists of one cover type.

Although including other aspects of ecosystem diversity such as wildlife and understory species diversity is possible using the index function defined here, we restricted our analysis to tree species diversity, which was the focus of this study. The diversity index values obtained with this function, as well as with any other numerical index measures, are not species-specific. For example, a forest that consists of one-half conifer stands and one-fourth each of mixed and hardwood stands will have the same diversity index value as a forest that consists of one-half hardwood stands and one-fourth each of conifer and mixed stands.

Three type conversion policies were analyzed in this study:

1) <u>No restrictions</u>. All type conversion patterns were permitted.

2) <u>Non-decreasing diversity</u>. Diversity must increase or remain the same as that of the initial forest. This policy reflected an interpretation of the NFMA biological diversity requirements which did not allow diversity to decrease from the initial level (Stockwell 1990). Upper or lower bounds were placed on the forest acreage in each cover type in every period, depending on the contribution of that cover type to the diversity index value:

$$\sum_{s=1}^{S} \sum_{i=1}^{3} \sum_{m=1}^{M} \sum_{h=1}^{H+1} \sum_{r=b}^{h-g} x_{simrh}^{j_p} \leq a_1^j + 10{,}000 \quad \mathit{if}\ a_1^j > \frac{1}{3}A$$

$$\sum_{s=1}^{S} \sum_{i=1}^{3} \sum_{m=1}^{M} \sum_{h=1}^{H+1} \sum_{r=b}^{h-g} x_{simrh}^{j_p} \geq a_1^j - 10{,}000 \quad \mathit{else}$$

$$j=1,\ldots,3, \quad p=1,\ldots,H$$

using the same notation as in (1) - (3) above.

a_1^j is the number of acres in cover type j in period one.

A is the total number of acres on the forest.

To reflect a tolerance in the diversity requirements, standing inventory in any cover type was allowed to deviate from the initial distribution by up to 10,000 acres in the direction of decreasing diversity.

More than one-third of the forest land base in the study area fell into the conifer category initially, and less than one-third fell into each of the mixed and hardwood categories. Consequently, constraints under this policy effectively placed an upper limit on the number of acres in the conifer cover type and lower limits on the number of acres in the mixed and hardwood cover types.

3) <u>Constant diversity</u>. Under this policy, biological diversity had to be similar to that of the initial existing forest. Both upper and lower bound constraints were placed on each cover type in every period:

$$\sum_{s=1}^{S} \sum_{i=1}^{3} \sum_{m=1}^{M} \sum_{h=1}^{H+1} \sum_{r=b}^{h-g} x_{simrh}^{j_p} \leq a_j^1 + 10{,}000$$

$$\sum_{s=1}^{S} \sum_{i=1}^{3} \sum_{m=1}^{M} \sum_{h=1}^{H+1} \sum_{r=b}^{h-g} x_{simrh}^{j_p} \geq a_j^1 - 10{,}000$$

$$j=1,\ldots,3, \quad p=1,\ldots,H$$

No constraints were imposed after 350 years, in order to more easily obtain solutions to the above formulations.

Each forest plan (an objective and a set of constraints) was optimized with a maximum present net worth (PNW) objective as well as an objective of maximizing first-period harvest. No ending inventory constraints were imposed on the forest plans. Such constraints are usually aimed at specifying a perpetually sustainable steady-state target forest at the end of the planning horizon. Defining these target conditions is problematic under the multiple outcome formulations used in this study, however, because it is unlikely that the forest will ever reach a steady-state distribution of cover types. Achieving a steady-state distribution of cover types requires stationary transition probabilities. Transition probabilities in the forest plans in this study, however, which are based on the cover type transition model in (4) above, are non-stationary. They change with old stand age, old stand cover type and vegetation management regime.

Instead of ending inventory constraints, a planning horizon of 400 years was used in all runs in order to diminish ending inventory effects on early periods' harvest, as well as to capture the long-term effects of cover type transitions. Under a maximum PNW objective, ending inventory was assigned a value consisting of the PNW which would result from harvesting the stand at an age as close to 90 years as possible, plus the soil expectation value (SEV) resulting from managing the land in perpetuity with a 90-year rotation age.

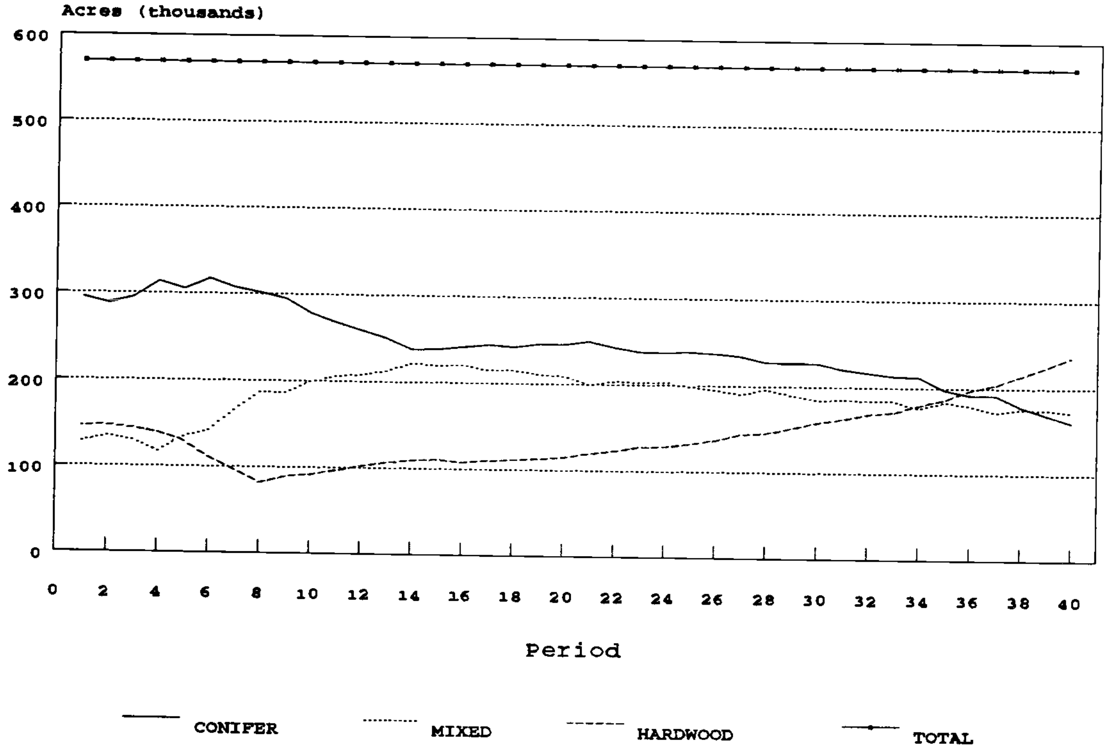
Forest planning formulations were generated using a custom designed matrix generator program (Eng 1991b), which incorporated the forest planning formulation and the cover type transition model reported here. The linear programming forest planning formulations generated in this study were approximately 500 rows by 12,000 columns. Each formulation was solved using a 486/33 IBM-compatible personal computer and the MPSIII/pc mathematical programming software.

RESULTS

The cover type distribution of standing inventory over time of a forest plan under a strategy of no vegetation management is shown in figure 3-4. The forest cover type distribution diverged initially, with a modest increase in the CONIFER cover type offset by a corresponding decrease in the MIXED and HARDWOOD type. The cover types then gradually converged and crossed toward the planning horizon. Behavior near the planning horizon was influenced by the ending inventory specifications in the forest planning formulations used in this study. As discussed previously, no ending inventory conditions were imposed on the forest plans. As a result, standing inventory above minimum rotation age will be harvested near the planning horizon in order to increase the non-declining yield level. However, the 400 year planning horizon will diminish these ending inventory effects on early periods' harvest.

The initial plateau in the CONIFER cover type was due to the effect of mature existing stands on predictions from the cover type transition model. Rotation age (AGEOLD) was an explanatory variable in the cover type transition model in (4). Increasing values of this variable unambiguously increased the relative frequency of the CONIFER cover type outcome. Most existing stands were harvested in the first ten planning periods. These comparatively mature existing

Figure 3-4. Acres of standing inventory by cover type over time, for a vegetation management strategy of no treatments. The minimum rotation age was 60 years.



stands resulted in greater relative frequencies of the CONIFER type after harvest than did regenerated stands, which were often harvested at a younger age in the absence of binding policy constraints such as the biological diversity constraints described above.

Manual and chemical vegetation management treatments shifted the standing inventory towards the CONIFER cover type, at the expense of the HARDWOOD type and eventually also the MIXED type. Figures 3-5 and 3-6 show the cover type distribution of forest plans under a strategy of one and two whole-area chemical vegetation management treatments, respectively, and a minimum rotation age of 60 years.

The figures show that increasing vegetation management treatment intensities caused the cover type amounts to diverge, with the CONIFER cover type acreage increasing and the HARDWOOD and eventually also MIXED type acreages decreasing as vegetation management increased. One whole-area treatment caused an increase in the number of CONIFER acres relative to the equivalent forest plan without vegetation management, primarily at the expense of the HARDWOOD type, throughout the planning periods. The MIXED type acreage increased to near no-treatment levels after the first ten periods. Two whole-area treatments did not further reduce the number of acres in the HARDWOOD type very much, but rather shifted the distribution towards the CONIFER type at the expense of the MIXED type.

Figure 3-5. Acres of standing inventory by cover type over time, for a vegetation management strategy of one whole-area treatment with chemical methods. The minimum rotation age was 60 years.

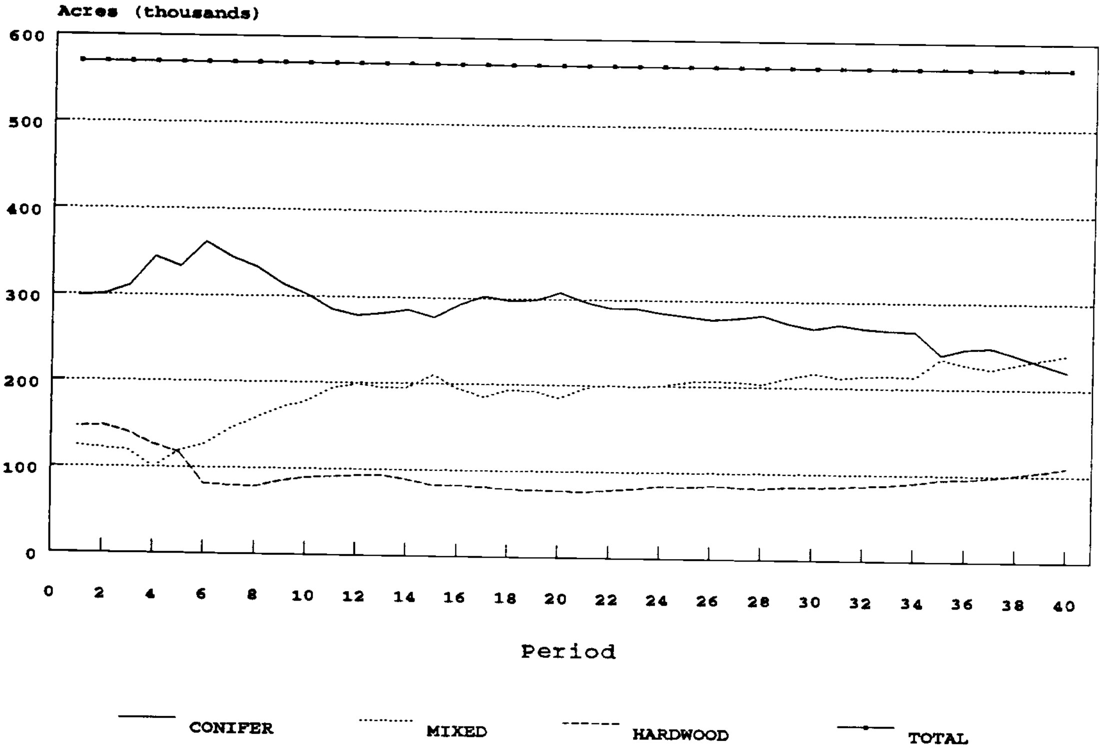
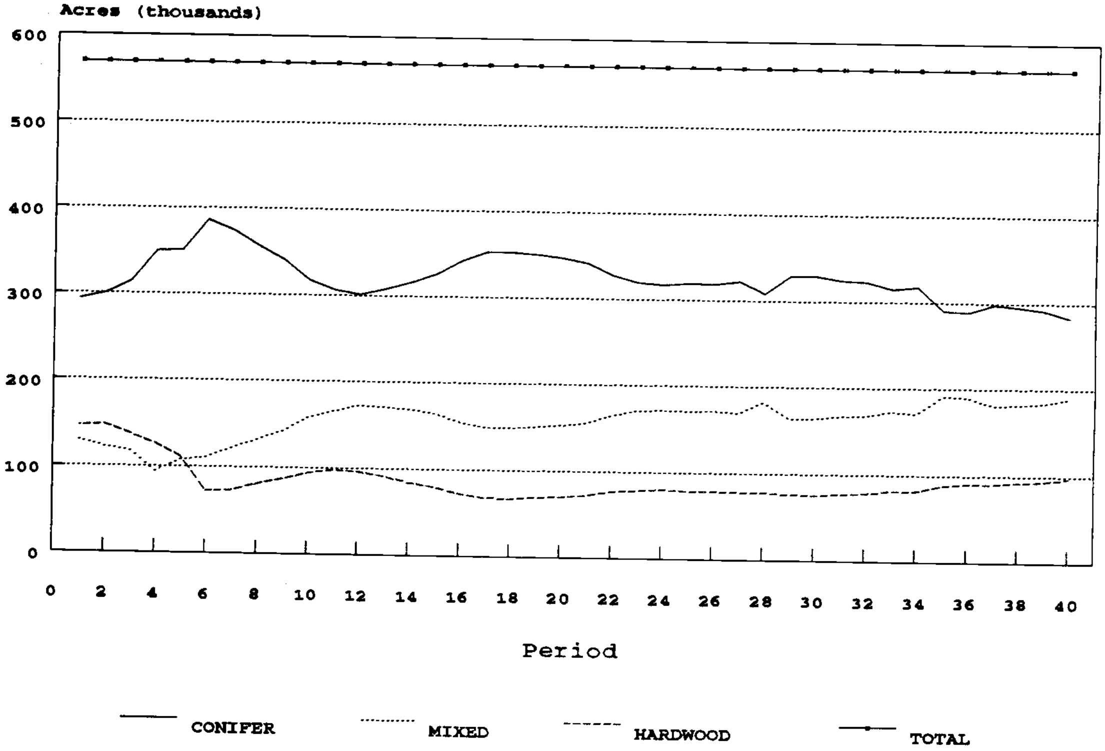


Figure 3-6. Acres of standing inventory by cover type over time, for a vegetation management strategy of two whole-area treatments with chemical methods. The minimum rotation age was 60 years.



The cover type distributions in figures 3-4 to 3-6 include the 212,000 acres of reserved land that was withdrawn from timber production. Harvest-related cover type transitions did not occur on this land, as no harvest occurred. Cover type distributions are likely to be different in situations in which the entire forest is managed for timber production.

Because, as shown in table 3-2, the CONIFER cover type consistently contained greater per-acre volumes than the MIXED and HARDWOOD types, increasing vegetation management intensities also generally resulted in higher harvest levels and forest present net worth (PNW). Tables 3-3 to 3-5 show forest PNW as well as annual first-period harvest levels, under a PNW-maximizing objective, for forest plans that represent different combinations of vegetation management strategies and minimum rotation ages. Manual (MVT) and chemical (CVT) vegetation management are shown in units of whole-area treatments.

For compactness of representation, tables 3-3 to 3-5 only present results under a PNW-maximizing objective. Consequently, although not stated explicitly, all the results pertaining to harvest levels in this discussion will refer to harvest levels obtained under a PNW-maximizing objective. However, although numerical values differed somewhat, the major harvest level results discussed below

TABLE 3-3. Optimal forest plans under a PNW-maximizing objective and a policy of <u>no restrictions</u> on type conversion, different chemical (CVT) or manual (MVT) vegetation management strategies, and minimum rotation ages ranging from 60 to 100 years. The first table entry is the forest present net worth, in millions of dollars. The second table entry is the first period annual harvest levels associated with this optimal solution, in millions of cubic feet.

	Minimum Rotation Age				
Vegetation Management Strategy	60	70	80	90	100
0.0	61.0 1,923	60.7 1,915	60.1 1,882	55.9 1,758	52.1 1,647
CVT 0.5	64.1 1,995	63.8 1,983	61.6 1,891	56.1 1,764	52.6 1,657
CVT 1.0	66.7 2,052	66.2 2,023	62.3 1,896	56.5 1,769	53.0 1,661
CVT 2.0	69.5 2,108	68.4 2,035	63.2 1,897	57.1 1,769	53.5 1,664
MVT 0.5	62.7 1,959	62.4 1,950	61.3 1,882	56.0 1,757	52.4 1,648
MVT 1.0	64.4 1,990	64.1 1,977	61.7 1,881	56.2 1,754	52.6 1,648
MVT 2.0	67.2 2,036	66.6 2,001	62.5 1,873	56.5 1,747	53.0 1,641
MVT 3.0	69.0 2,056	68.0 1,992	63.0 1,862	57.0 1,736	53.4 1,633

TABLE 3-4. Optimal forest plans under a PNW-maximizing objective and a policy of non-decreasing biological diversity, different chemical (CVT) or manual (MVT) vegetation management strategies, and minimum rotation ages ranging from 60 to 100 years. The first table entry is the forest present net worth, in millions of dollars. The second table entry is the first period annual harvest levels associated with this optimal solution, in millions of cubic feet.

Vegetation Management Strategy	Minimum Rotation Age				
	60	70	80	90	100
0.0	60.0 1,900	59.5 1,863	56.5 1,732	49.2 1,575	44.5 1,416
CVT 0.5	60.3 1,930	57.5 1,812	51.9 1,641	45.3 1,465	39.9 1,305
CVT 1.0	59.2 1,911	56.3 1,781	50.1 1,602	43.7 1,435	38.9 1,284
CVT 2.0	61.1 1,934	54.7 1,739	48.6 1,569	42.9 1,416	38.5 1,275
MVT 0.5	60.2 1,914	58.7 1,825	52.8 1,661	46.4 1,488	40.8 1,325
MVT 1.0	60.2 1,921	57.2 1,799	51.7 1,630	45.0 1,455	39.7 1,298
MVT 2.0	59.7 1,902	56.3 1,760	49.8 1,588	43.5 1,427	38.8 1,279
MVT 3.0	60.7 1,906	55.1 1,730	48.9 1,565	43.1 1,413	38.5 1,272

TABLE 3-5. Optimal forest plans under a PNW-maximizing objective and a policy of constant biological diversity, different chemical (CVT) or manual (MVT) vegetation management strategies, and minimum rotation ages ranging from 60 to 100 years. The first table entry is the forest present net worth, in millions of dollars. The second table entry is the first period annual harvest levels associated with this optimal solution, in millions of cubic feet.

Vegetation Management Strategy	Minimum Rotation Age 60	70	80	90	100
0.0	58.3 1,835	57.5 1,749	53.0 1,660	49.2 1,567	44.5 1,415
CVT 0.5	55.8 1,750	52.5 1,663	50.1 1,594	45.3 1,459	39.9 1,305
CVT 1.0	55.3 1,768	53.4 1,695	49.8 1,578	43.6 1,426	38.8 1,277
CVT 2.0	59.1 1,871	54.3 1,714	48.4 1,549	42.8 1,404	38.4 1,267
MVT 0.5	57.8 1,772	53.2 1,665	50.2 1,596	46.4 1,480	40.8 1,322
MVT 1.0	55.5 1,738	52.5 1,656	50.1 1,586	45.0 1,448	39.7 1,293
MVT 2.0	55.8 1,765	53.7 1,688	49.6 1,559	43.5 1,412	38.8 1,279
MVT 3.0	58.1 1,823	54.4 1,695	48.7 1,537	42.9 1,394	38.4 1,259

also hold under an objective of maximizing first-period harvest volume subject to non-declining yield.

Each table represents one of the three type conversion policies described above. In table 3-3, as an example, under no type conversion restrictions, a minimum rotation age of 60 years and a vegetation management strategy of one whole-area treatment with chemical tools, a forest plan is obtained in which the first decade annual harvest level is 66.7 million cubic feet, and the PNW of the forest is 2.052 billion dollars.

Under the <u>no restrictions</u> type conversion policy all the vegetation management strategies paid off, in the sense that they resulted in a harvest level and PNW greater than that of the closest less intensive strategy (including no vegetation management). The most efficient strategy, in terms of producing the greatest harvest level and PNW, was two whole-area treatments with chemical methods. These results applied to all minimum rotation ages in table 3-3. The cost in terms of harvest volumes foregone of a vegetation management strategy consisting of no treatments ranged from a high of 8.5 million cubic feet to a low of 1.7 million cubic feet, depending on intensity and mode of treatment. In terms of the PNW of the forest, the equivalent figures were $185 million and $36 million.

The magnitude of the yield increases resulting from vegetation management should be interpreted in the context of this study, which was a highly aggregated strategic forest planning analysis. Yield responses were averaged across stands grouped into strata based on age, site index and forest cover type. Yield increases on individual sites may differ greatly from those found in this study.

Two treatments with chemical methods was also the most efficient strategy under the non-decreasing diversity and constant diversity type conversion policies and a minimum rotation age of 60 years. The gain in harvest level and PNW was considerably less than under the no restrictions policy, however, and some vegetation management strategies were less efficient than no vegetation management. At all minimum rotation ages greater than 60 years, vegetation management did not pay under the two diversity policies, in the sense that none of the treatment strategies resulted in harvest levels or forest PNW greater than those associated with no vegetation management.

The effect of vegetation management treatments on cover type distributions, harvest levels and forest value decreased as the minimum rotation age in the forest planning problem increased. The rotation age of a stratum in a given period in the forest plan represented the explanatory variable AGEOLD in the cover type transition model in (4) above. Increasing values of the variable AGEOLD were associated with an increasing probability of achieving the CONIFER outcome at the expense of the HARDWOOD outcome, and eventually also the MIXED outcome. At long rotation ages, the additional effect of vegetation management on cover type outcomes was small.

Chemical vegetation management was both less expensive and more effective than manual vegetation management in this study. The use of chemical vegetation management methods however, is restricted on National Forests in Oregon. These tools are to be used only when other methods are ineffective or will increase costs unreasonably (USDA Forest Service 1990). The results in table 3-3 show that if chemical vegetation management methods were replaced with manual methods, harvest levels would fall by 1.4 to 2.3 million cubic feet, depending on the vegetation management strategy, up to two whole-area treatments. The differences in PNW between equivalent manual and chemical vegetation management treatment strategies ranged from $36 million to $72 million.

A strategy of three whole-area manual vegetation management treatments resulted in a harvest level approximately equal to that associated with a strategy of two whole-area chemical vegetation management treatments. The majority of the data in this study however, described treatment regimes of two whole-area treatments or less. Three whole-area manual treatments may have been a prohibitively costly strategy under silvicultural budgets in existence at the time of these treatments. Because manual treatment methods usually are more expensive than chemical methods, budget limitations may lead to a lower treatment rate with manual methods than with chemical methods, resulting in additional reductions in yields.

Under the no restrictions type conversion policy, constraints were not placed on the distribution of acres by cover type. The non-decreasing diversity policy added lower or upper bounds on standing inventory in each cover type, depending on the initial cover type distribution. The overall constraint set representing this policy was binding for all the forest plans in table 3-4 in the sense that it caused a reduction in the PNW and harvest level below the same parameters in table 3-3.

Because the constant diversity policy in table 3-5 simply added an opposite bound on each cover type to the non-decreasing diversity policy in table 3-4, it follows that this policy also was binding when compared with the no restrictions policy in table 3-3 (if a policy is binding in the sense described above, a new policy which only differs from the first by imposing an additional set of constrains, must also be binding). By the same logic, the extra constraint set introduced by the constant diversity policy was also binding when compared with the non-decreasing diversity policy, for all but two of the forest plans analyzed.

Figures 3-7 and 3-8 show biological diversity profiles for different combinations of manual and chemical vegetation management strategies respectively, and minimum rotation age. A no restrictions type conversion policy was used. Diversity was calculated according to equation (5) above. Each box and whiskers represent a scatter plot of index values for one forest plan, with one index value for each period in the 40-period planning horizon. The box encloses the middle 50 percent of the data with the median drawn as a horizontal line inside the box. The lower whisker extends from the first quartile to the smallest data point within 1.5 interquartile ranges from the first quartile. The upper whisker extends from the third quartile to the largest data point within 1.5 interquartile ranges from the third quartile. Data points beyond the whiskers were plotted individually.

Each diversity profile was identified with a two-part identification code. As an example, 1/60 refers to a forest plan with a vegetation management strategy of one whole-area treatment and a minimum rotation age of 60 years.

Increasing minimum rotation ages and vegetation management treatments, which were both associated with an increasing probability of the CONIFER outcome and a decreasing probability of the HARDWOOD outcome, caused a decrease in diversity index values. Forest plans such as 1/100, 2/90, and 2/100 had comparatively low biological

Figure 3-7. Diversity profiles of forest plans with different manual vegetation management strategies and minimum rotation ages. Each box-and-whisker plot summarizes diversity index values for each period in the planning horizon, for one forest plan. Numerical codes beside each box-and-whisker plot denote minimum rotation age in decades / number of whole-area treatments of vegetation management.

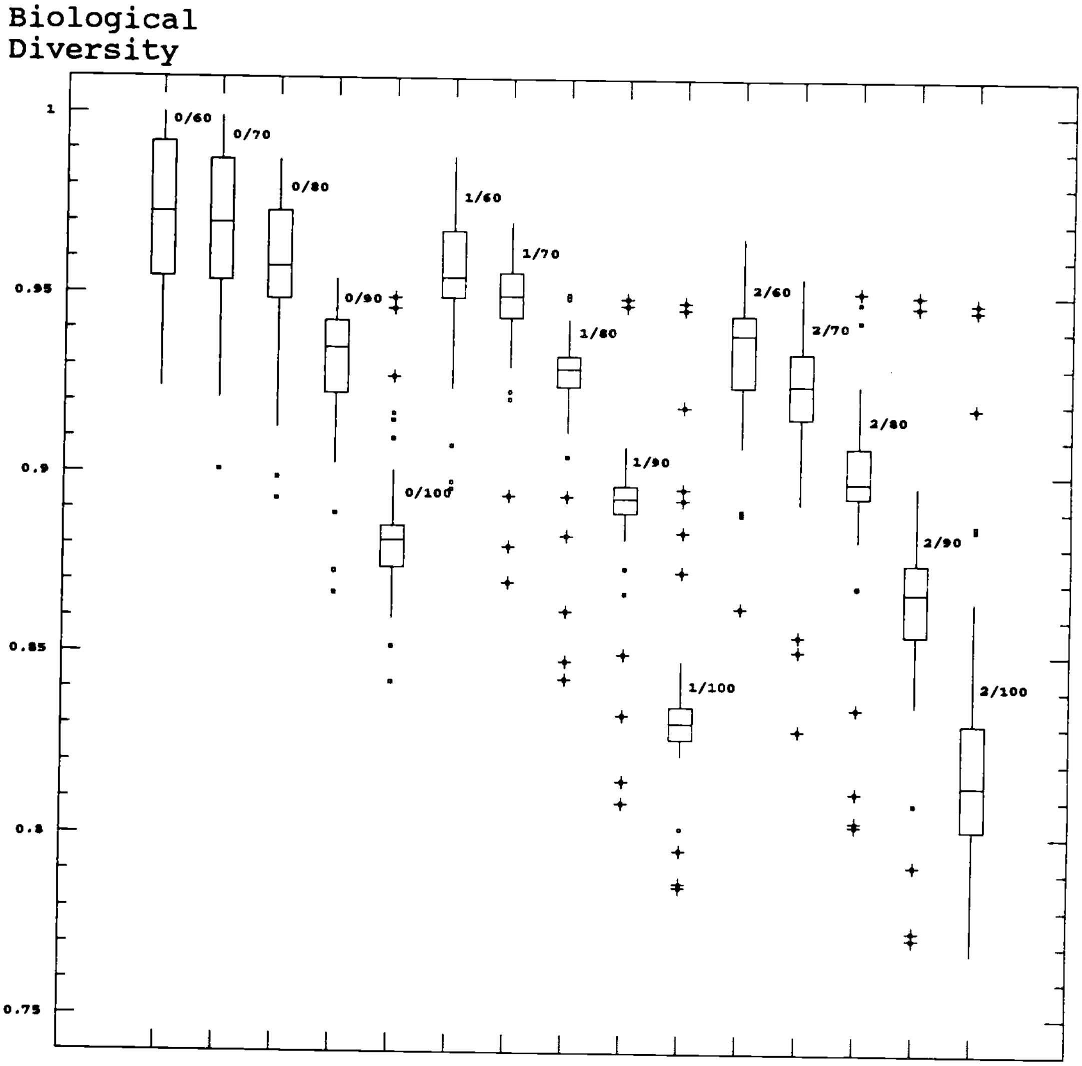
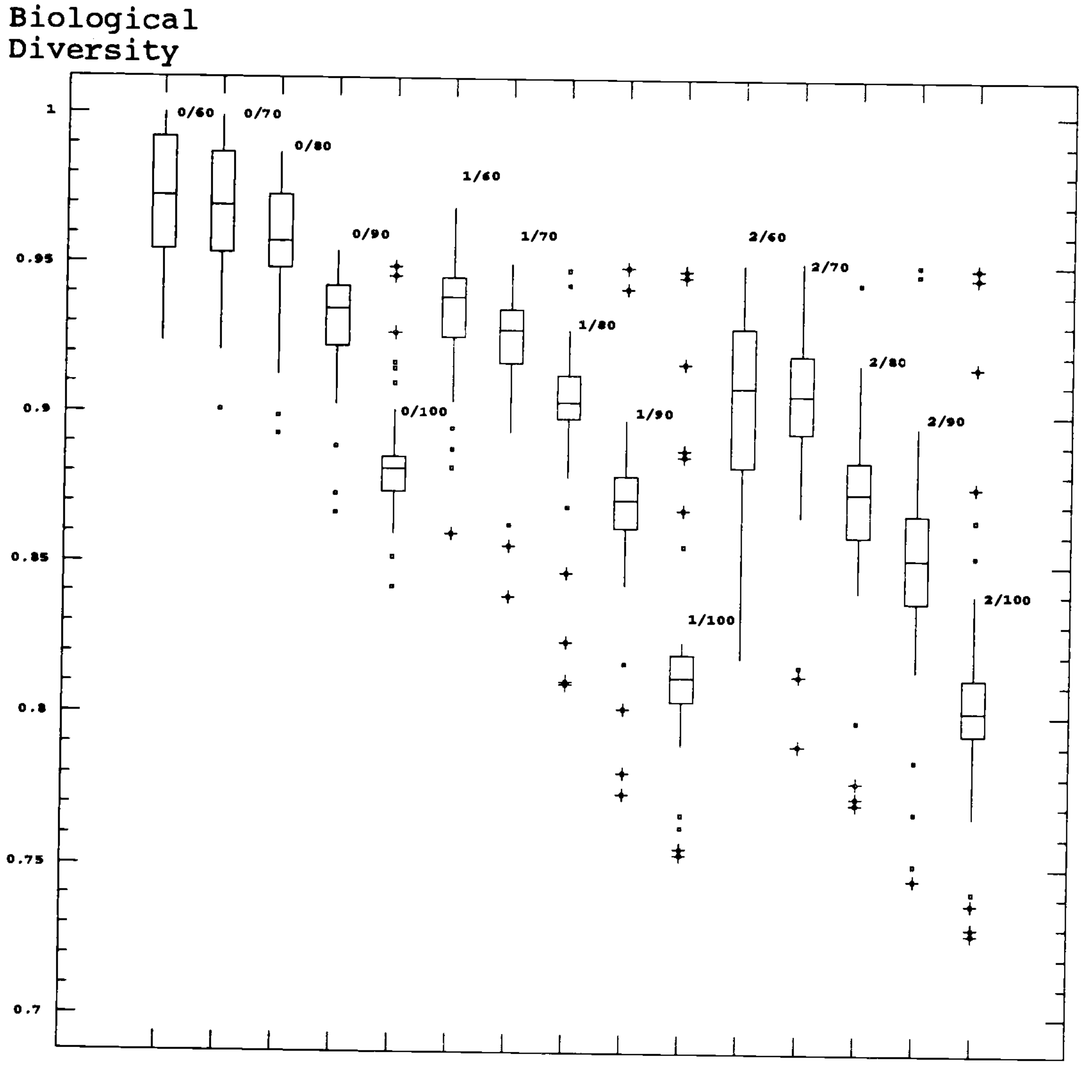


Figure 3-8. Diversity profiles of forest plans with different chemical vegetation management strategies and minimum rotation ages. Each box-and-whisker plot summarizes diversity index values for each period in the planning horizon, for one forest plan. Numerical codes beside each box-and-whisker plot denote minimum rotation age in decades / number of whole-area treatments of vegetation management.



diversity index values through most of the planning horizon. Due to the high minimum rotation ages in these forest plans, the harvest levels were among the lowest in table 3-3. The forest plans representing moderate combinations of manual vegetation management treatments and rotation ages, such as 0/90, 1/60, 1/70, 1/80, 2/60, and 2/70, maintained a diversity profile fairly close to the initial diversity index value of the forest of 0.94, and also produced high harvest levels. Forest plans with short minimum rotation ages and no vegetation management, such as 0/60, 0/70, and 0/80 produced the highest biological diversity profiles over time. As shown in table 3-3, however, they produced low harvest levels, due to the reduced importance of the high-yielding CONIFER cover type.

Chemical vegetation management generally resulted in lower and more dispersed diversity profiles than manual vegetation management treatments applied at the same intensity. Most of the diversity profiles of the forest plans in figures 3-7 and 3-8 were within ten percent of the initial index value of 0.94.

CONCLUSIONS

The results of this study indicated that the attractiveness of vegetation management in the study area depended on minimum rotation age as well as cover type conversion policies in the forest planning formulation. Vegetation management was most effective at low minimum rotation ages. Vegetation management was always profitable in the sense of increasing forest value or harvest level, in the absence of restrictions on cover type conversion. This treatment was consistently a marginal or unprofitable investment, however, under policies aimed at maintaining a constant or non-decreasing level of biological diversity.

Chemical vegetation management methods were less costly and more efficient than manual methods in every case, thus consistently producing higher harvest levels and forest value than manual methods. The results of this study supported the hypothesis that restrictions on the use of chemical vegetation management methods reduce yields. The difference in yields between equal chemical and manual vegetation management application rates reflected a technological difference in effectiveness between the two methods. In addition, manual methods were almost four times as costly as chemical methods in this study. With chemical methods unavailable, budget limitations may force a lower rate of application for manual methods than for chemical methods, resulting in further yield reductions.

The NFMA-mandated consideration of biological diversity in forest planning was implemented in the forest plans in this study as policy constraints that limited changes in the distribution of standing inventory by cover types over time. The two policies analyzed maintained a constant level or a constant or increasing level of biological diversity respectively, and both lowered the non-declining harvest level in almost all the forest plans.

Under a policy placing no restrictions on type conversion, most of the forest plans incorporating one or two whole-area vegetation management treatments and a rotation age of 60 to 90 years, followed a pattern in which diversity dropped up to 13 percent below the initial level in the early planning periods and then increased to a level near or higher than the initial diversity for the rest of the planning horizon. If some reduction in biological diversity is accepted in early periods when most mature existing stands are harvested, most of the forest plans analyzed in this study can produce a higher harvest level and PNW than if held to a strict adherence to a constant or increasing biological diversity in every planning period.

The forest plans in this study divided the forest land base into a managed portion and a reserved portion on which no timber harvest could occur. The objective of dedicating a portion of the forest as reserved may be to manage for late successional communities or leave natural development processes to occur except for fire protection. In either case, in the study area, the reserved portion of the forest is likely to consist largely of late seral conifer stands. This implies that the attainment of diversity objectives has to be achieved by manipulating the managed portion of the forest. In order to meet the intent of biological diversity requirements for the entire forest and given the extensive stands of late seral conifers that are likely to dominate reserved lands, it may be necessary to cultivate some mixed and hardwood stands on the managed portion of the forest.

Chapter 4

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APPENDICES

APPENDIX 1

Starting yield parameters for existing and regenerated stands.

Definition of terms:

Stratum	physical strata defined by site index, stand age, and stand cover type.
Acres	the number of acres on the forest in this stratum.
Cover Type	the cover type, CONIFER, MIXED or HARDWOOD, of forest stands in this stratum.
Age	the 10-year age class of forest stands in this stratum.
SI50	50-year site index class of forest stands in this stratum: 130: $130 \leq SI50$ 119: $109 \leq SI50 < 130$ 108: $SI50 < 109$
TPA	trees per acre.
Top Height	the total height of the 20 percent of the largest-diameter trees per acre.
DBH	diameter at breast height.

Starting yield parameters for existing stands:

					Conifers			Hardwoods		
Stratum	Acres	Cover Type	Age	SI50	TPA	Top Height	DBH	TPA	Top Height	DBH
E01	2797	CON	20	130	234	10.5	60.5	0	0.0	0.0
E02	2044	MIX	20	130	243	9.2	62.8	239	9.5	60.9
E03	29	HWD	10	130	94	5.6	59.3	130	5.3	64.6
E04	19378	CON	10	119	237	7.0	58.9	11	8.3	61.4
E05	4066	MIX	10	119	160	5.5	51.8	120	6.0	53.2
E06	1318	HWD	20	119	78	9.2	50.6	117	7.8	54.6
E07	6845	CON	10	108	458	4.5	58.8	30	4.9	59.2
E08	1436	MIX	10	108	149	4.2	59.7	99	4.4	62.2
E09	82	HWD	10	108	102	3.9	46.7	157	4.0	55.2
E10	8988	CON	40	130	245	13.2	91.0	3	3.7	57.8
E11	958	MIX	40	130	70	16.9	115.3	38	13.1	88.9
E12	3301	HWD	40	130	78	17.0	97.1	192	8.7	71.3
E13	25078	CON	40	119	230	12.9	82.2	14	4.4	79.7
E14	5521	MIX	40	119	177	12.9	90.8	70	12.7	71.5
E15	2093	HWD	40	119	37	19.2	74.1	157	11.9	67.8
E16	7910	CON	40	108	317	11.6	64.8	0	0.0	0.0
E17	1320	MIX	20	108	149	4.2	59.7	99	4.4	62.2
E18	12155	HWD	30	108	36	15.3	86.1	272	9.8	70.9
E19	7043	CON	50	130	191	16.8	124.6	5	8.5	92.2
E20	11280	MIX	60	130	74	17.6	106.3	44	13.7	87.8

					Conifers			Hardwoods		
Stratum	Acres	Cover Type	Age	SI50	TPA	Top Height	DBH	TPA	Top Height	DBH
E21	16677	HWD	60	130	27	27.7	144.0	74	14.4	80.1
E22	25451	CON	60	119	183	16.7	105.2	6	8.1	79.0
E23	9262	MIX	60	119	88	20.1	107.0	39	12.0	74.2
E24	12105	HWD	60	119	40	19.5	106.0	114	12.7	69.3
E25	10769	CON	50	108	152	16.3	84.7	9	4.9	80.3
E26	2721	MIX	60	108	109	16.9	99.2	70	11.7	82.4
E27	26496	HWD	60	108	19	26.9	116.4	119	14.6	80.3
E28	14801	CON	70	130	97	25.3	143.6	5	5.4	89.0
E29	13681	MIX	80	130	64	23.3	128.0	35	16.7	90.8
E30	20198	HWD	70	130	23	32.6	141.5	49	15.9	75.7
E31	20347	CON	70	119	134	21.0	128.7	6	6.9	86.6
E32	6385	MIX	80	119	82	20.4	116.4	38	14.3	85.2
E33	9036	HWD	70	119	25	26.2	110.2	56	15.7	92.9
E34	4169	CON	80	108	118	19.9	102.4	2	5.9	114.5
E35	1829	MIX	80	108	75	17.5	114.2	39	17.0	93.5
E36	16985	HWD	70	108	9	30.2	116.9	87	17.3	85.9
E37	38549	CON	100	130	72	26.7	165.0	3	7.1	99.6
E38	20234	MIX	100	130	40	29.4	181.2	19	19.3	95.0
E39	7791	HWD	90	130	9	38.7	158.9	22	20.9	90.6
E40	63568	CON	100	119	87	24.1	135.8	3	6.5	106.8
E41	19321	MIX	100	119	43	26.0	131.0	26	17.1	90.0
E42	4518	HWD	100	119	29	32.7	162.1	59	16.4	77.0

					Conifers			Hardwoods		
Stratum	Acres	Cover Type	Age	SI50	TPA	Top Height	DBH	TPA	Top Height	DBH
E43	31758	CON	110	108	102	21.1	119.1	2	2.7	94.8
E44	11562	MIX	100	108	67	21.7	114.6	28	15.7	83.7
E45	7434	HWD	100	108	21	24.6	110.5	68	17.7	78.7
E46	4006	CON	140	130	32	36.1	146.1	1	10.5	130.0
E47	3749	CON	180	119	50	30.9	135.6	1	10.9	120.0
E48	6184	MIX	130	119	54	25.5	149.3	18	19.4	74.9
E49	1871	HWD	150	119	9	40.6	196.1	29	23.0	93.1
E50	10390	CON	180	108	66	27.0	137.1	1	5.7	101.9
E51	4050	HWD	190	108	16	38.7	147.0	32	13.0	98.0

Starting yield parameters for regenerated stands:

		Conifers			Hardwoods		
SI50	COVER TYPE	TPA	DBH	TOP HT	TPA	DBH	TOP HT
108	CON	458	4.5	58.8	30	4.9	59.2
	MIX	149	4.2	59.7	99	4.4	62.2
	HWD	102	3.9	46.7	157	4.0	55.2
119	CON	237	7.0	58.9	11	8.3	61.4
	MIX	160	5.5	51.8	120	6.0	53.2
	HWD	138	4.6	37.4	171	5.4	48.7
130	CON	380	7.2	76.8	0	0.0	0.0
	MIX	201	5.9	70.5	149	6.5	72.1
	HWD	94	5.6	59.3	130	5.3	64.6

APPENDIX 2

Costs and revenues used in the forest planning analysis.

Vegetation Management

At the time of this study, manual vegetation management was not a common treatment in the study area. Reforestation records from the Siuslaw National Forest showed a high turnover rate of release contractors, suggesting that a stable equilibrium between supply and demand of release services had not yet been reached. This conclusion was supported by Fiddler and MacDonald (1990), who suggested that the real cost of manual release, which would cover operators' costs and a fair profit, was at least $350 per acre. This cost was used in this study.

Chemical vegetation management costs were set at $90 per acre. This cost reflected historical costs in the study area as shown in reforestation records (USDA Forest Service, 1990).

Fertilization

A cost of $75 per acre was used for fertilization in this study. This figure reflected an aerial application rate of 200 pounds of active Nitrogen per acre (Eng et al. 1990).

Road Construction and Maintenance

Road construction and maintenance was charged at $175 per acre per entry of timber harvested in commercial thinnings or final harvest (Eng et al. 1990).

Timber Sale Preparation

The cost of this item was $43 for final harvest, and $50 for commercial thinnings. These costs were based on harvest records on the Siuslaw National Forest (USDA Forest Service, 1990).

Reforestation

Reforestation costs were estimated to be $200 per acre, and were based on reforestation records from the Siuslaw national Forest (USDA Forest Service, 1990).

Stumpage Prices

Stumpage prices by diameter classes were obtained from the Siuslaw National Forest Land and Resource Management Plan (USDA Forest Service, 1990). Table one describes the prices used, in dollars per thousand cubic feet, by diameter class. Different prices were used for final harvest and commercial thinning in the conifer species category, whereas a single price was used for all harvests in the hardwood category.

	Conifers		Hardwoods
DBH Class	Final Harvest	Commercial Thin	All Harvest
- 10.0	755.68	13.91	47.07
10.0-11.9	820.82	103.15	51.10
12.0-13.9	885.96	221.01	55.16
14.0-15.9	938.08	360.79	58.40
16.0-17.9	1003.22		62.46
18.0-19.9	1055.34		65.70
20.0-21.9	1107.46		68.94
22.0-23.9	1146.54		71.38
24.0-25.9	1172.60		73.00
26.0-27.9	1185.63		73.81
28.0-29.9	1198.66		74.62
30.0-31.9	1224.72		76.24
32.0-35.9	1237.74		78.68
36.0-37.9	1263.80		78.68
38.0-39.9	1289.90		80.30
40.0 -	1302.89		81.11

APPENDIX 3

Cover type transition model data.

Definitions of Terms:

Ranger District -	1) Alsea 2) Waldport 3) Hebo 4) Mapleton
Compartment, Unit -	administrative codes identifying the geographical location of forest stands.
C	constant term in the cover type transition model.
Old Stand Type	the cover type of the mature stand on a site before harvest. 1 = CONIFER, 2 = MIXED, 3 = HARDWOOD.
Old Stand Age	the age of the mature stand on a site before harvest, in years.
Manual Veg Mgt	the number of whole-area treatments of manual vegetation management applied to the reforestation unit.
Chemical Veg Mgt	the number of whole-area treatments of chemical vegetation management applied to the reforestation unit.
New Stand Type	the cover type of the regenerated stand at the end of the reforestation phase.

Ranger District	Compartment	Unit	C	Old Stand Type	Old Stand Age	Manual Veg Mgt	Chemical Veg Mgt	New Stand Type
1	3101	22	1	1	300	0.000	0.207	1
1	3101	107	1	1	300	0.000	0.000	1
1	3101	109	1	1	300	0.333	0.000	1
1	3101	161	1	1	300	0.333	0.000	1
1	3102	59	1	1	300	0.000	0.000	1
1	3102	98	1	1	200	0.238	0.000	1
1	3102	135	1	1	200	0.000	0.000	1
1	3201	34	1	3	80	0.163	1.000	2
1	3202	71	1	3	20	0.444	1.000	3
1	3202	171	1	3	25	1.000	1.000	2
1	3204	59	1	2	120	0.063	0.313	1
1	3204	60	1	2	120	0.055	0.000	1
1	3401	41	1	1	200	0.000	0.000	1
1	3401	107	1	2	100	0.000	1.000	1
1	3401	209	1	2	100	1.000	1.000	1
1	3401	210	1	2	100	0.227	0.000	1
1	3402	134	1	3	40	1.000	2.000	2
1	3403	52	1	1	130	0.000	0.000	1
1	3403	78	1	1	60	0.143	0.000	2
1	3403	97	1	1	130	0.000	1.000	1
1	3404	78	1	2	120	0.000	1.000	1
1	3404	79	1	2	120	0.000	1.146	1
1	3404	86	1	3	90	1.000	1.000	1
1	3404	87	1	3	90	1.000	1.000	1
1	3405	43	1	1	150	0.000	1.000	1
1	3406	68	1	2	150	0.000	1.000	1
1	3406	69	1	1	150	0.000	0.000	1
1	3406	93	1	1	160	2.000	0.000	1
1	3501	38	1	1	120	0.097	0.000	1
1	3501	52	1	2	85	0.376	0.705	2
1	3501	62	1	2	120	0.000	1.203	1
1	3501	148	1	1	130	0.000	2.000	1
1	3501	181	1	1	130	0.000	0.000	1
1	3502	70	1	1	120	0.000	0.000	1
1	3502	78	1	2	120	0.000	0.649	1
1	3502	159	1	1	120	0.000	0.000	3
1	3503	125	1	2	130	0.000	0.000	1
1	3504	67	1	2	60	0.000	0.000	2
1	3504	118	1	1	150	1.294	0.000	1
1	3504	119	1	1	130	0.000	0.000	1
1	3505	77	1	2	100	0.000	1.000	1
1	3505	78	1	1	120	0.000	0.000	1
1	3505	102	1	1	120	0.000	0.000	1
1	3505	142	1	1	120	0.000	0.000	1
2	1101	114	1	1	130	0.433	0.000	1
2	1102	76	1	2	60	0.000	0.000	2

Ranger District	Compart-ment	Unit	C	Old Stand Type	Old Stand Age	Manual Veg Mgt	Chemical Veg Mgt	New Stand Type
2	1102	82	1	2	60	0.000	0.000	2
2	1102	136	1	2	70	0.000	0.000	2
2	1102	137	1	2	70	0.000	0.000	2
2	1102	138	1	2	60	0.000	0.000	2
2	1102	139	1	2	90	0.125	0.000	1
2	1302	93	1	2	90	0.708	0.000	2
2	1302	94	1	2	130	0.000	0.000	1
2	1303	3	1	1	100	1.000	0.000	1
2	1303	7	1	1	80	0.000	0.000	2
2	1303	100	1	1	100	0.000	0.000	2
2	1303	103	1	1	65	0.000	0.000	2
2	1303	110	1	1	50	3.000	0.000	2
2	1303	113	1	1	50	0.000	0.000	2
2	1306	120	1	2	60	0.881	0.000	2
2	1306	119	1	2	60	1.789	0.000	1
2	1306	121	1	3	60	1.500	0.000	3
2	1307	186	1	2	75	0.000	0.000	2
2	1308	48	1	3	90	1.000	0.000	1
2	1308	144	1	2	90	2.000	0.000	2
2	1308	145	1	1	90	0.076	0.000	1
2	1313	170	1	2	50	1.897	0.000	2
2	1313	171	1	1	130	0.321	0.000	1
2	1313	173	1	3	60	0.000	0.000	3
2	1314	29	1	3	75	2.000	0.000	1
2	1315	101	1	3	45	3.000	0.000	2
2	1315	205	1	2	120	1.000	0.000	1
2	1316	245	1	2	110	0.000	0.000	1
2	1316	246	1	2	110	0.000	0.000	1
2	1402	51	1	1	120	0.000	0.000	1
2	1407	51	1	2	70	0.000	0.000	2
2	1602	184	1	2	90	1.563	0.000	2
2	1602	189	1	1	70	0.000	0.000	2
2	1603	64	1	1	120	0.078	0.000	1
2	1604	16	1	1	100	1.000	0.000	1
2	1604	36	1	1	140	0.000	0.000	1
2	1604	83	1	1	60	0.000	0.000	2
2	1605	127	1	1	130	0.000	0.000	1
3	2111	9	1	2	80	0.600	1.000	1
3	2111	51	1	1	60	1.000	0.000	2
3	2111	56	1	3	60	2.185	0.000	2
3	2121	11	1	1	100	0.174	0.000	1
3	2121	97	1	1	115	0.000	0.000	1
3	2121	98	1	1	120	0.058	0.000	1
3	2121	100	1	1	120	0.000	0.000	1
3	2123	23	1	1	120	0.000	0.000	1
3	2124	3	1	1	110	0.341	0.000	1

Ranger District	Compartment	Unit	C	Old Stand Type	Old Stand Age	Manual Veg Mgt	Chemical Veg Mgt	New Stand Type
3	2125	72	1	1	110	0.300	0.000	1
3	2125	73	1	1	110	0.000	0.000	1
3	2125	75	1	1	110	0.000	0.000	1
3	2125	77	1	1	115	0.000	0.000	1
3	2125	79	1	1	110	0.275	0.000	1
3	2125	81	1	1	110	0.140	0.000	1
3	2125	85	1	1	110	0.833	0.000	1
3	2125	97	1	1	100	0.167	0.000	1
3	2125	106	1	1	110	1.625	0.000	1
3	2131	143	1	3	65	1.000	0.000	2
3	2133	35	1	1	110	2.060	0.000	1
4	5001	38	1	2	90	0.000	0.000	2
4	5001	40	1	2	90	0.292	0.000	2
4	5011	62	1	1	120	0.032	0.000	1
4	5011	63	1	1	110	0.000	0.000	1
4	5011	64	1	1	130	0.107	0.000	1
4	5012	38	1	1	120	0.353	0.000	1
4	5012	40	1	1	110	1.030	0.000	1
4	5022	38	1	1	120	0.129	0.000	1
4	5022	39	1	1	120	0.518	0.000	1
4	5024	24	1	1	115	0.000	1.000	1
4	5024	25	1	1	115	0.000	0.563	1
4	5032	151	1	1	120	0.417	0.000	1
4	5033	55	1	1	120	0.368	0.000	1
4	5034	60	1	1	120	0.286	0.000	1
4	5035	43	1	1	100	0.515	0.000	1
4	5035	44	1	2	100	0.333	0.000	1
4	5036	81	1	1	130	0.191	0.000	1
4	5041	10	1	1	115	0.222	0.000	1
4	5052	33	1	1	125	0.429	0.000	1
4	5053	107	1	1	150	0.438	0.000	1
4	5055	39	1	1	130	1.191	0.000	1
4	5073	46	1	1	115	0.122	0.000	1
4	5082	49	1	2	100	0.878	0.000	2
4	5082	75	1	1	100	0.000	0.000	1
4	5082	87	1	1	115	1.167	0.000	1
4	5083	23	1	2	80	2.000	0.000	1
4	5091	74	1	1	115	2.000	0.000	1
4	5092	38	1	1	125	0.359	0.000	1
4	5092	59	1	1	100	1.180	0.000	1
4	5092	62	1	1	120	0.000	0.000	1
5	0001	22	1	3	20	0.000	0.000	3
5	0001	23	1	3	30	0.000	0.000	3
5	0001	24	1	3	40	0.000	0.000	3
5	0001	25	1	3	50	0.000	0.000	3
5	0001	26	1	3	60	0.000	0.000	3

Ranger District	Compartment	Unit	C	Old Stand Type	Old Stand Age	Manual Veg Mgt	Chemical Veg Mgt	New Stand Type
5	0001	27	1	3	70	0.000	0.000	3
5	0001	28	1	3	80	0.000	0.000	3
5	0001	29	1	3	90	0.000	0.000	3
5	0001	30	1	3	100	0.000	0.000	3
5	0001	1	1	1	40	0.000	0.000	3
5	0001	2	1	1	60	0.000	0.000	3
5	0001	3	1	1	100	0.000	0.000	3
5	0001	4	1	2	40	0.000	0.000	3
5	0001	5	1	2	60	0.000	0.000	3
5	0001	6	1	2	120	0.000	0.000	3
5	0001	7	1	2	50	0.000	0.000	3
1	3203	51	1	1	120	0.000	0.000	1
1	3502	77	1	2	85	0.000	0.000	2
1	3503	78	1	2	130	0.000	0.000	2
1	3504	124	1	1	120	0.000	0.000	2
1	3505	114	1	2	120	0.000	0.000	2
1	3505	153	1	1	120	0.000	0.000	1
2	1404	62	1	2	115	0.185	0.000	1
2	1404	123	1	1	75	1.000	0.000	1
2	1408	193	1	1	110	1.000	0.000	1
2	1501	43	1	2	70	0.328	0.000	2
2	1601	23	1	1	100	0.000	0.000	1
3	2111	35	1	2	100	3.000	0.000	1
3	2121	93	1	1	110	0.082	0.000	1
3	2123	22	1	1	120	0.150	0.196	1
3	2124	10	1	1	100	0.333	0.000	1
4	5022	4	1	2	115	0.434	0.000	1
4	5031	58	1	1	110	0.000	0.000	1
4	5032	150	1	2	115	0.545	0.000	1
4	5042	33	1	1	115	0.157	0.000	1
4	5061	59	1	1	100	0.322	0.000	1
4	5071	42	1	1	120	0.093	0.000	1
4	5071	69	1	1	120	0.000	0.000	1
4	5082	77	1	1	120	0.222	0.000	1

APPENDIX 4

Documentation for matrix generator

MGEN PROGRAMMER'S DOCUMENTATION

Program Structure

MGEN is written in standard FORTRAN 77, with the exception of the use of the INCLUDE statement. This statement follows standard notation as used in the Lahey and RM Fortran compilers: INCLUDE 'filename'. The program has been compiled and tested on the Lahey, Ryan-McFarland, and Microsoft FORTRAN compilers. MGEN consists of approximately 5,000 lines of code, including the report writer, but not including the SPS growth-and-yield engine.

LP formulations are developed in MPS format, with a single column of variables in the COLUMN section. The program develops the LP formulation column-wise according to the problem parameters in the data file. The array of constraints is traversed for every column in search of constraints that apply to that column. There is no limit on the number of columns in the problem. The maximum number of rows is currently 999. This allows the program to run within 640K of memory on personal computers. Larger versions are easily created by increasing the size of the array ROWA in the "CON1" common block.

Execution time for the matrix generator is directly proportional to the number of columns. Since a complete growth-and-yield model (SPS) is built into the matrix generator, generating each row requires a growth and yield projection of the entire life of the stand represented by the column. A typical growth-and-yield projection for an 80 year old stand takes 2-3 seconds. In other words, a 10,000 column problem will require at least 5-8 hours to generate. A fast computer is recommended.

Data Structures

Data structures are fixed-size arrays. All integer variables are defined as 4-byte integers. Extensive use is made of common blocks, which define the main data structures, such as the vector of decision variables, strata, and constraints. The following is a list of the major common blocks and their functions:

MAIN1: CHARACTER variables that define the fundamental parts of the LP formulation such as names of existing and regenerated stands strata and management prescriptions.

MAIN2: REAL and INTEGER variables that define fundamental parts of the LP formulation such as starting yield parameters for existing and regenerated stands, the internal representation of each decision variable.

CON1: CHARACTER variables that define the data structures for user-defined constraints.

CON2: REAL and INTEGER variables that define data structures for user-defined constraints.

OBJ: Data structures related to the objective function, cover type transitions and inventory constraints.

The growth-and-yield model model SPS is included as a module in the program, providing unique yield estimates for every decision variable. The following modifications were made to the SPS model:

1) Commercial thinnings were performed by a basal area criterion, allowing up to 30 percent of the standing basal area to be removed in one commercial thinning. Up to two commercial thinnings are available.
2) The original bubble sort used to sort trees by diameter class after thinning was exchanged with a heapsort algorithm written by the author.
3) All non-standard FORTRAN 77 features such as Microsoft FORTRAN metacommands were removed if non-essential (date and time), or converted to standard FORTRAN 77 (INTEGER*2).

MGEN USER'S DOCUMENTATION

MGEN is a matrix generator for strata-based Model II harvest scheduling formulation. It generates linear programming formulations in standard MPS format from input parameters specified in the data file. The program was written for a personal computer environment. There is no upper limit on the number of columns in a given problem. The maximum number of rows varies with the versions of the program. The smallest version which can accommodate 999 rows, requires 640K of RAM memory. Larger versions are available.

How to run: `MGEN < 'control file'.`

The control file looks as follows:

Example	Comment
TEST RUN	Title
TEST.DAT	Data file name
TEST.STS	Stand summary file name
TEST.ROW	MPS row file name
TEST.COL	MPS column file name
TEST.RHS	MPS rhs file name
TEST.MPS	MPS file name
COMPLETE	COMPLETE MPS file or PARTIAL (row, column, rhs files only).

The control file specifies the name of the MPS output files as well as intermediate log and debug files. The matrix generator can produce yield summary tables in the stand summary file for each decision variable. Example yield summaries are given below. The decision variables for which yield summaries are desired must be specified individually in the data input file. An option exists for generating yield summaries for the specified variables only, bypassing the matrix generation - a fast and valuable debugging feature. Key features of yield summaries: SPS yield summaries, transition probabilities, PNW with a breakdown of costs and revenues by period, SEV for ending inventory.

Data Input File

Input is free format under the restriction that items must be in the order shown within lines and between lines. The following is a step-by-step description of how to set up a data file (for examples of options not illustrated here, see the example data file below):

```
|----------------------------------------------------------------------------------
|                            MGEN
|        (Matrix GENerator for harvest scheduling)
|        Helge Eng, Dept. of Forest Resources, OSU.
| Data File  MFIL65.DAT. 5/23/91.
|
|----------------------------------------------------------------------------------
```

Comment: each line in the heading must begin with a vertical line.

TIME HORIZON: 15

Comment: planning horizon in 10-year periods. Maximum 99.

OBJECTIVE FUNCTIONS: PNV 0.04 VOL 1

Comment: two objective functions are available: Present net value with specified interest rate, or harvest volume up to and including the period specified.

ACTIVITIES AND OUTPUTS 12

Symbol	Meaning	Age	Fraction of Area	Cost/ Return	Units
VM1	Vegetation Management	VARIABLE FINAL HARV	1.0	-350.0	ACR

Comment: Fraction of area relates to vegetation management. Multiplied by cost/revenue. Unit is per ACRe or per unit VOLume. Age is VARIABLE (associated with FINAL HARVest, COMMercial THINning or ALL HARVest) or CONSTANT (fixed age). Costs (negative)/returns (positive) are for the units specified.

THINNING SCHEDULES 2

Sched #	Rotation Age		Number of Thinnings	— Ages at which thinnings occur —					——— Residual Stand TPA ———				
1	6	99	0	0	0	0	0	0	0	0	0	0	0
2	6	8	1	4	0	0	0	0	300	0	0	0	0
2	9	99	1	6	0	0	0	0	250	0	0	0	0

Comment: each thinning schedule can have a different number of thinnings within each rotation age interval. The age of each thinning is specified as well as the residual trees per acre/basal area removed. Each decision variable is matched with the appropriate subset of the thinning schedule to which it has been assigned.

MANAGEMENT PRESCRIPTIONS 16 Rxs 0 Rx combinations

Symbol		Meaning	Rotation Min	Rotation Max	Thinning Schedule	Acts & outputs assoc w this rx
13	M	Chem veg mgt on 1X unit,fert & 1 CT	6	99	2	TMB RDC TSC TSF REF VC2 FT1

Comment: specify minimum and maximum rotation age for each prescription as well as the thinning schedule and the activities and outputs that are associated with the prescription.

```
--------------------------------------------------------------------------------
STAND STRATA                    5


 RD    Stratum 4: Ranger District            4 Elements    2 Element combinations
ALS             Alsea
HBO             Hebo
WLD              Waldport
MPL             Mapleton

NTH    North     ALS  HBO
STH    South    WLD  MPL


Comment: define the elements of strata here. Up to 20. The three-letter symbols are then used in the specifications for each existing and regenerated stratum, below.
--------------------------------------------------------------------------------
EXISTING STANDS STRATA:              51

NAME      ACRES RXS  AGE  SP  RD   SA   SI  ACC   PRESCRIPTIONS         BEGIN   CON     HWD   SI  TOP HT   AVG DBH
                                                      AGE TPA   BA  TPA   BA     C    H   C    H

E01      2797    4    2  CON  015  130  ALL  ALL    1 14 15 16
                                                       2  234   83    0    0  157 60.5  0.0 10.5  0.0


Comment: specify the size, prescriptions, stratum affiliations, and starting yield parameters for each existing stratum.
--------------------------------------------------------------------------------
REGENERATED STANDS STRATA:              9

NAME         RXS      SP  AGE  SI  RD   ACC   PRESCRIPTIONS         BEGIN   CON     HWD   SI  TOP HT   AVG DBH
                                                      AGE TPA   BA  TPA   BA  SI  C    H   C    H

R01           3     CON  ALL  108  ALL  ALL    1 14 15
                                                       2  458        30       108 58.8 59.2  4.5  4.9


Comment: specify the size, prescriptions, stratum affiliations, and starting yield parameters for each regenerated stratum.
--------------------------------------------------------------------------------
USER-SPECIFIED CONSTRAINTS:
```

```
001WDA DIR  ACR        G    1044.0
 ALL  STA  CON  015  130  ALL  ALL   Z   0  99   1   1
```

END OF CONSTRAINTS

Comments: constraints can be DIRect - with a scalar right-hand side, or RELative - the right-hand side is another combination of decision variables. Units can be ACRes or VOLume. Inequality can be Greater than, Equal, or Less than. The right-hand side is specified in acres for direct constraints and left blank for relative constraints. The constraint can apply to ALL, EXIsting, or REGenerated stands.

The constraint can apply to FHR (final harvest), COM (commercial thinnings), or STA (standing inventory). The stratum combinations to which the constraint applies must be specified. Regardless of the cover type specified in the stratum specification, the constraint will key on the cover type in the period specified, according to the projected yield parameters. The management prescription to which the constraint applies is specified next - "*" denotes all prescriptions.

The constraint applies to all decision variables that exist within the specified age range and period range. In order to key on age or period only, not both, specify the maximum range for that which is not desired. All values will then be accepted. Warning: The period range option does not specify a constraint for each period within the range. It specifies one constraint that accepts all variables that dump into that range. Every constraint desired must be typed out explicitly.

NON-DECLINING YIELD: YES

Comments: can be disabled by typing NO, for stand-level analysis.

MULTIPLE SPECIES PATHWAYS: YES

Comment: determines whether the formulation will be single-pathway or multiple outcome cover type transitions at harvest.

```
STAND SUMMARY VARIABLE LIST: SUBSET          YIELD TABLES ONLY
   1   4  14   3  12
   0  10  14   4  16
```

Comment: The matrix generator will write out, to the summary file you specified in the control file, a summary of yield parameters for every period in the life of the stands in the SUBSET of the total number of decision variables that you specify in the list above, as well as estimated transition probabilities and a financial summery of costs, revenues, and PNW. Each line in the list above is the five- variable internal representation of a decision variable. For example, the first line specifies a yield summary for a regenerated stand (1), stratum number 4, management prescription 14, regenerated in period 3 and harvested in period 12.

Yield summaries can be had for ALL decision variables in the problem, for the SUBSET you specify in the list above, or NONE. Hint: for anything larger than the most trivial problems, you probably want to go with the SUBSET or NONE option (can you think of a reason why?).

The option YIELD TABLES ONLY bypasses the matrix generation process entirely, and just runs through the variable list, generating yield summaries for the few select variables you specified. A useful feature for debugging purposes.

```
--------------------------------------------------------------------------------------------------------------------------------
DECISION VARIABLE:        R0400312    1    4   14    3   12

 YIELD AND PNV SUMMARY:

PERIOD:             1       2       3       4       5       6       7       8       9      10      11      12
STAND AGE:          0       0       0       1       2       3       4       5       6       7       8       9

CON STND TPA      0.0     0.0     0.0     0.0   236.0   228.0   223.0   218.0   149.0   149.0   149.0     0.0
CON STND  BA      0.0     0.0     0.0     0.0    66.5   130.8   185.1   229.0   186.4   211.2   232.5     0.0
CON STND VOL      0.0     0.0     0.0     0.0     1.4     3.9     6.7     9.4     8.5    10.3    12.0     0.0
HWD STND TPA      0.0     0.0     0.0     0.0    11.0     9.0     8.0     8.0     3.0     3.0     3.0     0.0
HWD STND  BA      0.0     0.0     0.0     0.0     4.3     7.2     9.0    10.5     4.9     5.3     5.5     0.0
HWD STND VOL      0.0     0.0     0.0     0.0     0.1     0.3     0.4     0.5     0.2     0.3     0.3     0.0
CON STND DBH      0.0     0.0     0.0     0.0     7.0    10.0    12.1    13.6    15.0    16.0    16.7     0.0
CON STND  HT      0.0     0.0     0.0     0.0    58.9    83.5   103.6   120.1   130.6   141.7   151.0     0.0
HWD STND DBH      0.0     0.0     0.0     0.0     8.2    12.0    14.3    15.4    17.3    17.9    18.4     0.0
HWD STND  HT      0.0     0.0     0.0     0.0    61.0    85.7   102.7   113.7   124.3   129.9   134.0     0.0
CON HARV TPA      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0    62.0     0.0     0.0   149.0
CON HARV  BA      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0    78.0     0.0     0.0   248.6
CON HARV VOL      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     3.5     0.0     0.0    13.3
HWD HARV TPA      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     3.4     0.0     0.0     3.0
HWD HARV  BA      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     5.1     0.0     0.0     5.7
HWD HARV VOL      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.3     0.0     0.0     0.3
CON HARV DBH      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0    14.5     0.0     0.0    17.3
CON HARV  HT      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0   124.8     0.0     0.0   158.3
HWD HARV DBH      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0    16.4     0.0     0.0    18.7
HWD HARV  HT      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0   121.9     0.0     0.0   136.7
TMB  $/VOL                                                                        360.8
TMB  $/VOL                                                                         62.5
TMB  $ TOT                                                                       1273.1
TMB  $/VOL                                                                                               1003.2
TMB  $/VOL                                                                                                 65.7
TMB  $ TOT                                                                                              13368.3
RDC  $/ACR                                                                       -175.0
RDC  $/ACR                                                                                               -175.0
TSC  $/ACR                                                                        -50.0
TSF  $/ACR                                                                                                -43.0
REF  $/ACR                                                                                               -200.0
FT1  $/ACR                                                       -75.0

PNW =           211.565720000
 TRANSITION PROBABILITIES:          P         (SPPNEW)        SPPOLD   AGEOLD     MNLVEG    CHMVEG
                              0.555638          CON           1.0      90.0       0.0       0.0
                              0.412664          MIX
                              0.031698          HWD
```

Example of input data file:

```
|---------------------------------------------------------------------------------------------------
|                        MGEN
|        (Matrix GENerator for harvest scheduling)
|        Helge Eng, Dept. of Forest Resources, OSU.
|
|
| Data File  MFIL24.DAT. 10/20/91.
|
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TIME HORIZON:                     40

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OBJECTIVE FUNCTIONS:                 PNV      0.04       VOL        1

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ACTIVITIES AND OUTPUTS            12

                                                               Fraction       Cost/
Symbol       Meaning                           Age             of Area       Return     Units

 VM1    Vegetation Management          VARIABLE  FINAL HARV        3.0        -350.0      ACR

 VM2    Vegetation Management          VARIABLE  FINAL HARV        0.5        -350.0      ACR

 VC1    Vegetation Management          VARIABLE  FINAL HARV        1.0         -90.0      ACR

 VC2    Vegetation Management          VARIABLE  FINAL HARV        0.5         -90.0      ACR

 PCT    Precommercial Thinning         CONSTANT           2        1.0        -200.0      ACR

 FT1    Fertilization                  CONSTANT           4        1.0         -75.0      ACR

 STX    Stand exam                     VARIABLE  ALL    HARV       1.0         -23.0      ACR
```

```
RDC    Road construction and maintenance      VARIABLE  ALL    HARV         1.0         -175.0      ACR

TSC    Timber sale prep, commercial thins     VARIABLE  COMM   THIN         1.0          -50.0      ACR

TSF    Timber sale prep, final harvest        VARIABLE  FINAL  HARV         1.0          -43.0      ACR

REF    Reforestation                          VARIABLE  FINAL  HARV         1.0         -200.0      ACR

TMB    Harvested timber                       VARIABLE  ALL    HARV         1.0          300.0      VOL

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THINNING SCHEDULES                     2

 Sched     Rotation      Number of    ---- Ages at which thinnings occur -----       ---------- Residual Stand TPA ----------

   #          Age        Thinnings

   1    6        99         0         0        0        0        0        0        0        0        0        0        0

   2    6         8         1         4        0        0        0        0      300        0        0        0        0
   2    9        99         1         6        0        0        0        0      250        0        0        0        0

-------------------------------------------------------------------------------------------------------------

MANAGEMENT PRESCRIPTIONS                16 Rxs          0 Rx combinations

Symbol            Meaning                          Rotation   Thinning      Acts & outputs assoc w this rx
                                                   Min  Max   Schedule

 1  A     Final harvest only                        6    99      1       TMB  RDC  TSF  REF

 2  B     Manual veg on 1/2 of unit                 6    99      1       TMB  RDC  TSF  REF  VM2

 3  C     Manual veg mgt on whole unit              6    99      1       TMB  RDC  TSF  REF  VM1

 4  D     Chemical veg mgt on 1/2 of unit           6    99      1       TMB  RDC  TSF  REF  VC1
```

5	E	Chemical veg mgt on whole unit	6	99	1	TMB	RDC	TSF	REF	VC2		
6	F	Manual veg on 1/2 of unit + 1 CT	6	99	2	TMB	RDC	TSC	TSF	REF	VM1	
7	G	Manual veg mgt on whole unit + 1 CT	6	99	2	TMB	RDC	TSC	TSF	REF	VM2	
8	H	Chemical veg mgt on 1/2 of unit + 1 CT	6	99	2	TMB	RDC	TSC	TSF	REF	VC1	
9	I	Chemical veg mgt on whole unit + 1 CT	6	99	2	TMB	RDC	TSC	TSF	REF	VC2	
10	J	Manual veg on 1/2 of unit + fert & 1 CT	6	99	2	TMB	RDC	TSC	TSF	REF	VM1	FT1
11	K	Manual veg mgt on 1X unit + fert & 1 CT	6	99	2	TMB	RDC	TSC	TSF	REF	VM2	FT1
12	L	Chem veg mgt on 1/2 of unit, fert & 1 CT	6	99	2	TMB	RDC	TSC	TSF	REF	VC1	FT1
13	M	Chem veg mgt on 1X unit,fert & 1 CT	6	99	2	TMB	RDC	TSC	TSF	REF	VC2	FT1
14	O	1 CT, fertilization & final harvest	6	99	2	TMB	RDC	TSC	TSF	REF	FT1	
15	N	1 CT & final harvest	6	99	2	TMB	RDC	TSC	TSF	REF		
16	Z	No harvest (withdrawn)	98	99	1							

STAND STRATA 5

SPP	Stratum 1: Species	3 Elements	0 Element combinations
CON	Conifer stands		
MIX	Mixed stands		
HWD	Hardwood stands		
AGE	Stratum 2: Age	10 Elements	2 Element combinations
005	0 - 10 years old		
015	11 - 20		
025	21 - 30		
035	31 - 40		
050	41 - 60		

```
   070                 61 -  80
   090                 81 - 100
   110                101 - 120
   135                121 - 150
   999                151 - 999

   IMM     Immature    005  015  025  035  050  070
   MAT     Mature      090  110  135  999

    SI     Stratum 3: Site Index @ 50 years           3 Elements      1 Element combination
   108                       SI50 <= 108
   119                123 <= SI50 <= 129
   130                130 <= SI50

    HI     High        119  132

    RD     Stratum 4: Ranger District                 4 Elements      2 Element combinations
   ALS                Alsea
   HBO                Hebo
   WLD                Waldport
   MPL                Mapleton

   NTH     North       ALS  HBO
   STH     South       WLD  MPL

   CTA     Stratum 5: Accessibility to comm thin      2 Elements      0 Element combinations
   ACC                Accessible
   INA                Inaccessible


EXISTING STANDS STRATA:                    51

NAME      ACRES  RXS  AGE  SP   RD   SA    SI  ACC    PRESCRIPTIONS              BEGIN    CON       HWD    SI   TOP HT    AVG DBH
                                                                                   AGE TPA   BA  TPA   BA       C     H    C    H

E01        2797    4    2  CON  015  130  ALL  ALL    1 14 15 16
                                                                                    2  234   83    0    0  157 60.5  0.0 10.5  0.0
E02        2044    2    2  MIX  015  130  ALL  ALL    3 16
```

```
                                                                     2  243   16  239   24  144 62.8 60.9  9.2  9.5
E03           29   2    1  HWD  015  130  ALL  ALL    3 16           2   94    0  130    0  130 59.3 64.6  5.6  5.3
.
.
.

E49         1871   2   15  HWD  130  119  ALL  ALL    3 16          15    9  100   29   72  116196.1 93.1 40.6 23.0

E50        10390   2   18  CON  130  108  ALL  ALL    1 16          18   66  301    1    2   89137.1101.9 27.0  5.7

E51         4050   2   19  HWD  130  108  ALL  ALL    3 16          19   16  114   32   44   90147.0 98.0 38.7 13.7

REGENERATED STANDS STRATA:                 9

NAME              RXS       SP  AGE   SI  RD   ACC    PRESCRIPTIONS    BEGIN    CON        HWD     SI   TOP  HT    AVG DBH
                                                                        AGE TPA   BA  TPA    BA  SI    C     H     C    H


R01                 3      CON  ALL  108  ALL  ALL    1 14 15            2  458        30        108 58.8 59.2  4.5  4.9

R02                 1      MIX  ALL  108  ALL  ALL    3                  2  149        99        108 59.7 62.2  4.2  4.4

R03                 1      HWD  ALL  108  ALL  ALL    3                  2  102       157        108 46.7 55.2  3.9  4.0

R04                 3      CON  ALL  119  ALL  ALL    1 14 15            2  237        11        119 58.9 61.4  7.0  8.3

R05                 1      MIX  ALL  119  ALL  ALL    3                  2  160       120        119 51.8 53.2  5.5  6.0

R06                 1      HWD  ALL  119  ALL  ALL    3                  2  138       171        119 37.4 48.7  4.6  5.4

R07                 3      CON  ALL  130  ALL  ALL    1 14 15            2  380         0        130 76.8  0.0  7.2  0.0

R08                 1      MIX  ALL  130  ALL  ALL    3                  2  201       149        130 70.5 72.1  5.9  6.5

R09                 1      HWD  ALL  130  ALL  ALL    3                  2   94       130        130 59.3 64.6  5.6  5.3
```

```
------------------------------------------------------------------------------------------------------------

USER-SPECIFIED CONSTRAINTS:

001WDA DIR  ACR          G    1044.0
  ALL  STA  CON  015  130  ALL  ALL    Z    0   99    1    1

002WDA DIR  ACR          G     763.0
  ALL  STA  MIX  015  130  ALL  ALL    Z    0   99    1    1

003WDA DIR  ACR          G      11.0
  ALL  STA  HWD  015  130  ALL  ALL    Z    0   99    1    1

.
.
.


050WDA DIR  ACR          G    3877.0
  ALL  STA  CON  130  108  ALL  ALL    Z    0   99    1    1

051WDA DIR  ACR          G    1511.0
  ALL  STA  HWD  130  108  ALL  ALL    Z    0   99    1    1
---------------------------------------------------------------------------------------------------------
01GCON DIR  ACR          G  300000.0
  ALL  STA  CON  ALL  ALL  ALL  ALL    *    0   99    1    1

02GCON DIR  ACR          G  300000.0
  ALL  STA  CON  ALL  ALL  ALL  ALL    *    0   99    2    2

.
.
.


35LHWD DIR  ACR          L  151000.0
  ALL  STA  HWD  ALL  ALL  ALL  ALL    *    0   99   35   35
```

```
END OF CONSTRAINTS

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NON-DECLINING YIELD: YES

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MULTIPLE SPECIES PATHWAYS: YES

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STAND SUMMARY VARIABLE LIST: NONE
```