An Abstract Of The Thesis Of

Mark E. Lichtenstein for the degree of Master of Science in Forest Resources presented on June 5, 2001. Title: Tradeoffs Associated with Managing Forested Landscapes for Multiple-Uses

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This study focuses on the tradeoffs that exist for managing forested landscapes for biodiversity and timber production. Tradeoff evaluation is important to natural resource managers so they can understand the benefits and costs of alternative management prescriptions. The study examines three watersheds in the Oregon Coast Range and 166 terrestrial vertebrate species to determine the productive capacity of the site in terms of biodiversity and timber revenue. Two points are identified that maximize biodiversity and maximize timber revenue that serve as corner solutions for the production possibilities frontier for biodiversity and timber revenue. The frontier identifies all combinations of outputs that are equal in productive efficiency and the slope of the frontier identifies the marginal cost of biodiversity in terms of foregone timber revenue. A special case is then examined that reenacts the proposed management intentions of each ownership group in the study area. The special case model is used to examine the level of efficiency that exists with respect to the productive possibilities frontier.

The results of the study indicate that there is a high level of inefficiency in the proposed management intentions of the various ownership groups. Higher levels of

revenues can be achieved at the same level of biodiversity. Conversely more biodiversity can be produced at the same level of revenue. Marginal cost analysis also showed that biodiversity comes at an increasingly high cost at the extreme end of the productive capability of the study area. Results also indicate the species that are most affected by management activities are those that require large home ranges (> 200 acres) and species that are the most taxonomically unique.

Tradeoffs Associated with Managing Forested Landscapes for Multiple-Uses

by

Mark E. Lichtenstein

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented June 5, 2001
Commencement June 2002

Master of Science thesis of Mark E. Lichtenstein presented on June 5, 2001.

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Mark E. Lichtenstein, Author

Acknowledgements

I would like to thank everyone that helped me along the way. There are some people that played a significant role in the development of my thesis; in particular my major professor, Dr. Claire Montgomery, was instrumental in guiding me through the long and arduous process. I would also like to thank my other committee members Dr. Darius Adams, Dr. John Sessions and Dr. Jeff Arthur for all of their suggestions and comments. There were others whose contributions were vital to the completion of my thesis: Greg Latta, Neal Shunk, Jonathon Brooks, Andrew Herstrom and Woodom Chung. I would also like to thank my fellow forestry colleagues for all of their help in all areas of graduate school survival. Finally I would like to thank my parents for their continuing support of my seemingly endless academic career.

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Tradeoffs Associated with Managing Forested Landscapes for Multiple-Uses

I. Introduction

Conservation of wildlife species in the face of society's growing demands on natural resources requires painstaking efforts to understand the tradeoffs that occur between conservation and utilization. It is widely agreed that mass extraction of wood products from our forests, without regard to the needs of wildlife, degrades habitat that some forest-dependent species require to survive into perpetuity. The key for policy makers and researchers is to determine what the tradeoffs are, and how we can manage our forests to support society's need for wood products now and in the future, while providing some level of certainty that wildlife species will persist.

This balancing act comes at a cost to society and to forestland owners. Protecting habitats important to biodiversity comes at the cost of a reduction in the amount of timber extracted. For economists, the question is to identify the "best" balance between the biodiversity of wildlife species and timber production. Forested landscapes have the ability to produce both some level of biodiversity and timber revenue. The question is, how much is society willing to pay for increased biodiversity and what are they really getting for this payment.

While probably impossible to quantify the value of wildlife or biodiversity, one can evaluate the tradeoffs in producing both outputs, so that alternatives can be compared. That still requires measuring biodiversity in some way. One option is to evaluate species viabilities or their likelihood of persistence given various management intentions. Society can then determine the level of certainty it wishes to have regarding wildlife persistence that best fits its priorities and cost level. It is in society's best interest to achieve some level of certainty at the least cost, whatever that level may be.

A framework is presented in this thesis to calculate the level of certainty and the corresponding cost in terms of foregone timber revenue. The framework is based on economic principles and biological data of 167 terrestrial vertebrate species that occur in the Oregon Coast Range. The biological data were used to construct a logistic probability of persistence function for all species to determine the cumulative biodiversity of the study area. This was used to investigate the impacts of different management scenarios on biodiversity.

Using the biological and silvicultural data, the biodiversity and timber productive capacity was determined for the study area. The productive capacity model was constructed to maximize the values of timber revenue subject to a biodiversity constraint. The biodiversity constraint was incrementally increased from zero to identify production relationships between biodiversity and timber revenue.

From the productive capacity model, a production possibility frontier was identified for biodiversity and timber revenue. A production possibility frontier identifies all efficient combinations of two or more outputs. Efficiency has alternative definitions. Social efficiency is the maximum value of outputs that is best for society as a whole. Efficiency also can be measured subject to institutional objectives. For instance private landowners attempt to maximize their return on investments, while public lands are used subject to regulations that arise from the political arena. These objectives can be different from the objectives of society as a whole. The production possibility frontier embodies social efficiency and the inefficiency of institutional objectives can be evaluated relative to it.

The inefficiency of the existing ownership pattern with its corresponding specialized objectives was assessed with respect to the production possibilities frontier. A special case was examined in which proposed management intentions of various owners were imposed and simulations were run to identify the amount of timber and biodiversity that could be produced for a given set of ownership management constraints.

The overall objective of the study was to identify the tradeoffs that are associated with managing forested landscapes for biodiversity. This study expands upon and adds new ideas to an already existing body of work that deals with these tradeoffs. Various timber management strategies were implemented across the landscape to determine the productive relationship between biodiversity and timber revenue. This relationship was then described in a production possibilities frontier (PPF). A modified version of the frontier model was created and was used to understand the effects of managing forested landscapes based on ownership objectives.

Specific research objectives are as follows:

1. Determine the productive capacity of the study area in terms of biodiversity and timber revenue as defined by the production possibilities frontier.
2. Identify the level of inefficiency that exists due to current ownership patterns.

A literature review follows that gives background on the field of research dealing with production tradeoffs. Then methods are described. Finally the thesis closes with the results and conclusions that were observed.

II. Literature Review

INTRODUCTION

In recent years the body of research dedicated to understanding tradeoffs between commodity and non-commodity values has grown. A wide array of opinions and methodologies has been used to address this problem. I synthesize and highlight each of these ideas, noting their advantages and disadvantages to solving this complex problem, in the following section.

An array of academic disciplines must come together to examine the tradeoffs associated with managing forests for multiple use. Biologists have developed ideas concerning species viabilities, habitat associations, and species population thresholds. Economists have taken single and multiple species approaches to integrating complex model designs with biological data. I begin by describing a general history of evaluating tradeoffs in managing forested landscapes. I then examine the biology of modeling tradeoffs and discuss how economics is used to integrate biology with economic theory. This is followed by a discussion of some of the modeling techniques that are used, beginning with solution methods. This is followed by a discussion of the impacts of spatial elements on model methodology.

HISTORY

Gregory (1955) first applied production economics to evaluate tradeoffs associated with multiple-use in a forested environment. Gregory's emphasis was on differences in land values with various combinations of forage and timber production. His research intentions were the same as researchers of today, to evaluate the effects of managing forested landscapes for uses other than timber production.

Gregory's problem formulations with regards to tradeoffs were centered on basic economic theories of marginal cost and revenues and profit maximization alternatives between market goods. These theories provide the basis for most empirical studies evaluating biodiversity tradeoffs. There are some key differences. One is the focus on tradeoffs between market and non-market goods. Secondly, the complexity of modeling tools has advanced with computing technologies.

BIOLOGY AND BIOLOGICAL MODELS

Understanding the environmental conditions required to ensure some level of certainty that species will survive into the future is a challenge. Animals have evolved over millions of years. Few can adapt to the rapid environmental changes that have occurred over the last two hundred years due to human impacts. The scope of these changes is enormous. Human populations in the U.S. have grown from 76 million to 272 million in the last 100 years, causing urban sprawl to move deeper into naturally forested areas. These rapid environmental changes have lead to an increased rate of species extinction (Wilson 1992).

There are a few key areas of biological information that are needed to model tradeoffs associated with timber production and biodiversity. One important measure is species viability that best captures the impacts of environmental change on individual species. Another is integrating individual species measures together to obtain a measure of diversity of the set of species.

Viability Functions

Species viability is defined as the probability that a species population will exceed some threshold at the end of some time period (t) as seen in equation 1 (Shaffer 1981).

$$\text{Viability}(x) = \text{Prob}(\text{Population}_t(x) > \text{Population Threshold}) \quad (1)$$

If the threshold equals zero, species viability is equal to probability of survival. The population size at time t depends on the quantity and configuration of habitat that exists for a particular species (x). Viability can be used as a measure of accomplishment of conservation objectives for a single species.

Economists have turned to wildlife biologists to gain a better understanding of the variables that need to be accounted for in the modeling of species viability. In the case of lesser-known species even the wildlife biologists have very few answers. Tradeoff research is often done utilizing a single species that is endangered or threatened. When a species is listed as endangered or threatened, its population levels are dwindling, so the possibilities for future research are limited. With multiple species the problem of insufficient information is even more important. As our understanding of interspecies dependency, habitat requirements, and life cycles increases our multiple species models will become more effective and scientifically credible. In the meantime, economists and wildlife biologists are taking innovative approaches to using limited data to evaluate biodiversity.

Examples of approaches that use limited data to model viability for large sets of species include Montgomery et al. (1999) and Bevers et al. (1994). In order to find population thresholds Montgomery et al. incorporated the use of known imperilment rankings and population estimates that were developed by The Nature Conservancy (TNC) and the International Union for the Conservation of Nature (IUCN). The rankings are relayed in terms of levels of imperilment with each level having an associated population and probability of extinction. Habitat was assumed to have a linear relationship with population and was used directly in the assessment of viability. Using both study area habitat estimates and levels of imperilment, a logistic viability curve was constructed that is identical for each species examined. The slope, which is the marginal product of the viability with respect to habitat, increases as the amount of habitat initially increases until it reaches a maximum and then decreases as habitat continues to increase. The implications for conservation in this type of viability function is that conservation efforts are most fruitful at the midrange of the function while at high levels of imperilment species would become increasingly costly to save (Montgomery et al. 1999).

Bevers et al. (1994), which is an extension of Hof and Raphael (1992) calculated viability as functions of relative abundance. Relative abundance is the population with respect to the maximum population that could be carried on the landscape. This approach is useful in identifying species that are at risk due to low abundance (Hof and Raphael 1992). Given the study was dynamic, viability for each period provided a useful way of accounting for adjustments to available habitat due to managerial actions (Bevers et al. 1994).

More detailed models are being developed to simulate wildlife population performance on a changing landscape over time. These models differ from the previous studies by including spatial relationships in their evaluation of habitat. One model developed by Schumacher (1998) called PATCH (A Program to Assist in Tracking Critical Habitat) has the ability to model a single species throughout its lifecycle. It is a spatially explicit model that reads GIS imagery directly and uses the data to link attributes of a species life cycle to the quality and distribution of habitats throughout the landscape (Arthur et al. 2001). PATCH also has the ability to model species types (i.e. large or small body types). The model uses a series of simulations to derive an estimate of species viability for a particular land management scheme. One limitation of PATCH is that it can only model a single species, but further modifications of the model to make it compatible for multiple species are in design.

Viability measures the probability population levels will exceed some threshold at the end of a planning period. The threshold can be seen as a predefined standard for extinction risk as defined by Haight et al. (1995). Extinction risk has two parts, a risk standard and a margin of safety. The risk standard represents long-term risk, recognizing that management decisions are planned over a relatively short horizon. The margin of safety is the required probability for attaining the standard. Requiring the risk standard recognizes the relationship between population and the long-term risk of extinction. The margin of safety is used to accommodate for the uncertainties that arise in population dynamics and natural phenomenon.

Measuring Biodiversity

Biodiversity measures reflect diversity within a set composed of individual species. The calculus of biodiversity (May 1990), or the attempt to assign quantitative indicators of diversity to a set of species, can be derived in many different ways.

Ecologists tried to document the variations in the natural world as early as 1916. "The idea of biodiversity still stimulates the minds of ecologists today and the value assigned to biodiversity is often translated into an indicator of ecological well-being" (Magurran 1988, pg. 1). Measuring biodiversity is a complex problem. Hundreds of indices have been developed that attempt to give a biological diversity measure. Indices proposed by ecologists have two components: species richness and species abundance (Magurran 1988). Species richness is the number of species per specified area. Species abundance describes the distribution of species populations. These two components are usually used for evaluating species diversity but have also been applied to timber stand structure and habitat, and could conceivably be applied to any diverse set (Magurran 1988). There is no "right" diversity measure; the best measure is the one that answers the question at hand most accurately.

There are some standard approaches to measuring biodiversity. These include standardized indices that evaluate biodiversity based on a set of parameters. Examples of this include Shannon's and Simpson's indices that seek to merge richness and evenness into a single number (Magurran 1988). Shannon's index and Simpson's index incorporate and reflect the proportional species abundance with respect to total abundance. Shannon's index is an evenness measure; it reaches its maximum when there are equal amounts of all species in the sample. In contrast the Simpson's index, often referred to as a dominance measure, is weighted towards the abundance of the most common species.

Solow et al. (1993) proposed a biodiversity index that utilizes complete set of DNA pair-wise distances to distinguish between the genetic diversity of different species of cranes. This method captures species uniqueness at a genetic level. In contrast to Shannon's or Simpson's index, this method incorporates the contribution of each unique species on overall biodiversity. Luckily for Solow et al. this biological data was available. But for most species it is not, causing this system to be infeasible for most sets of species. Regardless of this fact their methodology does provide some other useful insights into evaluating biodiversity based on the genetic diversity of species, which could potentially help to focus preservation efforts.

The pure diversity measure, proposed by Weitzman (1992), is the evaluation of biodiversity with the objective being to have as diverse a set of species as possible. This method is similar to Solow et al. (1993) but does not recognize species uniqueness at the genetic level. A preservation or pure diversity measure is most commonly implemented when the diversity goal is to preserve as representative a sample of the existing population as possible. This measure severely punishes scenarios that extinguish unique species, while the loss of species with an abundance of close relatives would have only minor implications.

Another scheme for evaluating biodiversity that focuses on species uniqueness was introduced by Vane Wright et al. (1991) and then further modified by May (1990). This method called taxic diversity, gives a measure of taxonomic diversity. It is a simplistic attempt at assessing the effects of unique species in a biodiversity measure. In

Montgomery et al. (1999), this method was used to evaluate 167 different bird species in the Muddy Creek Watershed in Oregon. It consists of "counting the nodes" along the applicable taxonomic tree for each species. The larger the node count, the less unique the species is and, conversely, the smaller the count the more unique the species is. This assumes with large node counts, the species has more close relatives available that can fulfill its particular function in the ecosystem. The diversity measure is then calculated as the weighted sum (node count) of each species' viability; given from their viability function at their current population size, which ultimately gives a premium to more unique species. This measure combines quantitative measures of taxonomic distinctiveness with more familiar ecological considerations (May 1990).

ECONOMICS OF TRADEOFFS

Economics play an important role in determining the tradeoffs of alternative output combinations. Economic theory can be used to help understand and identify alternatives to current trends of species population reductions. Shogren et al. (1999) succinctly states the purpose of using economics to evaluate tradeoffs: "In a world of scarce resources, the opportunity cost of species protection …must be taken into account in decision making". This implies that if we can get more for our conservation efforts for the same cost, all of society would be better off. This requires using an integrated economic-biology approach.

Economic Analysis of Single Species Survival

The body of research into the production relationships between ecological objectives and commodity production on a forested landscape has evolved from analysis of a single species to analysis of a set of species. Both methodologies involve evaluating the impacts of particular land management activities on the likelihood of species survival. In a single species approach and some multiple species approaches, interspecies interactions are not modeled (e.g. species predation- prey relationships). In single species studies, the only effects that are of value are the ones that deal with the species under study. In the multiple species approach, effects of management on individual species are aggregated into one of a variety of biodiversity indices.

The single species approach has often been applied to species which are endangered or threatened and are on the endangered species list. It is often the purpose of the research to examine the various alternatives that exist to protect the listed species. Examples include Hyde (1989) Montgomery et al. (1994) and Haight (1995). Hyde (1989) used a reserve system to identify the least cost management alternative for preserving any population level of the red-cockaded woodpecker. Montgomery et al (1994) identified a marginal cost curve for a single species likelihood of survival based on reserve site selection for the Northern Spotted Owl. Haight (1995) modeled the marginal opportunity cost of achieving population standards within some margin of safety.

Multiple Species Approach

Multiple species evaluation is useful in examining the effects of land management activities on an entire natural system. This approach may take into account species interdependence and uniqueness as well as the need for a diversity of habitats on the landscape. Increasing the scope of the study to include multiple species requires large amounts of data and calls for a dramatic increase in the level of sophistication in modeling methods.

Economic studies of tradeoffs usually involve major simplifications in biological models. Ando et al. (1998) used an algorithm that found the minimum cost of attaining target levels of expected number of species present in a reserve system. Montgomery et al. (1999) utilized simple viability functions and aggregated them into a biodiversity measure as expected species richness.

Even determining what species are present can be a problem. Various groups such as the Nature Conservancy and the Biodiversity Research Consortium produce species location databases, but information is limited. Continued emphasis on acquiring knowledge about species habitat relationships and existence will only serve to make future studies more accurate in their assessment of species survival.

SOLUTION METHODS

Traditional methods of optimization use basic concepts of calculus to maximize linear or non-linear objective functions. Because traditional methods require well-behaved objective functions, many model parameters are simplified. The advantage of using traditional methods is that the solution is a global optimum. But simplification can cause the "realness" of the model to be compromised. Simplifications include ignoring spatial constraints and complex habitat-species relationships.

Spatial Models

Spatially explicit models of wildlife population dynamics are complex, especially if they examine large landscapes like an ecoregion or the entire U.S. For instance, Ando et al. (1998) examined the entire U.S. to discover an efficient allocation of land that will protect the greatest amount of endangered species in a reserved base system. Although their model did not incorporate many of the components I have discussed, such as viability functions and biodiversity measures, it does show that spatial elements can be incorporated in a study of biodiversity at very large scales.

Other studies that incorporate spatial information are Calkin (2001)and Bettinger et al. (1996). Spatial issues such as adjacency and edge effects are important in determining species habitat preferences. Spatial parameters not only increase the difficulty of writing the code for the modeling, but also in processing time and evaluation of the results.

Heuristics

The need for a method to solve complex problems has led researchers to the field of heuristics. Heuristics are an alternative to traditional optimization methods. Heuristics is a technique, to seek good solutions without being able to guarantee optimality (Reeves 1993). Heuristics have the ability to handle complex spatial constraints and ill-behaved objective functions.

Heuristics can handle unusually large and or spatial problems. Wildlife scenarios are modeled more realistically when spatial elements such as adjacency are included. Heuristics use neighborhood searches that explore areas of the solution space based on the value of the objective value that is returned. Landscape level problems are quite large and standard optimization techniques can be infeasible. Heuristics are used to explore large areas of the solution space with minimal time and computational effort.

While heuristics do not necessarily identify the global optimum, there are statistical tests using extreme value theory to approximate how "good" the heuristic performed. Other methods such as comparing the results of one algorithm to other algorithms can be used to judge the performance of the heuristic. (Bettinger and Sessions, in press) Heuristics have created a platform for landscape level analysis of tradeoffs and have allowed researchers to examine spatial effects of timber management on wildlife species and biodiversity.

CONCLUSIONS

The range of possibilities that exist in examining tradeoffs is endless. Economists have vastly improved the models of past economists such as Gregory. Use of spatially explicit models and heuristics while integrating biological data with economics are only a handful of the positive changes that have occurred in the theoretical framework.

Incorporation of complex biological data such as inter-species dependence and habitat requirements, as well as more spatially explicit models, are the future of tradeoff research. Economics and biology compliment each other in the evaluation of tradeoffs.

As our knowledge of species biology increases, so does our accuracy in modeling tradeoffs.

The limiting factor of understanding tradeoffs is incorporating biological data and relationships into models. Biological data drive the biodiversity component of tradeoff evaluation. Without quality data results of these studies are hard to implement in real world situations. The best use for tradeoff analysis is to provide policy makers with alternatives that can be used to guide forest policy.

III. Methods

RESEARCH DESIGN

The primary focus of this research was to identify the productive capacity of the study area in terms of biodiversity and timber revenue. The production relationship was represented by an estimate of the production possibility frontier (PPF) for biodiversity and timber revenue. Ownership boundaries were ignored and all forested land was treated as if managed under a single objective, as defined by the objective function. The PPF identifies all efficient combinations of biodiversity and timber revenue. Secondarily, I examined a special case that imposed ownership boundaries and the proposed management intentions of each ownership group in the study area. The special case model was used to evaluate inefficiencies of current systems and to suggest possible efficiency-improving policies.

The format of the methods section is as follows. First I describe components of the production possibility frontier, and how the frontier was identified. Second I describe the basic characteristics of the study area and provide greater detail about the model parameters. Finally I describe the special case and how it differs from the original production capacity model.

PRODUCTIVE CAPACITY MODEL

Solving the following problems identified end points of the production possibility frontier:

1) Choose the timber management prescription (x) that maximize the output of biodiversity (B):

$$\max_{x} B$$

2) Choose the timber management prescription (x) that maximize the output of timber revenue (R):

$$\max_{x} R$$

Points along the production possibility frontier (PPF) between (1) and (2) were identified by using constrained optimization:

3) Choose the timber management prescription (x) that maximizes R subject to achieving specified levels of B:

$$\max_{x} R$$

$$\text{Subject to } B > \bar{B}$$

The model was solved iteratively for each incremental level of the constraint until the maximum biodiversity level was achieved. First I will describe the study area and then define the variables X, B and R.

Study Area

Geographic Location of Study Area

The study area contains three watersheds in the Northern Coast range of Oregon: the Neskowin, Little Nestucket and the Siletz/Yaquina. The study area was chosen from the Coastal Landscape Analysis and Modeling Study area (CLAMS) (Spies [in press]), which encompasses most of the Oregon Coast Range of Oregon. These particular watersheds were chosen for their diversity in ownership and vegetative cover, and the relatively large area they encompassed in aggregate (101,749 acres). A map of the study area can be seen in Figure 1.

Figure 1 Map of Study Area

Since the study area did not encompass a tremendously large area it was appropriate to evaluate the impacts of management activities within the study area relative to the greater surrounding landscape. I assumed that management outside the initial study area would be such that the status quo is maintained. The study area was expanded to approximately four times its original size (440,000 acres) to assess the amount of habitat that is initially available to each species. A map of the enlarged study area is in Figure 2.

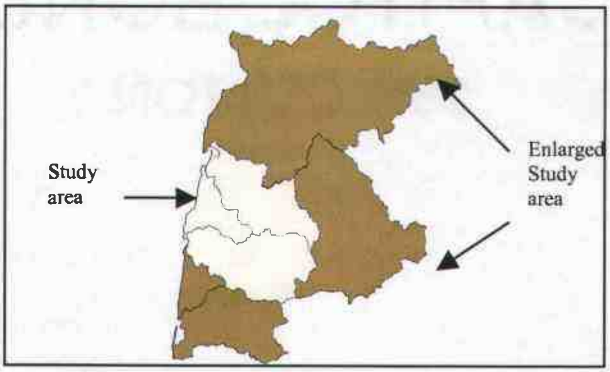

Figure2 Enlarged Study area

Ownership

The study area contains a relatively diverse composition of ownership groups. All major forest landowner types in Oregon are represented including the Forest Service (USFS), Bureau of Land Management (BLM), Oregon Department of Forestry (ODF), non-industrial private landowners (NIPF) and large and medium-sized private forest industry. Forest industry owns the majority of the area; 40,605 acres (40% of total area) while the Forest Service and BLM own the second largest portion totaling 40,074 acres (39% of total area). A complete breakdown of acreage by ownership can be seen in Table 1. A map of the ownership configuration is shown in Figure 3.

OWNER	ACREAGE
NIPF	19,111
PRIVATE INDUSTRY	40,605
USFS/BLM	40,074
STATE	1,960
TOTAL	101,749

Table 1 Acreage per ownership group for study area

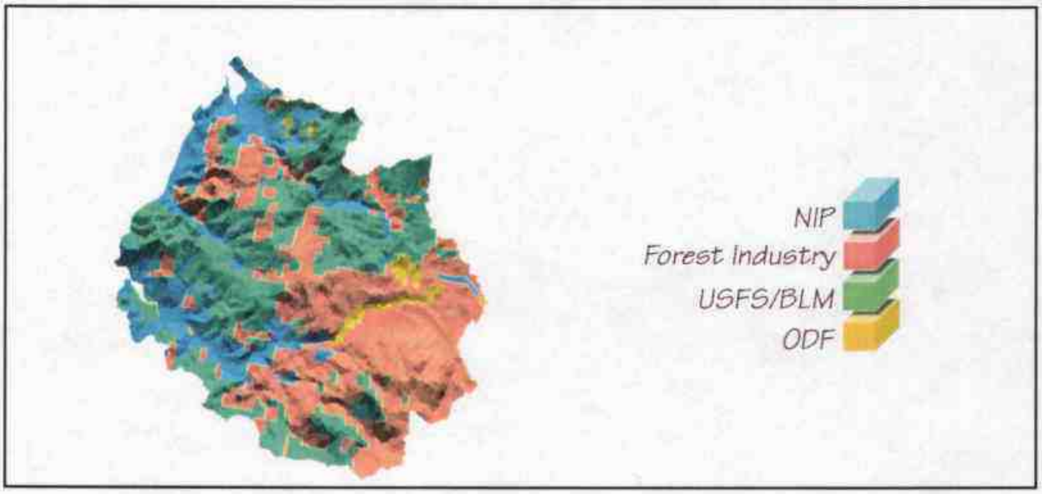

Figure 3 Ownership map of study area

Initial Forest Conditions

The study area contains an assorted mix of vegetation, including 12 different coniferous forest stand types as well as hardwood stands and patches of small woodlands. The classification of the various vegetation types was done previously in the CLAMS project and then adapted for this study. This facilitated the interpretation of the GIS layers that were pre-designated in the CLAMS format. The dominant vegetation class is broadleaf, which encompasses 23,681 acres (23% of total area). The second largest vegetation class is medium mixed and pure conifer, totaling 24,031 acres (20% of total area).. A complete breakdown of acreage of vegetation by owner and vegetation class is in Table 2. See Table 3 for a complete list of all vegetation classes and their attributes

VEGETATION CLASS	TOTAL ACRES	FS/BLM	NIPF	FOREST INDUSTRY	STATE
NON-FOREST	392	0	386	6	0
WOODLAND & OTHER	5,903	680	5,187	0	36
BROADLEAF	23,681	5,435	8,936	8,683	627
CONIFERS < 20 YEARS OLD	42,015	11,046	3,808	26,584	577
CONIFERS AGES 20 - 80	24,031	17,482	772	5,289	488
CONIFERS > 80 YEARS OLD	5,728	5,431	22	43	232
Totals	**101,749**	**40,074**	**19,111**	**40,605**	**1,960**

Table 2 Vegetation breakdown by ownership group

There are some vegetation patterns that are worth noting related to ownership. NIPF landowners have a plethora of land that contains small woodlands and broadleaf stands (14,000 acres out of 19,111) and a limited amount of coniferous forests (approximately 5100 acres out of 19,111). Hardwood stands and small woodlands in this particular ownership group are located primarily in riparian zones. Public land holdings (BLM & USFS) are dominated by old growth forest types; nearly half of their land base is conifer stands older than 45 years. In contrast, forest industry has 95% of their land base (38,574 acres), in stands that are less than 40 years old. These patterns are indicative of the different management objectives of each ownership group.

Parcel Designation

Individual management units (MU) were delineated in the study area. Each MU carried all necessary attributes that are required for the modeling process. These attributes included ownership group, specific owner, area, site class, MU number, and vegetation class.

Identification of MU's was originally done by the CLAMS project and their process served as the base for my MU designation. To identify individual MU's or as CLAMS refers to them, basic simulation units (BSU), the first step was to create an elevation map by using a 30-meter Digital Elevation Map or DEM. This layer is used to help identify streams and ridgelines. The next step was to identify the flood plains or headwaters of each stream. These three pieces of information were integrated to identify BSU's every 500 meters from the headwaters. This means that every 500 meters from the headwaters down the stream to the ridgelines are designated as a BSU. The next step was to overlay contour and ownership GIS layers to cut excessively long polygons and limit polygons to ownership boundaries. The final step was to dissolve or eliminate BSU's that fall below a certain area threshold (in this case 10 acres).

Each MU was assigned the appropriate attribute data that was required for modeling. In order to achieve this, vegetation, ownership and soil site class GIS layers were created in a raster-based format (grid) using ArcInfo v7.2 (Environmental Systems Research Institute 1995). Each layer was then overlaid with the BSU layer. Using the REGION command in ArcInfo, ownership, vegetation and site indices were assigned to each MU. The REGION command assigns a specific attribute to each MU in the grid layer based on majority or average function depending on the type of attribute. The final MU layer was delineated into approximately 8,700 MU's, each having its own ownership, vegetation and site class attributes.

Management Prescriptions (X)

One of the following management prescriptions was assigned to each management unit in the optimization.

1. Low intensity- clearcut between ages 45-85 with no thinning.
2. Medium Intensity- clearcut between ages 45-85 with a commercial thinning.
3. Medium Intensity II- clearcut between ages 45-85 with a pre-commercial and commercial thinning.
4. High Intensity- clearcut between ages 45-85 with a pre-commercial and commercial thinning and fertilization applied before each thinning.
5. Wildlife thinning I - Two commercial thins and no clearcut.
6. Wildlife thinning II – Two commercial thins and clearcut between ages 55-105.
7. No clearcut or thinning - grow only.

Prescriptions 1-4 and 7 were derived from a survey of management intentions conducted by the Oregon Department of Forestry (Oregon Department of Forestry 1999).

The prescriptions range in silvicultural intensity and rotation length. Prescriptions 5 and 6 were implemented to provide prescriptions that theoretically can produce old growth stand characteristics rapidly while providing some revenue.

Thinning regimes for each prescription were based on the results of the ODF study. Pre-commercial thinning occurred at an average stand age of 15 to 20 years and 30 to 45 years for commercial thinning. Commercial and pre-commercial thins removed thirty percent of the standing volume. Rotation lengths for each prescription ranged from 45 to 105. Once management units were clear-cut harvested, they were eligible to be reassigned to any of these management prescriptions.

The only restrictions were a 120-acre maximum clearcut size and a no harvest restriction within a 100-foot buffer around larger order and fish bearing streams, in satisfaction of the Oregon Forest Practices Act (1999). Management units that were classified hardwood or small woodlands were not managed for timber production and were assigned the "grow only" prescription.

Growth and Yield Projections

Timber harvest and thinning volumes were predicted for all coniferous-forested stands using ORGANON (Hann et al. 1995) a single tree type simulator for softwoods for Northwest Oregon. Organon calculates growth volume and other stand attributes from user-provided tree lists. The next section describes how tree lists were identified for this study.

Tree Lists

Each conifer forest vegetation class for the study area was converted into a tree list. Certain attributes of each vegetation class were required to create accurate tree lists. These attributes included trees per acre (TPA), quadratic mean diameter (QMD), average stand diameter, and average stand age per vegetation class. The CLAMS study is currently creating tree lists for each individual 30-meter by 30-meter pixel, or cell, for the entire CLAMS study area.

Stand attributes for each vegetation class, for this study, were derived based on the average value of each attribute from specific tree lists that CLAMS had established for each pixel. Final tree lists were generated by comparing the resulting averages to attributes of tree lists that are contained in the Forest Inventory Analysis (FIA) (USDA Forest Service 2000b)and Current Vegetation Survey (CVS) (USDA Forest Service 2000a). FIA data was used for non-industrial and industrial lands and CVS data was used for Forest Service, BLM and State lands. The FIA and CVS data both include plot-level inventory data of forested lands across Oregon, detailed by county. Tree lists for each ownership group were delineated from the appropriate data set that corresponded to the calculated attributes.

The resulting tree list parameters that were used for each forest vegetation class are outlined in table 3. Hardwood and small woodland vegetation classes were not transformed into tree lists because there were no growth and yield projections for these vegetation classes.

VEGETATION CLASS	QMD (INCHES)	AGE (YEARS)	TPA
NON-FOREST	N/A	N/A	N/A
WOODLAND & OTHER VEGETATION	N/A	N/A	N/A
BROADLEAF	N/A	N/A	N/A
OPEN (CLEAR CUTS)	0	0	0
SMALL MIXED	14.73	30	600
SMALL CONIFER	14.67	30	500
MEDIUM MIXED	22.06	35	426
MEDIUM CONIFER	26.64	40	314
LARGE MIXED	36.71	45	172
LARGE CONIFER	41.39	55	231
VERY LARGE MIXED	40.9	107	125
VERY LARGE CONIFER	55.65	85	144
VERY SMALL MIXED	7.97	20	650
VERY SMALL CONIFER	7.71	20	561
REMNANTS	63.67	>120	25

Table 3 Vegetation Class Attributes

Soils Maps

A map of individual management unit site indices was created to facilitate tree growth and yield projections. This process integrated multiple non-digital and digital sources into one complete digital layer. Sources included the Siuslaw National Forest (Siuslaw National Forest 1999), Natural Resource Conservation Service data compiled from their projects SSURGO (USDA - Natural Resources Conservation Service 1999a) and STASGO (USDA - Natural Resources Conservation Service 1999b), and Soil Surveys produced by the Department of Agriculture (Department of Agriculture et al. 1997). Missing data were interpolated using a simple linear regression model that used elevation, aspect, and slope as independent variables. The completed soil data were aggregated into four site classes: 50-year site indexes of 76, 99, 124, and 132.

Timber Valuation (R)

Timber value (R), was defined as the present value of timber harvest revenue, less treatment cost over twenty 5-year decision periods in a 100 year planning horizon, plus the value of standing timber at the end of the planning horizon using a 4% discount rate:

$$R = \sum_{t=0}^{20} ((P_t H_{tx} - C_t) / (1 + r)^{5t}) \quad + V_{end} / (1 + r)^{100} \qquad (2)$$

Where:

P_t = stumpage value of timber in period t ($/mbf)
H_{tx} = harvest volume in period t from prescription x
C_t = cost of treatment in period t
r = discount rate - 4%
V_{end} = value of standing timber at end of planning horizon

Stumpage price equals log price minus harvest and haul costs. Log prices were three saw, a common log grade, Douglas-fir pond values in first quarter 2000 for Northwest Oregon Willamette Valley, and were assumed to stay constant throughout the 100-year planning horizon (Forest Management Division 2001). Log prices were reduced by 10% for thinning revenue due to decreased quality of timber that is extracted during thinning. Table 4 shows the log prices that were used.

Treatment	Pond Value (Year 2000 dollars)
Clear-cut	$610
Commercial Thinnings	$549

Table 4 Treatment revenues

Harvesting costs were estimated using an equation supplied by the chief economist for the ODF (Gary Lettman, personal communication, May 1, 2001). The equation was based on volume extracted per acre and assigns higher logging costs for thinning and low volume clear cuts.

$$\text{Harvesting cost (\$/MBF)} = \$311.05 - \text{MBF extracted} \wedge -0.3773 \qquad (3)$$

Haul costs, given in $/mbf, were also derived from a personal contact with Gary Lettman (Gary Lettman, personal communication, May 1, 2001).

Harvest volumes for each prescription were based on the recoverable volume estimates made by ORGANON. Treatment costs were derived from the ODF survey of harvesting costs (Oregon Department of Forestry 1995). Table 5 shows the treatment costs that were used. The base year for treatment costs was 1995 and was inflated to year 2000 by using the producer price index (United States Bureau of Labor Statistics 2001).

Treatment	Cost (1995)	Cost (2000)
Site Prep	$159	$214.79
Planting	$119	$160.76
Pre Commercial Thinning	$93/Acre	$125.63/Acre
Fertilization	$75/Acre	$101.32/Acre

Table 5 Treatment costs

The value of the standing timber at the end of the planning horizon, V_{end}, was calculated based on the last management prescription that fell outside the planning horizon. The stand was assumed to be assigned that management prescription and clear-cut timber harvest age in perpetuity. That is, if a stand was clearcut in year 60 and scheduled to be clearcut again in year 110, V_{end} of the stand would be based on a 50-year rotation in perpetuity.

For each MU:

$$V_{end} = \sum_{t = t_{end}}^{T} (P_t{*}H_{tx} - C_t) / (1 + r)^{(T\text{-}t\ end)} + SEV / (1 + r)^{(T - t\ end)} \qquad (4)$$

Where:

$$SEV = \sum_{t=0}^{T} \{(P_t{*}H_{tx} - C_t) / (1 + r)^t\} * [1 + 1 / ((1 + r)^{T-1})] \qquad (5)$$

Biodiversity (B)

Biodiversity is measured using a weighted species richness function, which gives a premium to more taxonomically unique species. The biodiversity measure is an extension of Montgomery et al. (1999). Biodiversity is calculated as the sum across species of a joint probability of persistence measure for each species on the landscape as it is altered by management activities:

$$B = \sum_{s=1}^{167} w_s \{(\prod_{t=0}^{20} V_5 (X_{st}))\, V_{100} (X_{s,end})\} \qquad (6)$$

Where:

w_s = uniqueness ranking for species s
V_5= 5 year species probability of persistence function
X_{st} = Population index of species s in Period t
V_{100} = 100 year species probability of persistence function

This method portrays the contribution of individual species on overall landscape biodiversity. The data and calculations to compute each component of B are described in the next section.

Species (S)

Included in the final list were 167 terrestrial vertebrate species, including 57 mammals and 110 avian species (Northwest Habitat Institute 2000). The list was edited to remove aquatic species, since the project did not model aquatic habitat. A complete species list is given in appendix 1.

Species Uniqueness (W_s)

Each species was given a uniqueness ranking based on a hybrid of the taxonomic diversity index proposed by Vane-Wright et al. (May 1990; Vane-Wright R.K. et al. 1991). The value is derived by totaling the number of nodes contained in taxonomic progression of each species. The node counts are then inverted and normalized to one for the least unique species of the taxonomic divisions of the study. Individual species uniqueness values are seen in appendix 1. This formulation of uniqueness weights species with less closely related taxonomic relatives higher than species with more taxonomically close relatives. The range of uniqueness values across species was 1 to 3.4.

Probability of Persistence Function (V_s)

A single logistic joint probability of persistence function was constructed for each of the 167 species in the species list. With the logistic form, the highest incremental gain in persistence occurs in the middle range of the persistence curve (steepest slope), while having little or no gain in species persistence (V_s) when population indices are excessively small or large. This indicates that the marginal product of conservation is greatest when population indices are in the middle section of the probability of persistence function. A 5-year and 100-year form of the persistence function were estimated.

$$V_{st}\ (5\ \text{years}) = (1 + \exp(-4.78 - 1.3 * (\log(P_{st}/100))))^{(-1)} \tag{7}$$

$$V_{st}\ (100\ \text{years}) = (1 + \exp(-3.1 - 1.9 * (\log(P_{st}/100))))^{(-1)} \tag{8}$$

Where:

V_{st}= probability of persistence of species S in period t

P_{st} = Population index of species S in period t

Species population estimates were calculated from the Oregon National Heritage Foundation Rare and Threatened species list (Oregon National Heritage Program 1998). The Oregon National Heritage Foundation provides statewide imperilment rankings of animal species in Oregon. The imperilment rankings range from 1 to 5 with 1 being the most critically imperiled and 5 being the most secure. The levels of imperilment that are established have a corresponding population size, which was used to determine the current populations index (P_{s0}) of all species contained in the species list.

The same method that was used in Montgomery et al. (1999) was used to derive the probability of persistence curve. The method is based on International Union for the Conservation of Nature (IUCN) Red List (Mace 1994) and Oregon National Heritage Foundation population indices and their associated imperilment rankings (Oregon

National Heritage Program 1998). The logistic persistence curve was fitted through three points, which represent the thresholds between imperilment rankings as defined by the IUCN. The three threshold points were then normalized for 5-year and 100-year probability of persistence, to produce the 5-year and 100-year probability of persistence functions. Each species was assigned an imperilment ranking and associated population index from the Oregon Natural Heritage Program report (Oregon National Heritage Program 1998). This represented the current imperilment status of each species. A graphical representation of the 100-year probability of persistence curve can be seen in Figure 4.

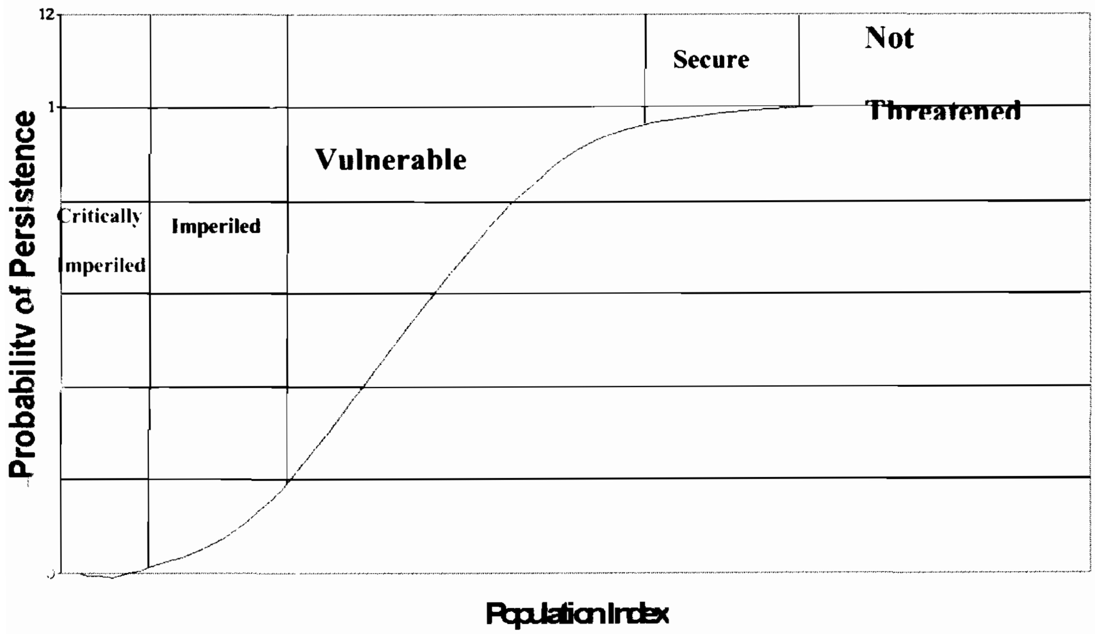

Figure 4 100- year species persistence function

Available Habitat

The amount of available habitat was determined by totaling the amount of preferred habitat clusters that exist in each habitat type. Habitat clusters are groups of adjacent MU's with the same habitat type. Habitat preferences ($HPREF_{st}$), which are used in the calculation of available habitat as a proxy for habitat quality, were established for each species on a 1-to-10 scale for five different types of forested habitat. The five forested habitat types are detailed in figure 5. Habitat preferences were derived from White et al. (1997), and were determined by a set of biologists familiar with each species.

NCON- 0 – 20-year-old mixed conifer stands
MCON – 20- 80-year-old mixed conifer stands
OCON – 80 or greater year old conifer stands
MIXED – woodland and other vegetation
DECID- deciduous dominated stands

Figure 5 Habitat attributes

Habitat clusters were only counted as contributing to species populations if they met or exceeded the size of individual species home ranges. Each species' home range size was derived from the Forest Service publication "Management of Wildlife and Fish Habitats in Forests of Western Oregon and Washington (U.S.D.A. Forest Service Pacific

Northwest Region 1985) and White et al. (1997). Individual species home ranges were grouped into five categories: 1,12, 75, 150, and 400 acres. Species home range serves as a proxy for the amount of habitat that is required to support an individual species member.

After prescriptions and clear cut times were assigned to each management unit, the model examined each management unit and evaluated the size of each habitat cluster that is formed by itself and its adjacent neighbors. The algorithm then assigned the habitat cluster to not only a habitat type but also to the appropriate home range size of habitat type (H_{rit}) where

r = habitat type (1= OCON, 2 = MCON, 3 = NCON, 4 = DECID, 5 = MIXED)
i = habitat size or home range(1,12,75, 150, 250 acres)
t = time period

To explain this concept in more detail I will use a rudimentary example. In this case there is a polygon that is 20-40 year old mixed conifer in period 1 and it has area of 15 acres. The model then explored adjacent polygons to determine which ones have the same habitat type in that same period. Once this is done it is determined that there is a habitat cluster that encompassed 78 acres in period 1. This cluster is then added to H_{211}, H_{221}, and H_{231}. These classifications represent habitat type 2 that falls within habitat sizes 1,12 and 75 acres in period 1.

Habitat Index (HINDEX$_{st}$) and Population Index (P$_{st}$)

The habitat index was used to measure the impact of management activities on population indices and the probability of persistence of individual species. The magnitude of the impact depends on the effect of the land management activities on available habitat. The habitat index is equal to the amount of available habitat units weighted by the habitat preference measure of each species.

$$HINDEX_{str} = H_{rit} \; * \; HPREF_{rs} \qquad (9)$$

Where:

$HINDEX_{str}$ = Habitat index for species s in period t for habitat type r
H_{rit} = Amount of habitat type r in home range size i in period t
$HPREF_{rs}$ = Habitat preference ranking of habitat type r for species s

The habitat index is then converted to the population index, X_{st}, using a scaling factor, δ_s, for each species based on the initial habitat conditions of the larger surrounding area:

$$\delta_s = X_{s0} \, / \, HINDEX_{s0} \qquad (10)$$

Where:

δ_s= scaling factor for species s
P_{s0} = Population index of species s at time 0 based on Oregon National Heritage Foundation imperilment rankings
$HINDEX_{s0}$ = Amount of available habitat units in the larger area for species s at time 0

This scales the habitat index to the population index used to calculate the probability of persistence function (V).

$$X_{st} = \delta_s * HINDEX_{st} \qquad (11)$$

Where:

X_{st} = population index of species *s* at time *t*
δ_s = Scaling factor for species s
$HINDEX_{st}$ = Amount of available habitat units in the study area for species *s* at time *t*

Individual species population indices were linked to the habitat index so a change in the habitat index would be accompanied by a proportional change in population index. The population index for individual periods is calculated as the amount of available habitat in the study area in each period multiplied by the scaling factor (Equation 11). Probability of persistence, V (X_{st}), was then determined based on the population index (Equations 7 and 8). To evaluate the effects of timber management on the landscape over time, the habitat index was computed for each time period following management activities that affect the vegetation cover.

Model Parameters

The productive capacity model, fully specified, is:

$$\text{MAX} \quad R = \sum_{t=0}^{20} ((P_t H_t - C_t) / (1 + r)^{5t}) \quad + V_{end} / (1 + r)^{100} \qquad (12)$$

Subject to:

$$B = \sum_{t=0}^{20} w_s \, \{(\prod V_5 (X_{st})) \, V_{100} (X_{5,\,100})\} >= \bar{B}$$

This model was solved using the neighborhood search heuristic optimization technique of simulated annealing. A model flow diagram is shown in appendix 2. Simulated Annealing (S.A.) is a stochastic optimization approach to solving complex nonlinear and linear problems (Lockwood and Moore 1993). S.A. is based on an algorithm that simulates the cooling of a material in a heat bath, the process of annealing. In the annealing of materials, the material is heated past its melting point and then cooled back into a solid state; the structural properties of the cooled solid depend on the rate of cooling. If the material is cooled too quickly the material is less structurally sound then if it was cooled slowly. Additionally, if the material is heated back up during the cooling process and then cooled again the cooled solid will be even more structurally sound. The process of annealing can be converted into an algorithm that can solve optimization problems by sampling neighborhoods randomly and allowing the acceptance of inferior solutions according to some probability. The neighborhoods are a proxy for the various energy states of the material and the acceptance probability can be seen as the reheating of the material during annealing.

The S.A. algorithm in this problem randomly chooses MU's and alters the management prescription and rotation length of that MU. The objective function or new energy state is then reevaluated to determine if the value has decreased or increased. S.A determines whether or not to accept the new solution based on two parameters temperature and the acceptance probability. If the solution is improving then the solution is automatically accepted; if it is non-improving the algorithm has two choices. If the difference between the value of the previous and new objective value is less than the acceptance probability, the new solution is accepted. If the difference is greater, the new solution is rejected and the original prescription and rotation length are put back.

The initial objective value or a function of the objective value served as the initial temperature and was reduced by the cooling rate after a certain number of iterations or changes to the solution. As the temperature decreased, the probability of accepting inferior solutions reduces. The annealing process is completed after the temperature falls below the ending temperature which is set by the programmer.

The initial temperature was initially set to allow a 50% probability of accepting an inferior solution. The probability decreases to < 1% by the time the ending temperature is reached. The cooling rate was set at 0.998, which allows for a thorough exploration of the solution space with a relatively low number of iterations (approximately 400).

The model was designed to allow infeasible solutions to be accepted while the model was at the same temperature. Before the temperature was reduced the solution was checked for feasibility. If the solution was infeasible the solution was reverted to the last best feasible solution, and the model repeated the iterations at the same temperature. The solution could be infeasible in two respects. Either the solution violated the clear-cut size constraint or fell below the target biodiversity level.

Model Verification

The results of the model were compared to solutions returned from the Great Deluge Algorithm. The Great Deluge is another Monte Carlo neighborhood search method. This was done to insure the results of the simulated annealing algorithm were comparable to the results derived from alternative problem formulations. The Great Deluge algorithm works approximately the same as S.A. in that it randomly chooses MU's and changes the rotation length and prescription until it finds the theoretical maximum value of the objective function. Great Deluge requires three parameters that control the effectiveness of the algorithm: initial water level, ending water level, and the rate of water rise. These parameters are analogous to the temperature, ending temperature, and cooling rate parameters of simulated annealing and followed the same formulations. The initial water level was set to allow approximately a 50% chance of accepting inferior solutions, and the ending water level allowed a < 1% chance. The water rate was set at .998 to allow maximum exploration of the solution space. Each model run had approximately 2 million iterations.

SPECIAL CASE STUDY –

Evaluation of the Efficiency of Likely Management Activities

The production possibility frontier was developed without regard to current land ownership objectives. Hence, while it represents the potential of the landscape, it is not likely to be representative of the realized productivity of the site. The reason is that private landowners do not have incentives to manage their lands for anything other than revenue production. Public lands are managed in response to the current political environment and legislation.

A simulation model was created to simulate the likely management intentions for each ownership group currently and for the future. This allowed me to evaluate the level of efficiency that exists with respect to the productive capacity of the site. Identifying this point is useful in determining the costs that are associated with managing landscapes based on political boundaries rather than on natural boundaries.

Model Structure for Special Case Study

The special case model is an adaptation of the productive capacity model. MU's were classified by ownership group and then modeled according to the management intentions that are described below. Private landowners were assumed to manage their lands to maximize the PNV of timber revenue, and public lands were managed according to regulations that govern the individual agencies. Modeling different management intentions created different objectives across the landscape, unlike the productive capacity model that had a single unifying objective for the entire study area that included both timber revenue and biodiversity.

Private landowners were further classified into NIPF and Forest industry. Management prescriptions for non-industrial private (NIPF) lands were based on the results of the Oregon Department of Forestry's management intention survey that was described earlier. Each of the management prescriptions was assigned to a percentage of the NIPF MU's derived from the ODF survey (ODF, 1999). The percentages are seen in table 6. The model randomly assigns a clearcut time to each NIPF management unit until the present net value of timber revenue of the entire NIPF land base is maximized, assuming constant prices and costs.

Prescription (PX)	% of Current Land Base Under PX	% of Future Land Base Under PX
Low intensity	20	55
Medium Intensity II	5	5
Medium Intensity	70	35
High Intensity	5	5

Table 6 – NIPF management Prescription percentages

Industry lands were not pre-assigned management prescriptions. The model randomly chose the prescription and the appropriate rotation length that maximized the present net value of timber revenues of all the forested industry lands.

Forest Service and BLM lands were assigned "grow-only" prescriptions. Forest Service lands in the study area do not lie within the management matrix delineated in the Northwest Forest Plan so they were not managed for timber production but instead were on a "grow-only" management regime. State lands that lie within the study area are a State By-Way and a State park, so they were designated as grow-only prescription as well. All other modeling parameters were the same as the productive capacity model.

The same restrictions were applied in the special case models that were used in the productive capacity model: no clearcuts larger than 120 acres and no harvesting in a 100-foot buffer around fish bearing and higher order streams. Lands that were designated hardwood, woodlands, or non-forested were assigned a grow-only prescription. All lands were included for in the calculation of biodiversity.

IV. Results

I first report the results of the productive capacity model. I discuss the production possibility frontier and then the results of the maximum biodiversity and maximum PNV scenarios. This is followed by the results of the special case model.

PRODUCTIVE CAPACITY MODEL

Production Possibility Frontier (PPF)

The PPF was identified for biodiversity and PNV and is shown in figure 6. The PPF shows all combinations of biodiversity and PNV that are efficient. The PPF is estimated by the extreme edge of all the solutions that were identified. The relatively flat shape of the frontier indicates that there does not have to be a substantial decrease in timber revenue to produce increasingly greater amounts of biodiversity. The greatest gains in biodiversity come between biodiversity values of 224 to 228, with an associated loss in timber revenue of $31 million. Alternatively, moving to biodiversity values near the corner solution of the frontier comes at a very high cost. For instance an increase in biodiversity from 228 to 229 reduces timber revenue by $32 million, $1 million more then a four point increase in the middle region of the frontier.

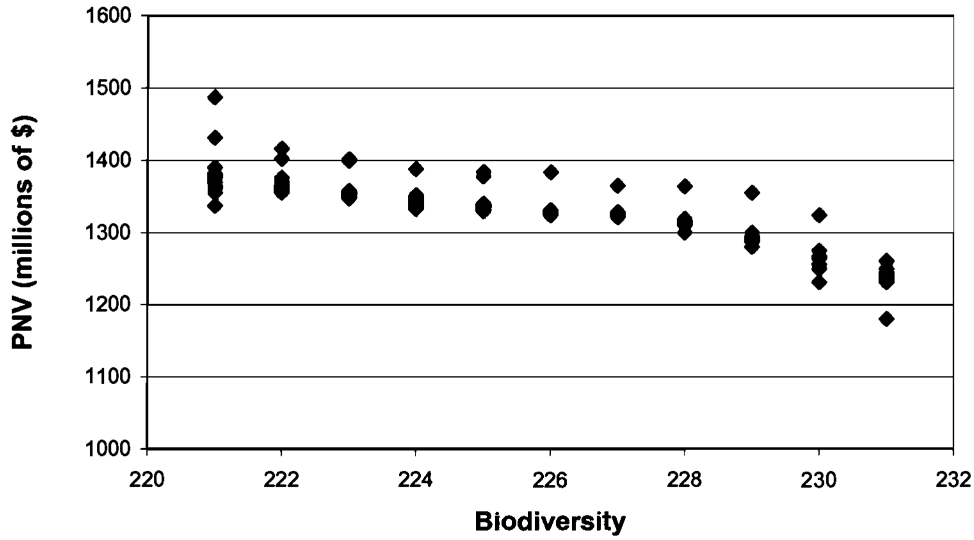

Figure 6 – Production Possibility Frontier

The results indicate that the focus of management actions should happen where the marginal gain in biodiversity comes at the least cost. Achieving maximum levels of biodiversity could come at a cost that is higher then society is willing to pay. Associating societal relative value curves for biodiversity and timber revenue with the PPF would identify socially efficient outputs of biodiversity and timber revenue. The point of tangency between the relative value and PPF curves would identify the socially efficient solution.

Max Timber Revenue (R) Scenario

Maximum timber revenue is achieved when the biodiversity constraint, right-hand side parameter B, equaled zero. The maximum timber revenue that was achieved was $1.48 billion with a biodiversity value of 221. Timber revenue equals the revenue produced from timber extraction less costs as given in Equation 2.

$$R = \sum_{t=0}^{20} ((P_tH_t - C_t) / (1 + r)^{5t}) \quad + V_{end} / (1 + r)^{100} \qquad (2)$$

The model has control of two parameters that influence the amount of revenue (R) that is produced. These parameters are rotation length and the type of silvicultural prescription. The combination of these two parameters dictated the amount of timber revenue that was produced.

Rotation Length

Average rotation length in the maximum R scenario was about 50 years, which corresponds to the Faustmann rotation. With no value given to biodiversity the model cuts MU's that have trees that are growing at a slower rate then the interest rate, approximately year 50. This rotation length does not create stands that meet the criteria for old growth.

No stands in this scenario that were eligible for harvest were prescribed a no-cut solution. All stands were regeneration harvested at least once in the planning horizon. On average, stands that were initially over 45 years old were clear-cut twice and stands under 45 were clear cut at least once with the most stands having the second clearcut occurring near the end of the planning horizon.

Volume Harvested

In the first periods of the model large harvests were recorded due to the over-abundance of older stands on the landscape, particularly on public lands. These stands were immediately regenerated and harvested again when they reached economic maturity, which is why harvest volumes jump to a high level near the middle of the planning horizon. Figure 8 shows the harvest volumes for each period.

Vegetation Outlook

Vegetation patterns reflect the short rotation length and regularity of clear-cut harvests that were previously discussed. A plethora of medium-aged stands and young stands are created in the first half of the planning horizon, a function of the economically over-mature stands primarily located on public lands. In this scenario the amount of economically over-mature stands remains relatively constant while the amount of young stands is steadily decreasing. Acreage in medium-aged stands stayed relatively constant throughout the planning horizon.

The scenario results in a fragmented vegetative landscape. No large patches of any forest habitat are produced, except for medium-aged stands. As a result, species with large home range size requirements were affected the most by management activities. Also, species that require older stands were affected due to the lack of old growth stand production in the early periods of the scenario. The 120-acre clear-cut restriction also plays a role in the lack of large patches of habitat being formed. Removing the restriction would not have changed the diversity of vegetation that was created, but might have allowed some more flexibility for the model to create larger patches of habitat in general, as well as more revenue production. The amount of habitat per period is seen in table 7, and vegetation maps are seen in appendix 4.

Habitat Class/ Period	5	10	15	20
Young Conifers	30,820	18,458	13,231	8,781
Medium Conifers	32,913	43,067	45,842	39,012
Old Conifers	3,234	5,443	7,895	19,174

Table 7 Acres per habitat class max PNV scenario

Max Biodiversity Scenario (B)

The maximum biodiversity for the study area was 231 with an average timber revenue equaling $1.26 billion. This was obtained by solving the productive capacity model for the maximum biodiversity corner solution of the PPF. The model was then solved using the maximum biodiversity value of B = 231 as a constraint and maximizing the amount of timber revenue that was produced.

Biodiversity Components

The biodiversity value represents the cumulative total of species probability of persistence across the planning horizon multiplied by individual species uniqueness as seen in equation 5.

$$B = \sum_{s=1}^{167} w_s \{(\prod_{t=0}^{20} V_5 (X_{st})) V_{100} (X_{st})\} \qquad (5)$$

One determinant of biodiversity is the amount of available habitat that exists for each species. As expressed earlier, habitat units only count if the habitat cluster meets or exceeds individual species home ranges. Species uniqueness and habitat preferences also are an important factor in determining the level of biodiversity that exists. I will explain how these parameters affected the results of the maximum biodiversity scenario.

Home Range and Habitat Preferences

The maximum biodiversity scenario garnered the greatest benefit in probability of persistence over the planning horizon to species that have small home ranges as well as species that have favorable habitat preferences to most forest habitat types. Average home range size of species that had the greatest population increases was approximately 13 acres. The average habitat preference for those species was approximately 6 for forested habitat types. In contrast, species with large home ranges and unfavorable habitat preferences for most forested habitats had the greatest reduction in persistence over the planning horizon. The average home range for these species was approximately 215 acres and average habitat preference was approximately 3 for forested habitats.

Species Uniqueness

Species uniqueness, which adds increased weight in the biodiversity function to species that are more taxonomically unique, played an important role in how the model behaved to maximize biodiversity. Species with low uniqueness rankings (< 2) had a lot of variability in average population index over the planning horizon. These species had an average population index change with respect to their initial population index of approximately (-11.6%) and had a standard deviation of approximately 22%. The middle range of uniqueness values (2<U < 3) had variability in population index, with a standard deviation of population index of approximately 26%. Species with the highest uniqueness rankings showed the most variability, with a standard deviation of 30% but there were only 7 species in this category. Figure 7 shows the change in populations of species with respect to their uniqueness ranking.

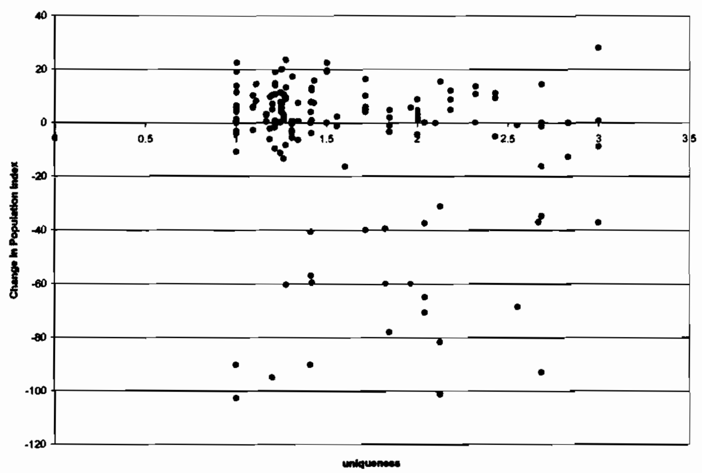

Figure 7 – Population Index change from initial population indices with respect to Species Uniqueness

Vegetation

The vegetative landscape for the maximum biodiversity scenario was very diverse. All vegetation types were represented throughout the 100-year planning horizon. Blocks of old growth stands were produced along with large blocks of medium-aged stands. Young coniferous stands were not produced at the same levels as in the maximum revenue scenario. This was because the model allocated a greater diversity of habitats across the landscape to accommodate for more species needs. Young stands in the maximum timber revenue (R) scenario were basically replaced by old growth stands in the maximum biodiversity scenario. Table 7 details the distribution of forested vegetation per period. The maps in appendix 3 show how the vegetation would look throughout the 100-year planning horizon.

Habitat Class/Period	5	10	15	20
Young Conifers	11,409	14,482	14,085	8,689
Medium Conifers	46,568	38,151	33,300	32,306
Old Conifers	8,851	14,335	19,583	25,972

Table 8 Acres of habitat per period- max biodiversity scenario

Silvicultural Attributes

Average rotation length for the maximum biodiversity scenario was approximately 65 years. This rotation length created more stands that characterized old growth characteristics. The old growth vegetation class included all stands with QMD greater then 30 inches or stands greater then 80 years old, as certain management activities had the potential to produce the necessary QMD before 80 years.

In contrast to the maximum R scenario, a large portion of management units (1705 out of 4500) that were eligible for harvest were prescribed a “grow-only” solution. This played a substantial role in the decreased harvest levels as well as in the production of more old growth stands relative to the maximum R scenario.

Total harvest volumes extracted from the landscape in this scenario were substantially less than the maximum R scenario. Fewer mature stands were harvested in the initial periods, which created much of the gap in revenue production between the two scenarios. Harvest volumes in both scenarios per period are shown in figure 8.

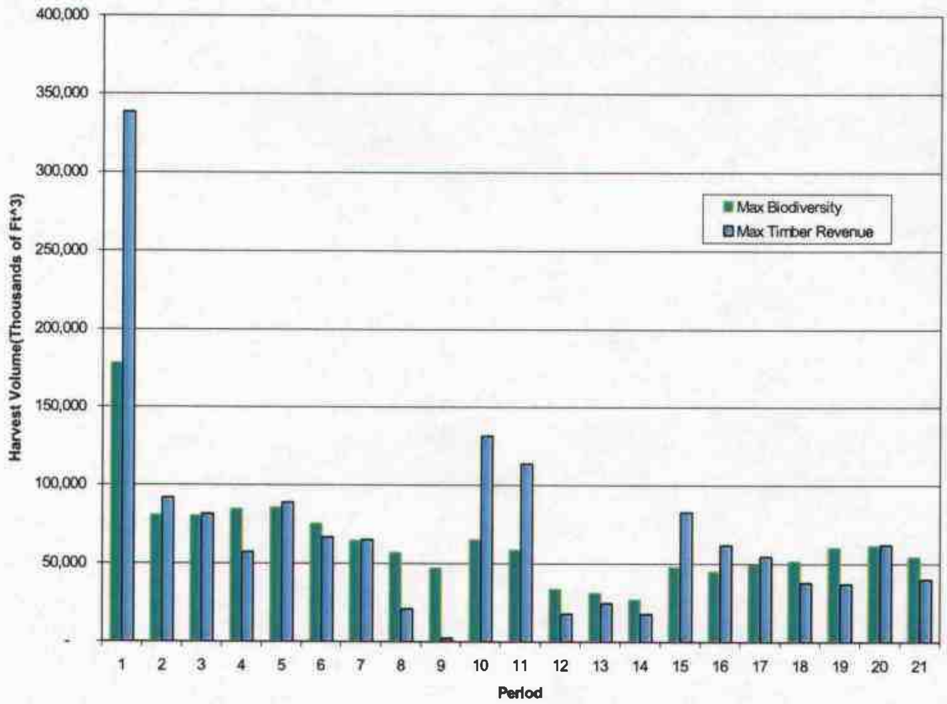

Figure8 Harvest Volume Per period

SPECIAL CASE STUDY

The special case study examined the effects of differing management objectives for each ownership group. This identifies the level of inefficiency that exists relative to the productive capacity for the site that was identified in the PPF. The PPF was identified without regard to current land ownership objectives. Hence, while the PPF represents the productive potential of the landscape, it does not represent the likely realized productivity of the site. The reason is that there are no incentives for private landowners to change their management objectives. Revenue maximizers, primarily private landowners, have no incentive to manage for biodiversity. Public lands are simply following agency guidelines that do not necessarily guide them to manage for either biodiversity or timber revenue.

The special case produced some very interesting results with respect to the productive capacity model. The level of biodiversity that was produced was 227 with corresponding timber revenue of $360 million. The timber revenue is significantly less than the average of all productive capacity results ($1.2 billion). The difference in timber revenue can be attributed to the removal of public lands from harvest eligibility.

The results show that proposed management intentions are highly inefficient with respect to the two outputs that were modeled. Higher levels of biodiversity could be produced without reducing timber revenue. Conversely timber revenue could be increased dramatically without reducing the level of biodiversity. This result can be seen table 9, which shows the results of the special case study, compared to the results of the maximum biodiversity and PNV scenarios.

Scenario	*Timber Revenue (V)*	*Biodiversity (B)*
Max V	*$1.38 billion*	*221*
Max B	*$1.24 billion*	*231*
Special Case	*$350 million*	*227*

Table 9 Results of Special case Study with respect to MAX B and V scenarios

Vegetation Patterns

The resulting vegetation patterns are exactly analogous to ownership boundaries. Public landholdings are dominated by old growth stands due to the quasi-reserve system. NIPF and forest industry lands have less old growth and more medium aged and younger stands, which is analogous to the results of the maximum timber revenue scenario. Although more old growth stands are produced, the overall vegetative landscape lacks the diversity that the other scenarios exhibit. Maps of special case vegetation are in Appendix 5.

Solution Verification

The outcomes of the Great Deluge algorithm were approximately 99% of the simulated annealing results, indicating that the results of the simulated annealing are comparable to the results achieved using an alternative problem formulation using the Great Deluge algorithm. Comparative results are in table 10.

Biodiversity	Simulated Annealing- Average PNV (millions of $)	Great Deluge- Average PNV (millions of $)
221	1,396	1,368
222	1,392	1,406
223	1,384	1,342
224	1,374	1,356
225	1,361	1,355
226	1,346	1,332
227	1,329	1,327
228	1,310	1,311
229	1,286	1,286
230	1,252	1,250
231	1,210	1,210

Table 10 Comparative results of algorithms

V. Conclusions

The production possibility frontier indicates that the study area has the ability to produce both biodiversity and timber revenue. The relatively flat shape of the frontier indicates that there does not have to be a substantial decrease in timber revenue to produce increasingly greater amounts of biodiversity as measured by expected weighted species richness. The greatest gains in biodiversity come in the middle region of the PPF. Alternatively, moving to biodiversity values near the corner solution of the frontier comes at a very high cost.

The special case showed that current management actions are inefficient with respect to the two outputs that were modeled - overall biodiversity as measured by weighted species richness and PNV of timber harvest. However, other values from the forest may be relevant and should be considered in moving from this study to its policy implications. For example, Forest Service policy in the Pacific Northwest forests is currently driven by needs of threatened and endangered species with old growth forest preferences (Thomas and Raphael 1993). In my analysis, 167 terrestrial species were considered and rare or threatened species were not given special treatment. Each species' marginal contribution to biodiversity depended on two things: diversity weights and the slope of the viability curve at their particular population index. For key species that are of concern for the Forest Service, the slope of the viability curve was flat and the diversity weight was not great enough to override that fact.

Some policy implications from this study are:

1. Forest management should occur at the landscape level. Currently forest landscapes are managed at the ownership level. Natural systems do not abide by ownership boundaries and as such should not be managed with regards to them. Landscape level planning has been mentioned as the possible future for managing our forests (Independent Multidisciplinary Science Team 1999). This would require that ownership groups discuss management intentions and develop landscape plans. This poses some obvious problems such as market-controlling activities and well-known industry policies regarding sharing business-sensitive information to competitors.
2. Owners should be provided with incentives to manage their lands for multiple use. There needs be a system that can replace the timber revenue that is lost due to changing management objectives. Public forestlands could be more actively managed to produce the monies necessary to fund the system and perhaps provide compensation.
3. Public forests should be managed more proactively to produce not only a greater variety of habitats, but also to improve overall forest health. The forest can be managed to produce some level of timber revenue that can be used to fund incentive programs.

There is an ever-evolving balancing act between utilitarian and preservation goals. There is no quick-and-easy answer to the problem of achieving a balanced in managing forested landscapes. This study does suggest some methods that can be used to determine how utilitarian and conservation goals can be implemented to provide more of both timber revenue and biodiversity.

One of the main contributions of this work is the use of spatial data in determining species probability of persistence for large numbers of species, so that not only is the amount of habitat important but also where it is located on the landscape. Also, this study incorporates stand-level management decision units to achieve prescribed objectives, a vast change from previous studies that mainly prescribe one prescription across the landscape without regards to on-the-ground implementation.

There are some limitations to the implementation and evaluation of the results of the study. The most important limitation is the biological information. Knowledge about individual species habitat requirements, home range sizes, and interdependence with other wildlife species is an evolving science that has just begun to produce detailed information about individual species. As this knowledge base grows, so will the accuracy of habitat modeling which is an important component of this type of research.

The future of this research will involve looking at even larger landscapes and modeling multiple land uses. This study only focused on forestlands but understanding conversion between land uses and the effects of urban sprawl are important issues in understanding what can be done to insure species persistence and timber revenue. Other improvements can be made in spatial elements of habitat requirements including using species dispersal distances in conjunction with home ranges to model species that require multiple habitats for foraging and nesting.

My analysis suggested that current management goals come at a great cost in terms of both timber harvest and biodiversity. However, it does not give much guidance as to whether it is worth the cost to change. Future studies must design a way to evaluate the relevant tradeoffs of managing for biodiversity and timber revenue, in particular a way to value biodiversity in a way that it can be used to directly measure the true benefits that are received by increasing the amount that exists.

The field of tradeoff research is quickly evolving to better answer tough questions about the managing lands for multiple objectives. Model improvements along with better solution methods, like heuristics, have allowed researchers to explore complicated and diverse problems. This study is just one example of the possibilities that exist in modeling tradeoffs associated with managing landscapes for multiple uses.

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